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Hearing Protector Attenuation and Noise Exposure Among Metal Manufacturing Workers

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Abstract

Objectives—This study utilized personal noise measurements and fit-testing in order to evaluate the association between noise exposures and personal attenuation rating (PAR) values among participating workers, and second, to compare the attenuated exposure levels received by the workers and the British Standards Institute's (BSI) recommended noise exposure range of 70–80 dBA.

Design—We measured HPD attenuation among a sample of 91 workers at 2 US metal manufacturing facilities, through performance of personal noise dosimetry measurements and HPD fit-testing over multiple work shifts. We compared this testing with participant questionnaires and annual audiometric hearing threshold results.

Results—The average 8-hr Time-weighted Average (TWA) noise exposures for study participants was 79.8 dBA (SD 7.0 dBA), and the average PAR from fit-testing was 20.1 dB (± 6.7 dB). While differences existed between sites, 84% of the 251 PAR measurements resulted in effective protection levels below the recommended 70 dBA (indicating overprotection), while workers were underprotected (i.e., effective exposures >80 dBA) during <1% of monitored shifts. Our results also demonstrated a significant positive relationship between measured noise exposure and PAR among non-custom-molded plug users (p=0.04). Non-custom-molded plug wearers also showed a significant increase in PAR by sequential fit-test interaction (p=0.01), where on average, subsequent fit-testing resulted in increasingly higher HPD attenuation. Workers at site 1 showed higher PARs. PARs were significantly related to race, even when adjusting for site location. While age, hearing threshold level, task, and self-reported tinnitus showed no significant effect on

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individual PAR in an unadjusted model, site, race, and sand- or water-blasting activities were significant predictors in adjusted models. Within-worker variability in TWAs and PARs across repeated measurements was substantially lower than variability between workers.

Conclusions—Careful selection of HPDs is necessary to minimize instances of over-protection to workers in low and moderate occupational noise environments. The use of fit-testing in hearing conservation programs to evaluate PAR is recommended to avoid overprotection from noise exposure while also minimizing instances of under-attenuation.

INTRODUCTION

An estimated 4.1 million workers are exposed to daily noise levels that exceed the National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limit of 85 dBA (A-weighted decibels) Time-weighted Average (TWA) (NIOSH 1998), and 22 million workers may be exposed to hazardous noise annually (Tak et al. 2009). Approximately 27.7 million adults 20–69 years old in the US live with a noise-induced hearing loss (NIHL) (Hoffman et al. 2017), making noise a critical workplace exposure in terms of associated health impacts. Recognizing this issue, in 1983 the Occupational Safety and Health Administration (OSHA) began requiring that employers enroll individuals with exposures exceeding 85 dBA in a hearing conservation program (HCP). These workers must have their hearing thresholds monitored annually by their employers in order to detect occupational hearing loss, and must be provided with hearing protection devices (HPDs) and training on how to prevent NIHL (OSHA 1983).

The Environmental Protection Agency (EPA) requires that HPDs sold in the US be labeled by their manufacturers with a Noise Reduction Rating (NRR) (EPA 1979), and in order to meet OSHA's Hearing Conservation Amendment, employer HPD selection is based on the NRR and a 7 dB spectral adjustment factor. An extensive body of literature indicates that NRRs do not accurately reflect the attenuation achieved in field studies on actual workers (Berger et al. 1998; Smith et al. 2014; Murphy et al. 2016; Rocha et al. 2016). OSHA also requires that employers have a variety of HPDs available for workers to use, but the agency does not mandate testing of the performance of these devices as used by individual employees. While not a legal requirement, personal fit-testing of the performance of individual workers with their own HPDs, which yields a personal attenuation rating (PAR), is considered a best-practice procedure to ensure HPD fit and to possibly reduce hearing loss and workers' compensation claims (Laws 2014).

Employer HCPs generally focus on HPD-use and insertion technique without confirming that an appropriate amount of protection is obtained; this validation is an important consideration in many high-noise industries (Schulz 2011; Voix & Hager 2009), where HPDs may not provide protection levels high enough to protect from NIHL (Groenewold et al. 2014; Verbeek et al. 2014). Training on insertion techniques like those provided by employer HCPs has been consistently shown to increase PARs in workers (Nodoushan et al. 2014; Smith et al. 2014; Samelli et al. 2015), while lowering the variability in PAR throughout and across work shifts (Tufts et al. 2013). For workers with very high noise exposures (e.g., 8-hour TWA levels in excess of 95 or 100 dBA), this is the safest approach to prevent workers from over-exposures that can occur with improper HPD use (Lutz et al. 2015). However, in work environments where TWA noise levels are close to the 85 dBA action level (above which hearing protector use is recommended by OSHA), a high PAR risks overprotecting workers.

While guidelines to avoid over-protection are lacking, the British Standards Institute (BSI 2016) and European Union (CEN 2016) have recommended a target attenuated exposure level (i.e., exposure level considering HPD attenuation) of 70–80 dBA, with an optimal attenuated exposure level of 75 dBA. Providing attenuation beyond this level may interfere with personal communication and safety. Workers in these environments may reduce their use of HPDs due to concerns about safety, and workers who are over-protected risk not hearing and properly responding to warning signals and alarms. Additionally, employees in HCPs have rated the ability to communicate as the second most important aspect of HPDs, behind attenuation (Goncalves et al. 2015). Overprotecting workers may reduce their ability to effectively communicate safety information (Berger 2000), and these effects may be greater among those with a hearing loss (Giguère & Berger 2016). Issues with detecting warning signals (Laroche et al. 2018) and disrupted or inefficient communication may be an underlying cause of increased injury risk. Workers with clinical hearing impairments have been demonstrated to have a higher injury rate in the workplace (Girard et al. 2014; Cantley et al. 2015a; Cantley et al. 2015b; Estill et al. 2017), further supporting the need to preserve communication ability in noisy workplaces. Additionally, tinnitus may be a risk factor for occupational injury in noise-exposed jobs (Cantley et al. 2015b), and may also be associated with increased use of HPDs compared to individuals without tinnitus (Beach et al. 2016). Consequently, while emphasis has previously been placed only on decreasing the risk of NIHL by assuring the highest level of protection against noise, utilizing personal noise exposure levels when performing fit-testing in order to choose earplugs with appropriate levels of protection for the ambient noise environment should also be considered to reduce the risk of over-protection.

To address this issue, our team used a real-ear attenuation at threshold (REAT) system for fit-testing and standard shoulder noise dosimetry measurements to investigate the relationship between noise exposure and HPD attenuation in this sample. Our study had 2 aims: first, to evaluate the association between noise exposures and PAR values among participating workers, and second, to compare the attenuated exposure levels received by the workers and the British Standards Institute's (BSI) recommended targeted attenuation of 70–80 dBA (BSI 2016).

