Original research

Hearing loss as a predictor for hearing protection attenuation among miners

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ABSTRACT

Objective This study investigated risk factors for poor earplug fit, with a focus on the association between hearing loss and personal attenuation ratings (PARs).
Methods Earplug fit was assessed by obtaining PARs using a real ear at attenuation threshold (REAT) system. Hearing loss was assessed using the unoccluded hearing thresholds measured during the REAT testing and the results of a speech-in-noise test. Potential predictors of PARs were modelled using both simple and multiple linear regression. Hearing loss was the primary predictor of interest.
Results Data were collected from 200 workers at ten above-ground mining sites in the Midwestern USA. Workers reported wearing their hearing protection on average 73.9% of the time in a high noise environment (mean 8-hour time-weighted average noise exposure 85.5 dBA, range 65–103 dBA). One-quarter (26.7%) of workers were found to have a hearing loss (hearing threshold ≥25 dB across 1–4 kHz), and 42% reported symptoms of tinnitus. Workers with a hearing loss had a significantly lower PAR than those without a hearing loss (β=−5.1, SE=1.7).
Conclusions The results of the adjusted regression models suggest that workers with hearing loss achieved significantly lower PARs than those without hearing loss. This association between hearing loss and hearing protection devices (HPD) fit brings into focus the potential benefit of fit checks to be included in hearing conservation programmes. Workers found to have hearing loss should be prioritised for fit testing, as their hearing impairment may be associated with poor HPD fit.

Key messages

What is already known about this subject?

- Previous studies have found that increased training and comfort leads to better earplug fit in occupational environments. In controlled laboratory settings, no difference has been found in attenuation achieved from earplugs between subjects with and without hearing loss.

What are the new findings?

- A multisite, cross-sectional study found that workers with hearing loss achieved on average 5.1 dB less protection from their earplugs compared with workers without hearing loss.

How might this impact on policy or clinical practice in the foreseeable future?

- A hearing impairment found during a routine audiometric assessment of noise exposed workers should trigger an assessment of whether the impairment is due to poor hearing protection device fit.

INTRODUCTION

Noise exposure is one of the most common occupational hazards in the USA, with an estimated 22 million workers reporting exposure to potentially hazardous noise levels.[1] Excessive noise exposure has been linked with noise-induced hearing loss (NIHL)[2] and an estimated 24% of cases of hearing difficulties in the USA are attributable to occupational exposures.[3] Hearing loss can lead to increased difficulty in communication, resulting in decreased quality of life for those with hearing impairment.[4] Noise exposure has also been linked with tinnitus[5] and cardiovascular disease.[6]

Hearing loss, including NIHL, is identified using pure tone audiometry, which measures the threshold (ie, lowest sound level) that an individual can hear across different test frequencies.[7] Although audiometry is a useful measurement for clinical assessment of hearing loss, it is not reliably predictive of the effect that this loss has on an individual's ability to understand speech.[8] Understanding speech in the presence of background noise is one of the most common complaints of people with hearing loss.[9] In light of these concerns, hearing professionals have begun to include measures of speech intelligibility in noise as part of routine hearing health testing.[10]

In addition to evaluating impacts of noise on hearing, occupational hearing loss prevention programmes also require the use of hearing protection devices (HPDs) to reduce occupational noise exposure. In the USA, a laboratory generated measure known as the noise reduction rating (NRR) is used to describe the potential noise reduction (attenuation) of an HPD.[11] The NRR is required for all HPDs sold in the USA, but this rating has been shown to be a poor estimate of the true attenuation achieved by HPD users,[12–14] which can vary widely between individuals wearing the same HPDs.[15] A more accurate alternative to the NRR, the personal attenuation rating (PAR), measures the amount of attenuation an HPD provides to individual workers.[16] Knowing the amount of attenuation that an HPD provides to individual workers is crucial to prevent overexposure to noise due to insufficient protection.