MATERIALS AND METHODS

Overview

The procedures for this study were approved for by the Yale University School of Medicine's Human Investigation Committee (HIC: 0509000588). Noise measurements and fit-testing were performed from November 2014-July 2015 by research team members at 2 US manufacturing facilities. All participants were selected from a group of participants enrolled in a longitudinal study monitoring daily noise exposure at a single metal manufacturing company (McTague et al. 2013). Workers in this cohort were enrolled in a workplace hearing conservation program and required to wear HPDs while at their job site. All workers were fitted and provided custom-molded earplugs free of charge at their enrollment. Workers who found the custom-molded plugs uncomfortable or inconvenient were encouraged to choose a disposable earplug of their liking (pre-molded flange or a variety of foam plugs). Participants wore personal noise dosimeters over the course of 3 work shifts, and completed a REAT HPD fit-test and brief survey during each of these shifts. Each of these methods is described in detail below. Inclusion criteria for this study were: enrollment and active participation in the ongoing longitudinal study and regular use of custom-molded or insert-type hearing protectors. As part of their participation in the ongoing longitudinal study, each participant in the current study received points towards a gift card-based compensation scheme. All participants were compensated using a point system and gift card distribution schedule previously established by the longitudinal study and received approximately $13 for each of the 3 shifts during which they completed the fit-test and personal dosimetry. Averaged site-level results and recommendations were provided to both participating facilities.

Personal Noise Dosimetry

Researchers attached 3M Edge 4 noise dosimeters (St. Paul, Minnesota) to each participant's shoulder on the side of their dominant hand, within 10 cm of their ear (ISO 2013). Dosimeters were configured according to the company's exposure limit for occupational noise (equivalent to the OSHA Hearing Conservation Amendment, i.e., a 90 dB criterion level with a 5 dB time-intensity exchange rate and 80 dB threshold, and an allowable dose of 50%, (OSHA 1983). The dosimeters recorded average (L_{AVG}) and maximum (L_{MAX}) noise levels at 1-minute intervals throughout each monitored shift, as well as the 8-hour equivalent TWA and highest maximum levels. Research staff started the dosimeters at the beginning of the shift and stopped and downloaded them at the end of the work shift. All dosimeters were calibrated according to the manufacturer's specifications immediately before and after each use.

Fit-Testing

Fit-testing was performed at a pre-arranged time during each participant's monitored shifts. Research staff escorted individual participants from their work station to a quiet office or room outside the production area to conduct this testing. Participants were tested using the Michael and Associates' FitCheck Solo (State College, Pennsylvania) REAT fit-testing system. This software program has been verified against ANSI S12.6–2008 (ANSI 2008) standards (Byrne et al. 2017). The program was installed on a laptop and used a mouse-based patient switch to measure participants' responses, and a sound-attenuating FitCheck earcup (TDH-49P) connected to the laptop with a 3.5mm electrical connector to deliver audible test stimuli. The headphones had an average calculated noise attenuation of 27 dB across all measured frequencies, and attenuated 23.9 dB (SD=2.5 dB) at 250 Hz, 33.6 dB (SD=2.7 dB) at 500 Hz, 40.2 dB (SD=3.3 dB) at 1000 Hz, and 37.4 dB (SD=2.7 dB) at 2000 Hz. Researchers instructed participants not to adjust their earplugs between leaving their work station and starting the fit-test; the audiocups were placed over participants' ears and earplugs by the researcher. Before testing, participants were instructed to select the lowest level they could possibly hear by using the mouse scroll wheel to reduce the level of the stimulus until they could no longer hear it, then returning it to a level where they could barely hear it. Occluded testing was performed first, followed by removal of the earcups and earplugs, repositioning of the earcups, and unoccluded testing. Due to the limited time that workers were permitted for testing, attenuation was measured in occluded and unoccluded conditions at only four frequencies: 250, 500, 1000, and 2000 Hz. The FitCheck program calculated a PAR at each frequency (PAR_F) as the difference between occluded and unoccluded hearing levels, and also computed an overall average A-weighted PAR (PAR_A) across all frequencies (Equation 1). At the end of each test, participants were provided with their results, and workers who received a <12 dB PAR_A were instructed that low levels of protection may result in an increased risk of NIHL. The FitCheck system was calibrated at the beginning and end of each monitoring day.

$$Awt_N = 10\log_{10}\sum_{f}^{N}10^{L_{Af}/10} - 10\log_{10}\sum_{f}^{N}10^{\left(L_{Af} - Af\right)/10} \quad \text{Equation 1.}$$

Questionnaires

The participants also completed a brief questionnaire on their monitored shift. The questionnaire asked workers 4 HPD-related questions: 1) the type of HPD they used; 2) how many times they removed their HPDs in a typical day; 3) the amount of time their HPDs were worn during a workday; and 4) whether or not they thought their HPDs gave them adequate protection. Participants also reported the date of the measured shift, their job title, and their main task for the day. Additionally, as part of the ongoing longitudinal study, a baseline questionnaire was completed by all individuals that contained questions regarding other noisy jobs and hobbies, and ear-related medical procedures and health issues, including tinnitus and family history of hearing loss.

Hearing threshold levels

Hearing threshold level data for the subjects in this study were available through an academic-corporate partnership between the company and Stanford University and Yale University. This partnership is designed to inform the development and implementation of occupational health and safety policies for the company. Participants in this study received annual hearing tests at the audiometric frequencies of 0.5, 1, 2, 3, 4, 6, 8 kHz from technicians certified by the Council for Accreditation in Occupational Hearing Conservationists (CAOHC) in audiometric test booths. Participant audiograms were maintained in a centralized electronic database accessible to the researchers under the academic-corporate data sharing agreement. The audiometric test results from the test closest in time to each participant’s 3 work shifts measured in this study were used as a measure of their hearing ability at the time of participation in this study.

Statistical Analysis

Statistical analyses were conducted using SAS version 9.4 (SAS Institute) and Stata version 14 (College Station, TX). We computed descriptive statistics overall and by location for all

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personal dosimetry TWA data, questionnaire responses, PAR measurements (including frequency-specific PAR_F and average PAR_A levels), and annual audiometric hearing threshold levels. We used Intra-class Correlation Coefficients (ICC) to evaluate within- and between-worker variability for both noise and PAR measurements. We then computed the effective protection (i.e., the estimated noise exposure level underneath each participant's HPDs) on each measured work shift using Equation 2 (Arezes & Geraldes 2009),

$$P_{EFF} = TWA_{ij} = PAR_{Aij} \quad \text{Equation 2.}$$

where P_{EFF} is the effective protected level for worker i on shift j, TWA is the measured personal dosimetry noise level, and PAR_A is the average PAR measured via FitCheck. This equation assumes that each participant was wearing the HPDs for 100% of their measured shift and does not account for periods of time where the worker removed their HPDs (i.e., going into a quiet office to speak with a supervisor).