Real ear attenuation at threshold (REAT) testing can be used to measure PARs.[17–19] REAT systems

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measure the threshold at which an individual can hear a range of frequencies with and without wearing an HPD; these conditions are referred to as 'occluded' and 'unoccluded,' respectively. In practice, this is equivalent to obtaining an audiogram with and without an HPD. The PAR is calculated from the difference between the occluded and unoccluded thresholds. Another approach, microphone in real ear (MIRE), assesses attenuation by measuring sound level inside and outside an ear canal occluded by an HPD and quantifying the difference.[15]

Although the PAR is considered to be the gold standard for assessing attenuation, there have been few studies of the predictors of PAR levels achieved by workers. Several studies have found a significant increase in earplug attenuation achieved by workers after being trained in proper fitting technique.[20–23] Additionally, a negative association has been found between earplug comfort and achieved attenuation,[24] and a recent study found a positive association between noise exposure and PAR for workers using foam earplugs.[25]

Given the high prevalence of NIHL due to excessive noise exposure among workers, hearing health practitioners need to understand factors that are associated with poor earplug fit and insufficient protection from noise. Workers in the mining industry have a notably high prevalence of hazardous noise exposure. Tak *et al* estimated that 76% of miners are exposed to hazardous levels of noise.[26] As a result, miners have among the highest prevalence of hearing loss of any industry, with an estimated 24%–27% of miners having clinical hearing loss.[27 28] Miners additionally report a higher level of HPD use among those who are noise exposed (87.1%) compared with workers in general industry (66%). Due to their high noise exposure, high use of HPDs, and high prevalence of hearing loss, miners are the ideal population in which to study the relationship between PAR and hearing loss.

The objective of this study was to identify potential predictors of HPD fit, as measured by the PAR. Hearing loss was the main predictor of interest a priori, but other factors were considered as well, including noise exposure and demographic information. We hypothesised that workers with greater hearing loss would have decreased PARs after controlling for other potential predictors of hearing protector fit.

METHODS

This cross-sectional study took place among workers at 10 above-ground mining facilities operated by two companies in Michigan, Ohio and Illinois. Of the 10 mines, six quarried and produced limestone products, and four quarried and produced silica.

Participants

All volunteers were over the age of 18. Prior to enrolment, all interested volunteer workers provided written informed consent after being provided with a description of the study. Participants received US$50. Each participant contributed data to the study over 3 days. During this period, they completed a background survey, a REAT-based PAR test, and two measures of hearing ability. On each of the 3 days, they also wore a noise dosimeter and completed daily activity logs. All tests were conducted by research staff during breaks in the workers' shifts.

Surveys

All participants filled out a background survey on demographics, noise exposure, hearing loss and HPD use (online supplemental materials A). Seven demographics questions addressed age, weight, height, sex, job title, years in industry and hours worked per week. Two questions on noise addressed frequency of perceived high noise exposure and number of years worked in a high noise environment. Eight hearing loss questions addressed perceived difficulty with hearing, healthcare provider visits related to hearing health, and tinnitus. Two questions on HPDs addressed percentage of time HPDs were used in high noise and perceived barriers to using HPDs in high noise.

Personal attenuation ratings

PARs were obtained using the HPD type and model primarily used by each participant. PARs were obtained for earmuffs using the FitCheck Earmuff, an MIRE system. PARs were obtained for earplugs using the FitCheck Solo, a REAT system. (Michael and Associates, State College, Pennsylvania, USA). The threshold at which a participant could hear a pure-tone stimulus with and without occlusion by an HPD was recorded at 0.25, 0.5, 1, 2, 4 and 8 kHz. Workers were given no instructions on how to fit the HPD, other than to use it as they normally would. The PAR for each participant was calculated using equation 1:

$$PAR_n = 10log_{10}\sum_f^N 10^{L_{Af}/10} - 10log_{10}\sum_f^N 10^{(L_{Af}-A_f)/10} \quad (1)$$

Where N is the number of frequencies tested, L_{Af} is 100 dB plus the A-weighting for each frequency (f) and A_f is the attenuation calculated per frequency by the FitCheck system (ie, occluded – unoccluded threshold).

Workers with higher degrees of hearing impairment were more likely to hit the output ceiling limit of the FitCheck system at 4 and 8 kHz, so only 0.5, 1 and 2 kHz were used to calculate PARs in order to maximise inclusion. All testing was done in a quiet room with a background noise level ≤70 dBC inside the offices of the participating sites. Background noise was measured using a model 407790 Sound Level Meter (Extech Instruments, Waltham, Massachusetts, USA). Background noise was further reduced by the FitCheck sound isolating headphones. PAR tests were restarted if obtrusive environmental sounds occurred during the test. The PAR system was calibrated each testing day.

Hearing ability

Hearing ability was evaluated in two ways: hearing thresholds and speech-in-noise performance. Audiometric testing was not feasible at each site, so hearing thresholds (dB) were assessed using the unoccluded hearing thresholds taken from the FitCheck Solo REAT system. Workers who did not use earplugs still completed the unoccluded portion of the test in order to obtain hearing threshold measures. Average hearing threshold was quantified as the mean hearing threshold across 1000, 2000 and 4000 Hz (HL 1–4 kHz). Hearing loss was additionally defined using a modified version of the NIOSH criteria for a 'material hearing impairment' as an average hearing threshold ≥25 dB across 1, 2 and 4 kHz.[29]

The speech-in-noise test was administered using the Apple Research Kit speech in noise task (Apple, Cupertino, California, USA). SE215 sound isolating earphones (Shure, Niles, Illinois, USA) were used to deliver the sentences, along with the unplugged FitCheck sound isolating headphones placed over the earphones for further background noise reduction. The speech-in-noise test generated a speech reception threshold (SRT), the signal to noise ratio where 50% of the keywords are correctly repeated by the subject. The SRT was calculated using the Tillman Olsen formula[30] as commonly used by the QuickSIN test (Etymotic, Elk Grove Village,

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Illinois, USA). Using an initial Signal-to-Noise Ratio (SNR) of 18 dB and 3 dB step size, we get the simplified equation:

Equation 2. SRT = 19.5(R0.6)

Where *R* is the number of correctly repeated keywords. Participants completed two sets of seven-sentence wordlists, with five keywords in each sentence. The first set was used to familiarise participants with the test, while the results of the second set (SRT_1) were used for analysis.

Noise exposure

Noise exposure was measured using a DoseBadge dosimeter (Cirrus Research, North Yorkshire, UK) worn on the shoulder of each participant for their entire shift for each of the 3 days they participated. The dosimeters measured two channels of data simultaneously). The first measured according to the Mine Safety and Health Administration (MSHA) Action Level (AL) of 85 dBA time-weighted average (TWA) with a 5 dB exchange rate and 80 dBA threshold[31] and the second measured according to the NIOSH Recommended Exposure Limit (REL) of 85 dBA TWA with a 3 dB exchange rate and no threshold.[29] The log-average TWA across the three shifts was used as the noise exposure estimate (TWA_{MSHA} and TWA_{NIOSH}). The required attenuation, PAR_{Needed}, was calculated by subtracting 85 dBA from each worker's TWA_{NIOSH}.

Data analysis

Statistical analysis was conducted using Stata V.16.0 (StataCorp). Descriptive statistics were calculated for all variables. Normality of each variable used in inferential statistics was determined using visual assessment of histograms. All variables were analysed visually using boxplots and scatterplots, followed by Student's t-tests and analyses of variance. Spearman correlation coefficients (r_s) and variance inflation factors (VIF) were used to evaluate potential collinearity between variables (r_s>0.3 or VIF >2.5 were dropped from the adjusted models). P values ≤0.05 were considered statistically significant.

Linear regression models were developed to assess the relationship between hearing loss and PARs for participants who wore earplugs. Hearing loss was included as a binary dummy variable (0=HL 1–4 kHz <25 dB, 1=HL 1–4 kHz ≥25 dB). Simple, unadjusted linear models were created regressing PAR on various independent variables. An adjusted linear model (adjusted model 1) was created by adding potential predictor variables and potential cofounders based on a priori assumptions. Perceived hearing health and age were not included due to collinearity with hearing loss. A second adjusted linear regression model (adjusted model 2) was created by adding an interaction term between tinnitus and hearing loss (hearing loss × tinnitus) to adjusted model 1. Unadjusted and adjusted logistic regression models were created in a similar fashion to adjusted model 1, but used hearing loss instead of PAR as the dependent variable. Finally, a mixed effects linear regression model was developed to assess the relationship between noise exposure and HPD usage. Shift level HPD use time was added as a fixed effect, and subject ID was included as a random effect. The dependent variable was shift-level TWA_{NIOSH}.

RESULTS

Demographics and hearing ability

Of 207 consented workers, 200 filled out the baseline survey (table 1). Age ranged from 18 to 67 years (mean=40.6 years) and work experience in mining ranged from <1 to 43 years (mean=11.6). The majority of workers (91%) reported working 40–60 hours per week. Almost all workers were male (96.8%).