In an effort to evaluate the influence of the peakiness (i.e., presence of brief but intense exposures to noise throughout the shift) on achieved PARs, we applied Equation 3, which we adapted from a study of construction workers (Seixas et al. 2005):

$$Peakiness_{ij} = 10 \times \log_{10}\left(\frac{1}{T}\int_{1}^{n} \frac{10^{\frac{L_{MAXijk}}{10}}}{10^{\frac{L_{AVGijk}}{10}}}\right) \quad \text{Equation 3.}$$

where L_{AVG} and L_{MAX} represent the 1-minute interval data collected by the noise dosimeters on the ith worker on the jth shift, T is the full-shift length (in minutes) and k is the first to the nth 1-minute interval of the shift. We then explored whether the association of this measure of peakiness to PAR values and TWA noise levels.

We used scatterplots and Spearman correlation coefficients to evaluate the bivariate relationships between questionnaire responses, hearing threshold levels, and PAR, TWA and P_{EFF} levels. We used paired and unpaired Student's t-tests to evaluate differences in means between continuous variables. We used mixed-effect linear regression models, with a random effect for participant to account for the repeated measurements on each participant, to evaluate the within- and between-worker variance components. We then used mixed-effects linear regression models, again with a random effect for participant, to identify predictors of achieved PAR and P_{EFF} levels. Variables were retained during the model development process where p<0.10 for all potential confounders and effect modifiers that were identified *a priori*.

RESULTS

Demographics

A total of 91 workers were monitored for an average of 2.8 work shifts each (SD=0.97, range=1–6, Table 1). Fifty-six (61.5%) of the workers were from Site 1, and 35 (38.5%) from Site 2. Mean participant age was approximately 50 years (SD=9.0 years), and was consistent across both facilities. Just over 60% of participants were male, and 77% of the participants identified their race as white, although both of these factors varied slightly by location, with Site 1 having a larger percentage of women (48.2%) and participants of color (21.4%). While hearing thresholds were similar across the 2 sites, a larger percentage of workers at Site 2 reported other noisy jobs and hobbies, a family history of hearing loss, and tinnitus; most notably, only 28.6% of workers at Site 1 participated in hunting/shooting activities, while 57.1% of workers at Site 2 reported hunting/shooting. Additionally, 25.7% of workers at Site 2 reported that they had other noisy jobs, but only 3.6% of workers at Site 1 had another noisy job. Only 3 participants (5.4%) reported having undergone an ear-related surgery, and all of these workers were from Site 1.

Noise Exposure

We collected 255 shoulder noise dosimetry measurements: 158 from Site 1, and 97 from Site 2 (Table 2, Figure 1). The results for 1 participant (at Site 1) were removed due to a measured TWA value of <35 dBA, which was untenable given ambient noise levels at that facility. Overall, the combined mean 8-hour TWA for Sites 1 and 2 was just under 80 dBA (SD= 7.0 dBA), with Site 1 noise levels (81.1 dBA) significantly higher than levels at Site 2 (77.6 dBA, p<0.001). Site 1 also had a significantly higher mean L_{MAX} level than Site 2 (p=0.01). Workers engaged in sand- or water-blasting activities had the highest overall noise exposure and the lowest degree of variability in their noise exposures (mean TWA=86.4 dBA, SD=1.9 dB), while workers who reported finishing and grinding tasks also had high noise exposures, but more variability in their exposure (mean TWA=85.7 dBA, SD=4.9 dBA, data not shown). Workers performing inspection tasks had the lowest noise exposures and highest variability (mean TWA=73.6 dBA, SD=6.9 dB), while workers performing lifting, loading, material handling, and general labor had generally low noise levels and low exposure variability (TWA=77.5 dBA, SD=2.5dB, data not shown). Although low noise levels were observed, workers reported wearing their HPDs for an average of 7.3 hours (7.4 hours at Site 1 and 6.8 hours at Site 2, Table 1). ICC values indicated a high degree of consistency in noise exposure across the 3 measured shifts (R^2=0.72, p<0.001). Bivariate analyses showed a significant correlation between TWA and L_{MAX} (R^2= 0.81, p<0.001); to address this issue, we did not model TWA and L_{MAX} together.

Fit-Testing

Four fit-testing measurements could not be conducted due to logistical difficulties in getting workers to the quiet room for testing during their work shift. Among the 251 successful fit-tests, the mean overall PAR_A for all types of HPDs was 20.1 dB, with the highest PAR_F observed at 2000 Hz (31.1 dB), and the lowest at 250 Hz (14.7 dB, Table 2). Background noise levels in fit-testing locations were as follows: 51.5 dBA (SD=4.6 dBA) at 250 Hz, 47.8 dBA (SD=5.0 dBA) at 500 Hz, 44.3 dBA (SD=5.1 dBA) at 1000 Hz, and 41.3 dBA (SD=4.9

dBA) at 2000 Hz. Significant differences in PAR_A were seen between sites (p=0.02) with Site 1 having higher values than Site 2 (20.9 and 18.7 dB, respectively). No significant differences were found in frequency-specific PARs when comparing custom- and non-custom HPD wearers. Workers performing lifting, loading, material handling, and general labor tasks had the highest PARs with the lowest SD (mean PAR=22.1 dB, SD=3.2 dB), while workers performing washing or cleaning tasks had the lowest average PAR (18.8 dB, SD=7.1 dB, data not shown). Individuals who performed sand- and water-blasting tasks had lower PAR_A variability (SD=6.6 dB), while workers engaged in sawing or cutting activities showed highest variability (SD=8.8 dB). Our evaluation of ICC indicated a slightly weaker, though highly statistically significant, degree of consistency in PAR across the 3 measured shifts when compared to noise measurements (R^2=0.54, p<0.001). No statistically significant differences were found between PAR_A measured on custom-molded HPDs (mean 20.5, SD 6.4 dB) and non-custom-molded devices (mean 19.1, SD 7.4 dB); however, non-custom-molded HPD users showed a significant increase in PAR and decrease in P_{EFF} with each additional fit-test (p<0.01 and p=0.01, respectively, Fig. 2). While the majority of workers at Site 1 wore custom-molded earplugs (90.5%), significantly fewer workers at Site 2 did (33.3%). Workers who did not wear custom-molded earplugs chose from a variety of roll-down foam earplugs (22.3% of fit-tests) and pre-molded earplugs (8.4% of fit-tests, data not shown).