Table 1 Participant demographics and hearing ability (N=200 workers)

Variable	N	Mean	SD	Range
Age (years)	199	40.6	12.2	18–67
Hours worked per week	198	48.6	9.6	20–84
Years in industry	200	11.6	9.7	<1–43
Hearing threshold 1–4 kHz (dB)	179	20.5	10.6	3.7–58.1
SRT_1 (SNR)	196	1.4	2.5	–1.5–11.7

SNR, signal-to-noise ratio.

Variable	N	%
Sex		
Female	5	2.7
Male	179	96.8
Other	1	0.5
Mine type		
Limestone	97	48.5
Silica	103	51.5
Hearing loss (HL1–4 kHz ≥25 dB)*		
No	132	73.3
Yes	48	26.7
Perceived hearing health*		
Good	94	47.5
A little trouble	93	47.0
A lot of trouble	11	5.5
Perceived difficulty with hearing†		
No	137	69.5
Yes	60	30.5
Tinnitus		
No	114	57.9
Yes	83	42.1

*Hearing loss was defined as an average hearing threshold ≥25 dB across 1, 2 and 4 kHz. Hearing thresholds were assessed using the unoccluded hearing thresholds taken from the FitCheck Solo PAR earplug system.
†χ^2 test between perceived hearing health and perceived difficulty with hearing=82.7, P<0.001.
PAR, personal attenuation rating; SRT, speech reception threshold.

The average hearing threshold across 1–4 kHz was 20.5 dB (SD=10.6). One-quarter (26.7%) of workers were found to have hearing loss (ie, an average hearing threshold ≥25 dB across 1–4 kHz). When asked to self-rate their hearing, half (52.5%) reported having 'a little trouble' or 'a lot of trouble'. Nearly half of the workers (42.1%) reported experiencing tinnitus in the past year. Mean SRTs for the Speech in Noise test were SRT_1=1.4 SNR. A moderate correlation was observed between hearing loss (HL 1–4 kHz ≥25 dB) and age (r_s=0.41, p<0.0001) and hearing loss and perceived hearing health (r_s=0.40, p<0.0001).

Noise exposures and hearing protection

The average TWA_{NIOSH} across all workers was 85.5 dBA (SD=6.0) and the average TWA_{MSHA} was 80.2 dBA (SD=6.0, table 2). Taking the average TWA across the three shifts, 50.5% of the workers had a TWA_{NIOSH} above the NIOSH REL and 4.9% had a TWA_{MSHA} above the MSHA AL. Nearly 80% of participants reported working in high noise at work 'Some of the Time' or more. There was a strong correlation between years in industry and years worked in high noise (r_s=0.63, p<0.0001).

Earplug PARs were highly variable across participants (mean=24.8 dB, range=1.3–43.1 dB). Earmuffs had lower average PARs compared with earplugs (mean=14.3 dB,

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Table 2 Noise exposure, hearing protection device usage and attenuation (N=205 workers)

Variable	N	Mean	SD	Range
TWA_{NIOSH} (dBA)	205	85.5	6.0	65.0–103.0
TWA_{MSHA} (dBA)	205	80.2	6.0	61.0–98.7
Years in high noise	192	14.7	11.9	0.0–55.0
PAR earplugs (dB)	162	24.8	9.3	1.3–43.1
PAR earmuffs (dB)	27	14.3	7.3	3.0–28.0
Time HPD worn (%)	199	73.9	32.5	0–100
Variable	**N**	**%**		
TWA_{NIOSH} >85 dBA				
No	101	49.3		
Yes	104	50.7		
TWA_{MSHA}>90 dBA				
No	195	95.1		
Yes	10	4.9		
Noise exposure at work				
None of the time	6	3.1		
Little of the time	35	17.8		
Some of the time	87	44.2		
Most of the time	60	30.5		
All of the time	9	4.6		
HPD type for PAR test				
Foam	155	79.9		
Muff	16	8.3		
None	9	4.6		
Premold	4	2.1		
Double protection (earplugs+muffs)	10	5.2		

HPD, hearing protection device; PAR, personal attenuation rating; TWA, time-weighted average.

range=3.0–28.0). Most PAR tests were done with foam earplugs (79.4%). Workers reported wearing their hearing protection on average 73.9% of the time. We found no correlation between HPD use and hearing loss (Spearman correlation coefficient=−0.03). The two most common reasons given for not wearing hearing protectors were 'Someone else does something noisy without warning' and 'Can't communicate properly with other workers'. Small, but significant correlations were observed between earplug PAR and hearing loss (r_s=−0.21, p=0.01) and earplug PAR and perceived hearing health (r_s=−0.17, p=0.04). No workers had inadequate PARs (figure 1).