Noise Exposure and PAR Modeling

Estimated P_{EFF} values were lower than the target level of 70–80 dBA, with 84% (N=211) of values falling below 70 dBA, and only 2 measurements (< 1%) above 80 dB (Fig. 3). Noise and PAR were not significantly related overall (p=0.13), but when stratified by custom- and non-custom-molded HPD users (Fig. 4), the effect of noise on PAR was significantly stronger among the users of non-custom-molded plugs (Fig. 4a, p value for slope coefficient 0.04) than custom-molded plugs (Fig. 4b, p value for slope coefficient 0.60). Hearing threshold levels and self-reported tinnitus were not significant predictors of PAR (Table 3). In mixed-effect linear regression models, site and race were each significant predictors of PAR when modeled individually. When analyzing the task-based variables while accounting for site and race, only performing sand- or water-blasting was a significant predictor of PAR. Since all participants who performed sand- or water-blasting came from Site 1, these factors were not modeled together. When combined into the most parsimonious model, white workers and workers at Site 1 had higher PARs overall (Table 3). When divided by site, workers at Site 1 who reported performing sand- or water-blasting during their monitored shift had a significantly lower PAR after adjusting for race (Table 3), even though their noise exposure levels were higher than individuals who did not perform these activities during their shift (86.4 vs. 80.7). White workers were less likely to wear custom-molded earplugs than workers of color (p=0.046). In modeling the odds of over-protection, TWA (p<0.001) and being a sand- or water-blaster (p=0.02) were protective against over-exposure (OR=0.82 and 0.16, respectively, data not shown). Odds of over-protection did not differ significantly by HPD type (p=0.50); additionally, we found no significant difference in PAR or P_{EFF} values by fit-test number (i.e., PAR was not increasing based on researcher feedback, data not shown). Although we had no significant changes in our results or levels of significance when we incorporated the hours of HPD use during the work shift, when limiting our model to workers with exposures >80 dBA (136 cases: 99 at Site 1, and 37 at Site 2), all of our model findings became null (likely due at least in part to reduced statistical power in this smaller and relatively homogeneous subsample), with the single exception of sandblasters, who continued to have a significantly lower PAR at Site 1 (slope coefficient=−4.6 dB, SE=2.2 dB, p=0.04) when controlling for race (data not shown).

DISCUSSION

We identified several factors associated with noise over-exposure and over-protection, which may place workers at increased risk of adverse health (e.g., NIHL) and safety (e.g., increased risk of injury) outcomes, respectively. While workers often achieve PARs below the NRR levels published by HPD manufacturers, even at a wide range of frequencies (Berger et al. 1998), our study focused on issues of over-protection, and our cohort consistently achieved PARs in excess of those which would be calculated using OSHA's NRR derating scheme. Using shoulder noise exposure monitoring and fit-testing of workers' HPDs as worn at their work stations, we demonstrated that a large percentage (84%) of our working population was over-protected and had a calculated P_{EFF} below the recommended 70 dBA (Fig. 3) (BSI 2016). This is consistent with previous studies on workers participating in our longitudinal study of daily noise exposures, where approximately 75% of measured in-ear noise levels were less than 85 dBA (Rabinowitz et al. 2013). However, our calculations may over-estimate the number of individuals overprotected, since we assume that HPDs were worn 100% of the shift. Some participants, particularly at Site 2, did not always work in areas where hearing protection was required, and therefore may have an actual PAR of zero for some periods instead of their fit-testing PAR, resulting in an overestimation of attenuation. While these low levels of noise exposure reduce the risk for NIHL, over-attenuation may increase the risk of worker injury by reducing their ability to hear instructions and warning signals (Berger 2000; Cantley et al. 2015a; Neitzel et al. 2015). Workers who are over-protected may also feel isolated at work (BSI 2016), resulting in reduced quality of life and work performance. However, Davis et al. (2011) found that some autoworkers may prefer over-protection in work locations where impulse noise is predominant (Davis et al. 2011). Only 2 measurements (1 worker) had a calculated P_{EFF} over the recommendation of 80 dB (BSI 2016); this individual may be at an increased risk of NIHL if they continue to be over-exposed.

Our results demonstrated a significant relationship between measured noise exposure and PAR among non-custom-molded plug users (Fig. 4). This relationship suggests that workers wearing non-custom-molded plugs may be adjusting the fit of their HPDs to achieve attenuation levels that they feel are commensurate with their workplace noise exposure. Additionally, non-custom-molded plug users also showed significant increases in attenuation across sequential fit-tests. This effect was not seen among custom-molded plug users, which is to be expected, since custom-molded earplugs generally result in more consistent PARs due to their structured fit (Tufts et al. 2013). While some studies have found that custom-molded plug users can have slightly higher attenuation ratings than non-custom-mold users (Neitzel et al. 2006), others have found slightly higher attenuation ratings among non-custom plug users (Tufts et al. 2013). Although our study found no significant difference in

PAR by HPD type, the increasing PAR and decreasing P_{EFF} that occurred for each fit-test may have had an effect on risk of over-protection among non-custom-molded plug users.

Our study also evaluated variability in both noise exposures (TWA) and PAR levels within- and between-workers. The results of our ICC analysis indicated that TWA was more stable across shifts than PAR; this is likely due to feedback received by individuals when their PAR values were low for the first fit test, although this trend did not reach a level of statistical significance. This feedback ultimately may have acted as pseudo-intervention and encouraged workers to obtain a better fit with their HPDs, increasing the variability of the measure. This is also supported by our finding of higher PAR variability for non-custom-molded plugs than custom-molded plugs, since workers would be more able to adjust the PAR of non-custom plugs upon receiving feedback, resulting in higher variability.

We found a significant relationship between race and PAR, which was unexpected and does not appear to have been noted or discussed in previous literature. While this relationship remained significant even when accounting for site location, it did lose statistical significance for site 2 only when modeling was stratified by site. This finding was likely influenced by HPD choice, where workers of color were more likely to use custom-molded plugs, which in this situation offered a lower PAR (although these results were not statistically significant). Use of HPDs has already been shown to be linked to acculturation (Rabinowitz & Duran 2001), and it may be that cultural practices with regards to HPD are linked to racial identity in some way. Race has already been noted as having differential association with HPD use among black and white workers (Hong et al. 2005), as well as between Hispanic and non-Hispanic white workers (Raymond et al. 2006), and perceptions of HPDs appear to differ by race (Crandell et al. 2004). Additionally, when we stratified the models by custom- and non-custom HPDs and controlled for site, race remained a significant predictor of PAR among custom-molded HPD wearers, where individuals who identified as white had higher PARs than non-white participants. For workers in our study, the use of lower PAR HPDs was likely protective due to the low noise levels and large percentage of workers who were classified as over-protected. However, similar findings in high-noise workplaces could be detrimental to workers of color, but due to the small number of participants in our study, these results should be taken with caution and warrant further investigation to determine whether they are site-specific or may be generalizable to other facilities.