Regression models

The unadjusted linear regression models (table 3) showed a significant negative relationship between PAR and hearing loss (β=−3.75, SE=1.61). Adjusted model 1 showed that workers with hearing loss had a significantly lower PAR than those with normal hearing. (β=−5.07, SE=1.72). No other variables showed a statistically significant relationship with PAR.

Adjusted model 2 showed that workers with tinnitus and no hearing loss achieved more attenuation than workers with neither (β=3.70, SE=1.74), while no significant difference was found for workers with hearing loss but no tinnitus. A significant negative interaction showed that workers with both hearing loss and tinnitus achieved less attenuation than workers with neither (β=−8.03, SE=3.33).

The unadjusted logistic regression model (table 4) showed a negative relationship between hearing loss and PAR (OR=0.95,

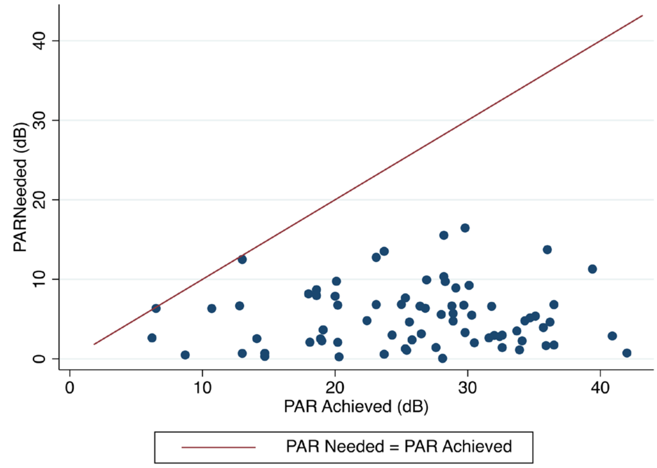

Figure 1 PAR needed versus PAR achieved. PAR, personal attenuation rating.

SE=0.02). The adjusted logistic regression model indicated that workers with higher PARs were less likely to have hearing loss (OR=0.93, SE=0.03). Age, SRTs and perceived hearing health were also associated with hearing loss in the adjusted model.

A positive, linear trend was found between shift level noise exposure and self-reported shift level HPD usage (online supplemental materials B). The mixed effects linear regression model confirmed this trend as being statistically significant (β=1.56, SE=0.16, p<0.001).

DISCUSSION

This study assessed whether hearing loss is predictive of attenuation achieved by an HPD in an occupational environment. The population studied had high noise exposure and a high degree of hearing loss. Participants self-reported working in noisy environments, which was supported by the TWA_{NIOSH}, but not the TWA_{MSHA}. We found an average −5.1 dB difference in earplug PARs for workers who had a hearing loss compared with workers with normal hearing, which suggests that hearing-impaired workers achieve less protection from their earplugs compared with non-hearing-impaired workers. Additionally, a significant association was noted between PAR values and hearing loss, with greater hearing loss associated with smaller PARs. No association was seen between hearing loss and tinnitus or hearing loss and TWA_{NIOSH}.

This is the first time that the relationship between hearing loss and PAR appears to have been studied in a real-world occupational environment. Past laboratory studies found no difference between attenuation achieved by normal hearing and hearing-impaired subjects.[32–34] However, in these studies the HPD was either fit or checked by researchers to assure proper fit. In the current study, all HPDs were fit by participants, which suggests that the difference in PARs between normal hearing and hearing-impaired workers was due to HPD fit, and not due to inherent differences in achievable attenuation.