Limitations

Our study had several limitations. For our exposure measurements, we used the participating company's occupational exposure limit, which involves a 5 dB exchange rate. This may not be the most health-protective method of noise measurement; NIOSH and most other agencies around the world instead recommend a 3 dB exchange rate for occupational noise assessment, although the scientific debate is on-going (Dobie & Clark 2014). Because of this, our use of the 5 dB exchange rate may have yielded noise exposures that underestimate the true risk of hearing loss or injury risk compared to a study utilizing a 3 dB exchange rate, which applies a greater penalty to high and fluctuating noise levels. This would result in overestimation of the number of workers who are over-protected and underestimation of the number of workers who are over-exposed. Nevertheless, the exposure limit utilized by the participating company is based on the 5 dB exchange rate, as are HPD recommendations for the 2 facilities, so use of the 5 dB exchange rate was warranted for this study.

Our fit-testing technique also had limitations. At the 2 facilities, fit-testing occurred in quiet room or office (~45–55 dBA overall, maximum 59.5 dBA) near the shop floor, but background noise levels in these locations varied between sites, between participants, and possibly even within participants across workshifts. Since the method of obtaining the PAR as a difference between 2 thresholds (occluded and unoccluded) assumes constant background noise levels, variations in background noise level during testing of a single frequency could have introduced bias into the overall PAR; however, we believe that any variation was likely random and only contributed to an increase in error and not a systematic bias of our results. Our use of sound-isolating earcups substantially reduced background noise levels during the FitCheck tests, further minimizing potential noise-related error. Additionally, REAT fit-testing systems are subjective measures that could present substantial variability within participants. However, our study demonstrated highly repeatable measures of PAR across multiple shifts, lending greater credibility to this subjective testing measure, and recent research has also demonstrated consistent results between REAT fit-testing and more objective testing methods (Valentin et al. 2017).

Finally, due to the low noise levels and high level of commitment to noise and hearing loss demonstrated by the company in our study, our results may not be generalizable to industry or metal manufacturing as a whole. Specifically, with the personal noise measurements obtained during our study, this workplace included many workers in their HCP who might not necessarily qualify for enrollment at the time of the study. While this conservative approach may seem unique to the facilities in this study, as noise levels continue to decrease in many US industries, other companies may begin adopting similar strategies, based on an assumption that a combination of lower noise levels and higher HPD attenuation ratings is optimal. This may increase the safety risks associated with over-attenuation in workplaces with exposure levels <85 dBA that rely on employee hearing protector use as a method of preventing NIHL. Fortunately, performing fit-testing to establish a PAR that complements individual employee noise exposure levels is a practice that can be generalized across industries with a wide variety of noise exposure levels and profiles.

Conclusions

Our study appears to be the first to perform repeated-measures fit-testing and personal noise measurements on a large sample of occupationally noise-exposed workers that also had hearing acuity data available. Our results demonstrate the need to incorporate fit-testing into hearing conservation programs to verify workers are being sufficiently protected for their noise exposure levels in order to reduce instances of over-attenuation which may increase the risk of workplace injuries. Additional studies of possible HPD over-attenuation are needed among workers with higher exposure levels and an unequivocal need for hearing protection.

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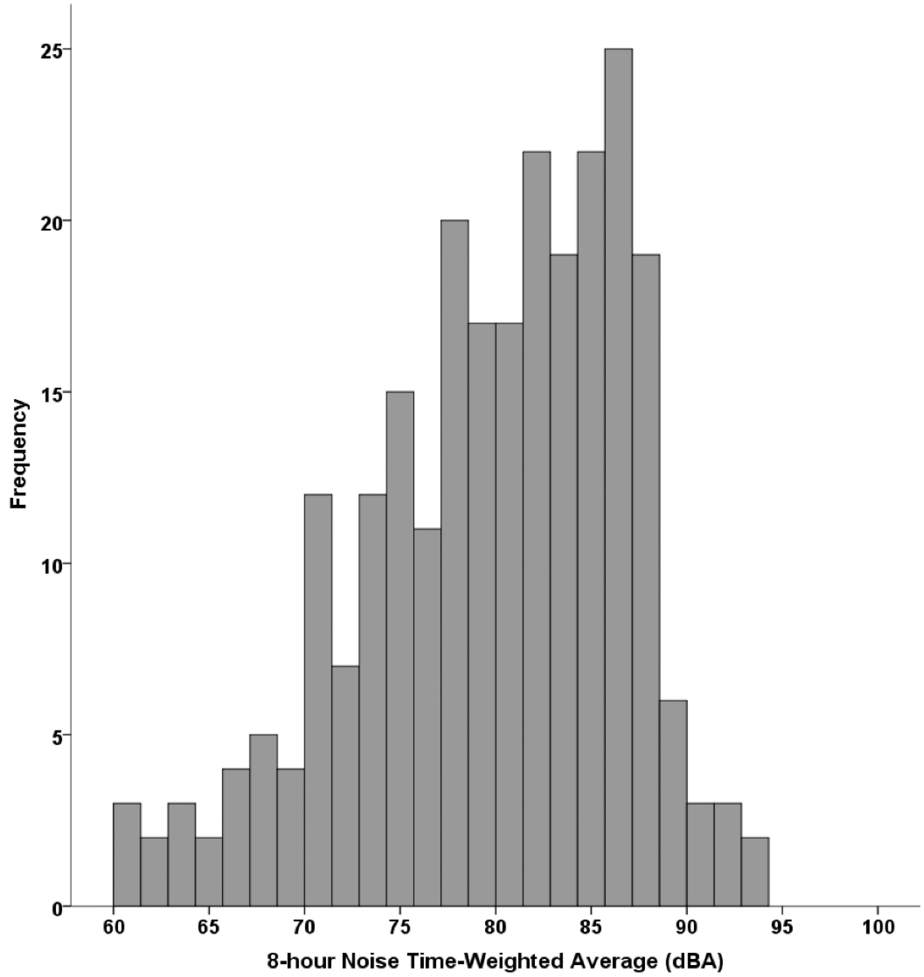


Figure 1.

Histogram of TWA noise exposures (dBA) among workers at 2 metals manufacturing facilities in the US (N=255).