Our findings indicate that hearing impairment is predictive of a worker achieving less attenuation from their HPD, and that less attenuation is also predictive of hearing loss. However, the cross-sectional study design makes it difficult to assess causality. One possible explanation for our results is that workers who already have a hearing loss purposefully fit their earplug poorly in order to increase their ability to communicate. In line with past

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Table 3 Linear regression models for predictors of personal attenuation ratings

	Unadjusted models (n=148–162)†				Adjusted model 1 (n=155)			Adjusted model 2 (n=155)		
Predictors	R‡	β	SE	p > |t|	β	SE	p > |t|	β	SE	p > |t|
Hearing loss§	0.03	−3.75	1.61	0.02*	−5.07	1.72	0.004*	−0.8	2.45	0.75
SRT_1	<0.01	0.2	0.3	0.51	0.54	0.33	0.11	0.44	0.33	0.19
% time earplug worn	<0.01	0.01	0.02	0.56	≤0.01	0.02	0.79	≤0.01	0.02	0.77
TWA_{NIOSH}	<0.01	0.01	0.12	0.93	−0.07	0.13	0.59	−0.12	0.13	0.37
Tinnitus	<0.01	0.76	1.44	0.6	1.46	1.51	0.34	3.66	1.74	0.04*
Age	0.01	−0.07	0.06	0.19						
Perceived hearing health‡	0.01	−2.08	1.41	0.14						
Hearing loss×tinnitus								−8.03	3.33	0.02*

*p≤0.05

†Range is due to incomplete data from survey questions being skipped.

‡'A Little Trouble' and 'A Lot of Trouble' were combined to transform perceived hearing health into a binary variable.

§Hearing loss was defined as an average hearing threshold ≥25 dB across 1, 2 and 4 kHz. Hearing thresholds were assessed using the unoccluded hearing thresholds taken from the FitCheck Solo PAR earplug system.

PAR, personal attenuation rating; SRT, speech reception threshold; TWA, time-weighted average.

research, decreased ability to communicate was one of the main reasons that workers cited for not wearing HPDs in loud environments.[35 36] However, workers' speech in noise performance was only predictive of hearing loss, and not PAR. This implies that a worker's ability to understand speech in noisy environments is not associated with how a worker fits their earplug. Another possibility is that workers who achieve less attenuation are exposed to more noise, which in turn leads to an increased probability of hearing loss. This study found that workers used HPDs 73.9% of the time in a fairly noisy environment (mean TWA=85.5 dBA), and that HPD use time was higher at higher noise levels. Taken together, these results suggest that HPD fit could influence whether a noise-exposed worker does or does not develop hearing loss.

The interaction found between tinnitus and hearing loss may shed further light on this relationship. Compared with workers with no tinnitus and no hearing loss, workers with tinnitus and no hearing loss had higher PARs, and workers with tinnitus and hearing loss had lower PARs. For workers with tinnitus without hearing loss, the tinnitus may act as a motivator to better fit their earplugs for fear of further hearing loss. This is in comparison to workers with both hearing loss and tinnitus, both of which may have resulted from their low PARs.

The prevalence of hearing loss (26.7%) among participants was consistent with past studies of miners.[27] Theoretically, all participants achieved a higher PAR than needed to reduce their noise exposure to below 85 dBA (figure 1), so factors other than earplug fit, such as unprotected noise exposures on or off the job, could additionally explain the hearing loss found in this population. It is also possible that our participants achieved higher attenuation during our tests than they routinely achieve during workplace noise exposures Additionally, 42.1% of miners reported tinnitus in the past year, a higher rate than previously reported (24.1%).[37] The question addressing tinnitus only asked about single occurrences of tinnitus in the past year, but could be indicative of the potential for younger workers to develop hearing loss as they age. This is especially alarming as only 10% of participants below the median age (39 years) had a hearing loss, yet 34% of workers under 39 years old reported experiencing tinnitus.

The finding that hearing loss is predictive of HPD fit is of particular relevance to audiologists, occupational hearing conservation technicians, and occupational health and safety managers. Miners exposed to excessive noise are required to be enrolled in a hearing conservation programme, which includes an annual audiometric assessment. A standard threshold shift (STS, defined as a 10 dB change in a pure tone average threshold of 2, 3 and 4 kHz and an average threshold ≥25 dB across these frequencies in either ear),[38] found during routine audiometric testing should trigger an assessment of whether the STS is due to poor HPD fit. An HPD fit test can be quickly conducted by taking a second audiogram with the worker wearing their HPD, with the original audiogram serving as the unoccluded portion of the fit test. The PAR calculated from the two audiograms can be used to diagnose fit problems and the need for retraining on earplug fit and HPD selection, and thus aid in the prevention of further hearing loss.