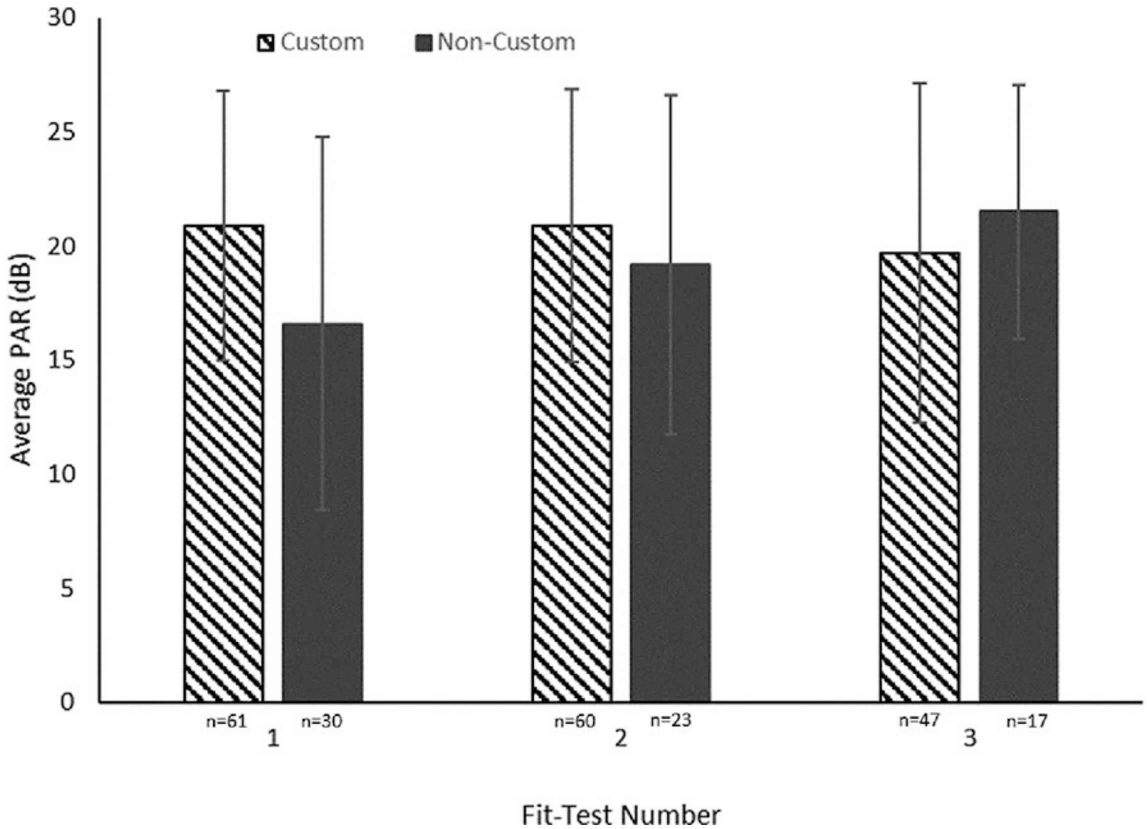


Figure 2.
Bar graph of personal attenuation rating (PAR) values by sequential fit-test number for workers wearing custom- (hashed bars) and non-custom-molded (solid bars) hearing protection devices at 2 metals manufacturing facilities in the US. Error bars represent ±1 SD.