Table 4 Logistic regression models for predictors of hearing loss

	Unadjusted models (n=162–179)		Final adjusted model (n=155)	
Predictors	OR	95% CI	OR	95% CI
PAR (dB)	0.95	0.92 to 0.99	0.93	0.88 to 0.99
Age (years)	1.09	1.06 to 1.14	1.07	1.03 to 1.12
SRT1 (SNR)	1.35	1.18 to 1.57	1.41	1.14 to 1.74
% time earplug worn	1	0.99 to 1.01	1	0.98 to 1.01
TWA_{NIOSH} (dBA)	1.06	1.00 to 1.12	1.09	0.99 to 1.19
Tinnitus	2.7	1.37 to 5.34	1.69	0.66 to 4.32
Perceived hearing health	6.61	2.87 to 15.22	4.27	1.42 to 12.76

PAR, personal attenuation rating; SNR, signal-to-noise ratio; SRT, speech reception threshold; TWA, time-weighted average.

LIMITATIONS

The main limitation of this study is the use of the unoccluded threshold measurements from the HPD fit test as a surrogate for audiometric testing, which is an unconventional measure to assess hearing loss. However, other unconventional measures have been explored and found to be promising surrogates for audiometric testing.[39] Potential bias could have been introduced in the regression models by using the fit test to assess both hearing loss and PAR. In addition, in order to expedite data collection, the software was set to present pure tones to both ears simultaneously, rather than to one ear at a time. This bilateral presentation meant that all calculated hearing thresholds are effectively the threshold for the better ear. Nevertheless, the hearing loss measure used (HL 1–4 kHz ≥25 dB) was significantly associated with well-established predictors of hearing loss (age, SRT and perceived hearing health). Further studies comparing the

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thresholds measured by the FitCheck Solo system to audiometric hearing level thresholds are needed for true validation.

Additionally, PARs for earplugs were measured using a different system than for earmuffs. Although earmuffs were found to provide lower attenuation than earplugs, it is unclear whether this was due to differences between the HPD type or PAR measurement systems.

CONCLUSIONS

Our results indicate that hearing-impaired miners achieved less attenuation from their HPDs compared with non-hearing-impaired miners. This suggests that HPD fit tests should be integrated into hearing conservation programmes by obtaining an occluded audiogram after the standard unoccluded audiogram. These results could be used to identify fit problems and initiate appropriate interventions, such as training in HPD selection and fitting.

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Patient consent for publication Not required.

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Data availability statement All datasets used in this study are freely available on reasonable request from elonu@umich.edu.