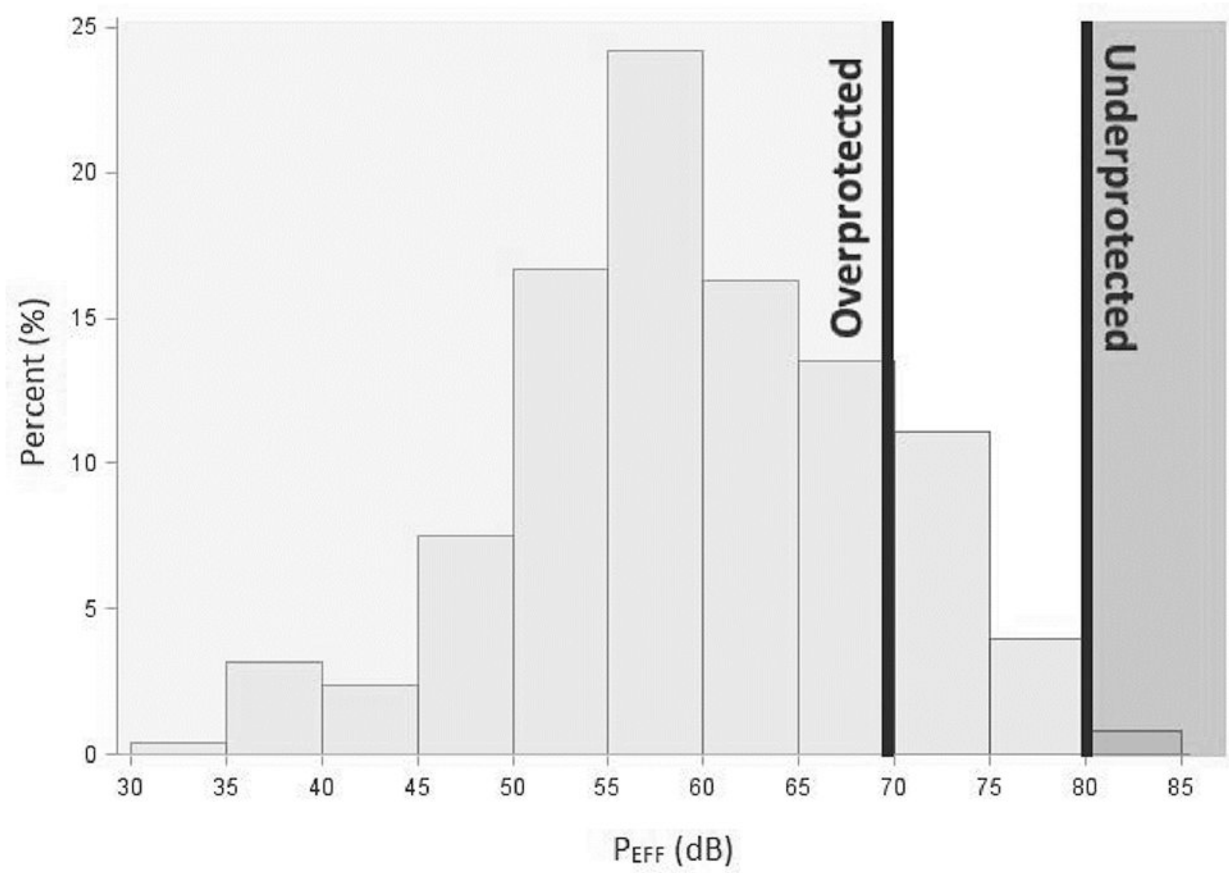
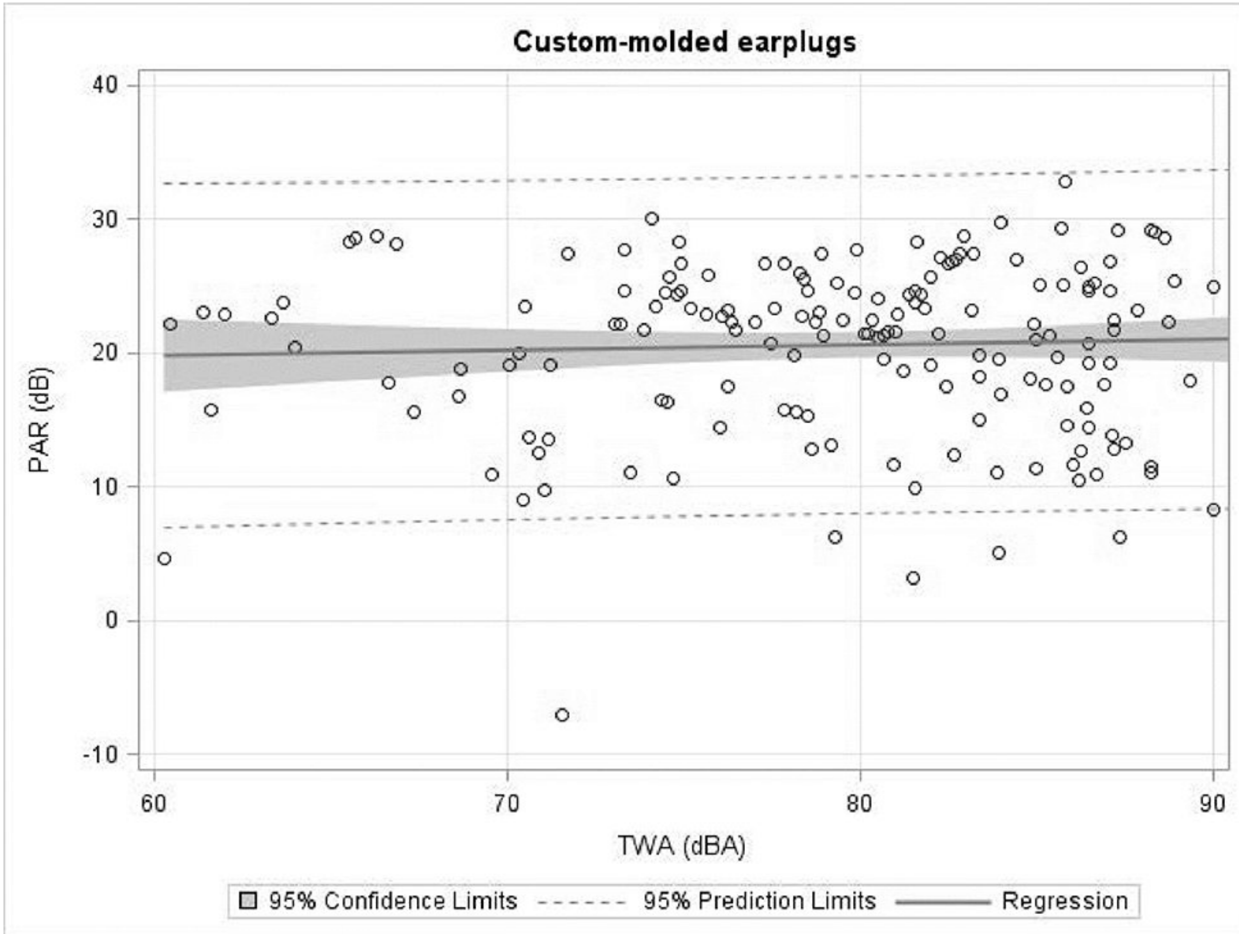


Figure 3.

Histogram of P_{EFF} values among workers at 2 metals manufacturing facilities in the US, where the shaded areas represent values that fall outside of the ideal 70–80 dB P_{EFF} range (BSI 2016).


Custom-molded earplugs
40
30
20
10
0
-10
PAR (dB)
60
70
80
90
TWA (dBA)
95% Confidence Limits
95% Prediction Limits
Regression

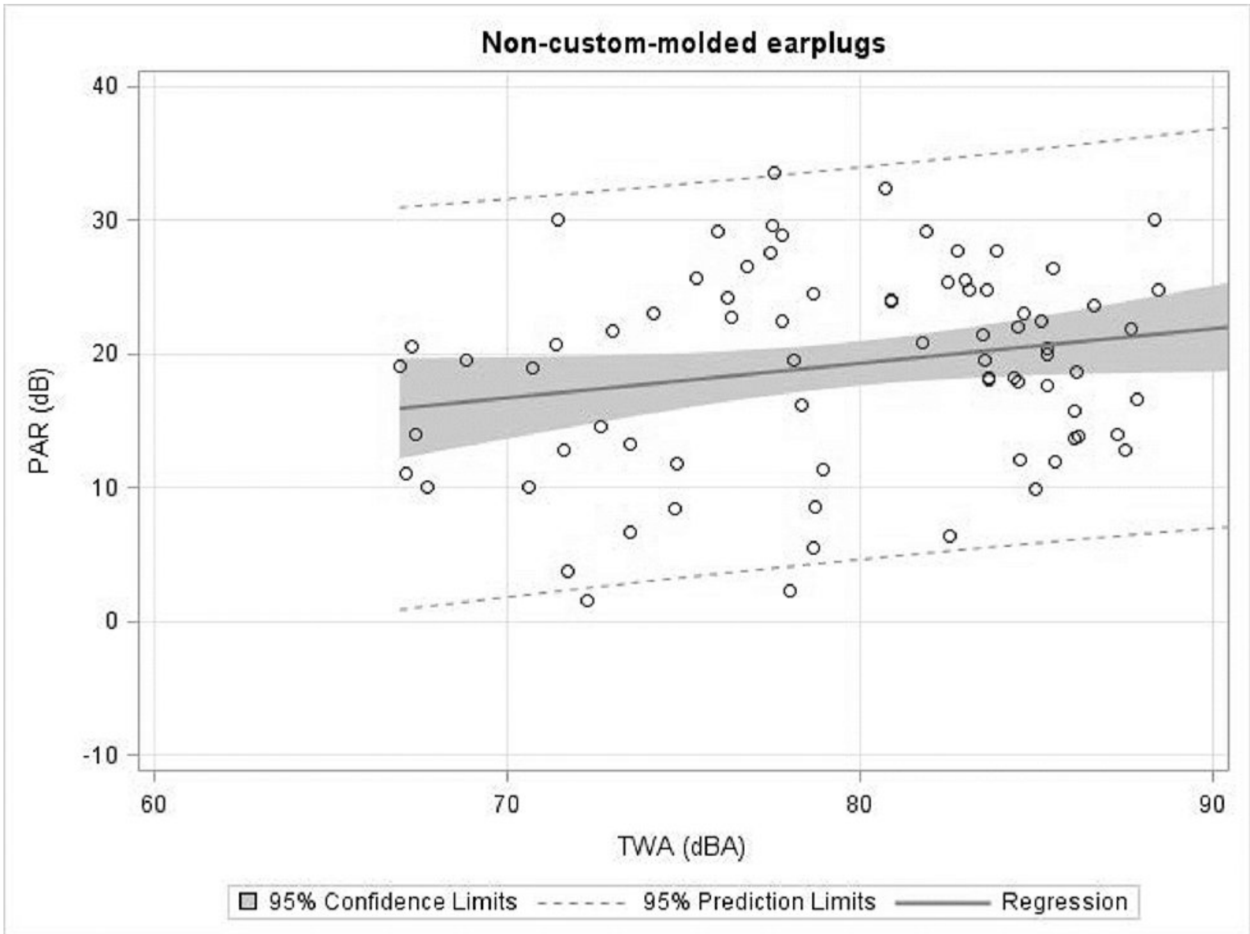


Figure 4.

Scatter plot of the relationship between TWA and PAR among workers at 2 metals manufacturing facilities in the US for non-custom-molded earplugs (4a) and custom-molded earplugs (4b), where the shaded area represents the standard error and the dotted lines mark the 95% confidence intervals for the slope (slope coefficient p-value for non-custom-molded earplugs 0.04; *p* value for custom-molded earplugs 0.62).

Table 1.

Characteristics of workers (n=91) and their repeated measurements (n=251) at 2 metals manufacturing facilities in the US.

	Overall (n=91)		Site 1 (n=56)		Site 2 (n=35)	
Variable	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Age	49.6	9.0	49.6	9.4	49.6	8.4
Hours hearing protection worn	7.3	1.9	7.4	1.1	6.8	2.8
Hearing threshold (dBHL)						
Average of 2, 3, 4 kHz	15.4	13.0	15.2	13.6	15.7	12.2
Average of 3, 4, 6 kHz	20.6	15.2	19.8	15.2	21.9	15.4
	N	%	N	%	N	%
Male gender	56	61.5	29	51.8	27	77.1
Race/ethnicity						
White	70	76.9	39	69.6	31	88.6
Black	11	12.1	10	17.9	1	2.9
Other	5	5.5	2	3.6	3	8.6
Unknown	5	5.5	5	8.9	0	0.0
Self-reported tinnitus	19	20.9	9	16.1	10	28.6
Underwent ear surgery	3	3.3	3	5.4	0	0.0
Participates in noisy hobbies	43	47.3	23	41.1	20	57.1
Participates in hunting/shooting	36	39.6	16	28.6	20	57.1
Works at another noisy job	11	12.1	2	3.6	9	25.7
Family history of hearing loss	58	63.7	34	60.7	24	68.6
	Overall (n=251)		Site 1 (n=158)		Site 2 (n=93)	
Model Workplace Variables	N	%	N	%	N	%
Custom-molded wearers	174	69.3	143	90.5	31	33.3
Sand- and water-blasters	12	4.8	12	7.6	0	0.0

Table 2.

Personal noise dosimeter exposures and hearing protector personal attenuation ratings (PAR) among workers at 2 metals manufacturing facilities in the US.

	Overall			Site 1			Site 2		
	n	**Mean**	**SD**	**n**	**Mean**	**SD**	**n**	**Mean**	**SD**
Noise Exposure									
TWA (dBA)	255	79.8	7.0	158	81.1	6.6	97	77.6	7.0
L_{MAX} (dBA)	255	91.3	4.5	158	91.9	4.1	97	90.2	4.8
Run Time (min)	255	475.0	88.8	158	449.2	43.8	97	517.0	121.9
PAR_A(dB)	251	20.1	6.7	158	20.9	5.6	93	18.7	8.1
PAR_f 250 Hz	242	14.7	7.4	153	15.7	7.1	89	12.9	7.5
PAR_f 500 Hz	245	18.2	7.4	158	18.9	7.1	87	17.1	7.9
PAR_f 1000 Hz	250	22.2	6.9	158	22.5	5.9	92	21.6	8.5
PAR_f 2000 Hz	249	31.1	8.2	156	31.1	7.5	93	31.0	9.2

Table 3.

Unadjusted (top) and adjusted (bottom) fixed-effects linear regression models with PAR as outcome variable and participant ID as a random effect among workers at 2 metals manufacturing facilities in the US.

	Variable	Coefficient	SE	p
Unadjusted	Intercept	18.86	0.90	<0.001
	Custom plugs	1.57	1.05	0.14
	Intercept	11.91	5.28	0.03
	TWA	0.10	0.07	0.13
	Intercept	19.36	1.91	<0.001
	Hours of hearing protection use	0.08	0.25	0.74
	Intercept	20.33	0.58	<0.001
	Tinnitus	−1.81	1.28	0.16
	Intercept	20.63	0.81	<0.001
	Hearing threshold (Average of 2, 3, 4K Hz)	−0.04	0.04	0.37
	Intercept	20.95	0.87	<0.001
	Hearing threshold (Average of 3, 4, 6K Hz)	−0.04	0.03	0.21
	Intercept	20.22	2.86	<0.001
	Age	−0.01	0.06	0.93
	Intercept	20.01	0.54	<0.001
	Task=sand/water-blasting	−1.14	2.48	0.65
	Intercept	18.34	0.85	<0.001
	Site 1	2.56	1.06	0.02
	Intercept	19.15	0.84	<0.001
	Male gender	1.31	1.07	0.22
	Intercept	17.51	1.19	<0.001
	White race	2.61	1.32	0.05
Adjusted Overall	Intercept	15.69	1.42	<0.001
	White race	3.06	1.31	0.02
	Site 1	2.39	1.05	0.02
Site 1	Intercept	18.84	1.05	<0.001
	White race	2.50	1.20	0.04
	Task=sand/Water-blasting	−5.19	2.10	0.02
Site 2	Intercept	13.36	2.93	<0.001
	White race	5.65	3.12	0.07
Custom-molded Wearers	Intercept	15.77	1.66	<0.001
	Site 1	2.34	1.41	0.10
	White race	3.17	1.34	0.02
Non-custom Wearers	Intercept	13.93	3.63	<0.001
	Site 1	1.36	2.47	0.59
	White race	5.05	3.73	0.18