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REFERENCES

1 Kerns E, Masterson EA, Themann CL, *et al*. Cardiovascular conditions, hearing difficulty, and occupational noise exposure within us industries and occupations. *Am J Ind Med* 2018;61:477–91.
2 Prasher D. New strategies for prevention and treatment of noise-induced hearing loss. *Lancet* 1998;352:1240–2.
3 Tak S, Calvert GM. 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 Med* 2008;50:46–56.
4 Ciorba A, Bianchini C, Pelucchi S, *et al*. The impact of hearing loss on the quality of life of elderly adults. *Clin Interv Aging* 2012;7:159.
5 Phoon WH, Lee HS, Chia SE. Tinnitus in noise-exposed workers. *Occup Med* 1993;43:35–8.
6 Babisch W. Road traffic noise and cardiovascular risk. *Noise Health* 2008;10:38.
7 Roeser RJ. *Roeser's audiology desk reference*. Thieme, 2013.
8 Nilsson M, Soli SD, Sullivan JA. Development of the hearing in noise test for the measurement of speech reception thresholds in quiet and in noise. *J Acoust Soc Am* 1994;95:1085–99.
9 Walden TC, Walden BE, Summers V, *et al*. A naturalistic approach to assessing hearing aid candidacy and motivating hearing aid use. *J Am Acad Audiol* 2009;20:607–20.
10 Grant KW, Walden TC. Understanding excessive SNR loss in hearing-impaired listeners. *J Am Acad Audiol* 2013;24:258–73.
11 EPA. Noise labeling requirements for hearing protectors. *Fed Regist 44* 1979:130–56.
12 Berger E. Using the NRR to estimate the real world performance of hearing protectors. *S V Sound Vib* 1983;17:12–18.
13 Casali JG, Park MY. Labortory versus field attenuation of selected hearing protectors. *S V Sound Vib* 1991;25:28–38.
14 Neitzel R, Somers S, Seixas N. Variability of real-world hearing protector attenuation measurements. *Ann Occup Hyg* 2006;50:679–91.
15 Berger EH, Voix J, Kieper RW, *et al*. Development and validation of a field microphone-in-real-ear approach for measuring hearing protector attenuation. *Noise Health* 2011;13:163.
16 Berger EH. International review of field studies of hearing protector attenuation. *Sci Basis Noise Induced Hear Loss* 1996:361–77.
17 Berger EH, Kerivan JE. Influence of physiological noise and the occlusion effect on the measurement of real-ear attenuation at threshold. *J Acoust Soc Am* 1983;74:81–94.
18 Berger EH. Methods of measuring the attenuation of hearing protection devices. *J Acoust Soc Am* 1986;79:1655–87.
19 Valentin O, John SM, Laville F. Using auditory steady-state responses for measuring hearing protector attenuation. *Noise Health* 2017;19:1.
20 Park M-Y, Casali JG. A controlled investigation of in-field attenuation performance of selected insert, earmuff, and canal cap hearing protectors. *Hum Factors* 1991;33:693–714.
21 Murphy WJ, Stephenson MR, Byrne DC, *et al*. Effects of training on hearing protector attenuation. *Noise Health* 2011;13:132.
22 Salmani Nodoushan M, Mehrparvar AH, Torab Jahromi M, *et al*. Training in using earplugs or using earplugs with a higher than necessary noise reduction rating? A randomized clinical trial. *Int J Occup Environ Med* 2014;5:187–93.
23 Williams W. Instruction and the improvement of hearing protector performance. *Noise Health* 2004;7:41.
24 Byrne DC, Davis RR, Shaw PB, *et al*. Relationship between comfort and attenuation measurements for two types of earplugs. *Noise Health* 2011;13:86.
25 Sayler SK, Rabinowitz PM, Galusha D, *et al*. Hearing protector attenuation and noise exposure among metal manufacturing workers. *Ear Hear* 2019;40:680–9.
26 Tak S, Davis RR, Calvert GM. Exposure to hazardous workplace noise and use of hearing protection devices among US workers--NHANES, 1999-2004. *Am J Ind Med* 2009;52:358–71.
27 Masterson EA, Tak S, Themann CL, *et al*. Prevalence of hearing loss in the United States by industry. *Am J Ind Med* 2013;56:670–81.
28 Lawson SM, Masterson EA, Azman AS. Prevalence of hearing loss among noise-exposed workers within the mining and oil and gas extraction sectors, 2006-2015. *Am J Ind Med* 2019;62:826–37.
29 NIOSH. A revised criteria for a recommended standard: occupational noise exposure. *Nat. Inst. Occup. Safety Health. Pub. No. 98-126.* 1998.
30 Tillman TW, Olsen WO. Speech audiometry. *Mod Dev Audiol* 1973;2:37–74.
31 Health standards for occupational noise exposure. mine safety and health administration (MSHA), 30 cfr part 62, section 120. *Final rule. Fed Regist* 1999.
32 Berger EH. Is real-ear attenuation at threshold a function of hearing level? *J Acoust Soc Am* 1985;78:1588–95.
33 Suter AH, Lempert BL, Franks JR. Real-ear attenuation of earmuffs in normal-hearing and hearing-impaired individuals. *J Acoust Soc Am* 1990;87:2114–7.
34 Abel SM, Armstrong NM, Giguère C. Auditory perception with level-dependent hearing protectors. The effects of age and hearing loss. *Scand Audiol* 1993;22:71–85.
35 Reddy R, Welch D, Ameratunga S, *et al*. Development of the hearing protection assessment (HPA-2) questionnaire. *Occup Med* 2014;64:198–205.
36 Arezes PM, Miguel AS. Hearing protectors acceptability in noisy environments. *Ann Occup Hyg* 2002;46:531–6.
37 Landen D, Wilkins S, Stephenson M, *et al*. Noise exposure and hearing loss among sand and gravel miners. *J Occup Environ Hyg* 2004;8:5312–41.
38 Occupational noise exposure, Occupational Safety and Health Standards. Occupational safety and health administration (OSHA). 29 cfr part 1910 section 95; 1983.
39 Flamme GA, Geda K, McGregor KD, *et al*. Stimulus and transducer effects on threshold. *Int J Audiol* 2015;54 Suppl 1:19–29.

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