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ORIGINAL ARTICLE

Variability in Fit Test Result for Earplugs and the Fraction of Noise Exposure Dose of Coal Miners due to Failure to Wear

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ABSTRACT

Researchers suggested that the individual fit test be conducted to estimate the protection effectiveness of workers' hearing protection device (HPD) while working. Practically, it is convenient to conduct single, instead of multiple, fit test measurement. This study examined if a single trial of earplug fit test can represent multiple performances. Additionally, it investigated how much noise exposure was due to the miners' failure to wear earplugs at work. A total of 11 subjects from 3 coal mines in West Virginia in 2009 were each repeatedly fit tested using the microphone-in-real-ear technique on their earplugs. For each miner values of noise reduction (NR) were determined. The same fit tested miners each wore the earplugs doing his normal full-shift work. The real-time noise doses were determined continuously using the two dosimeters, one at the shoulder and the other under the earplug for determining potential exposure dose and the dose the ear actually received. Most subjects' noise reduction values varied over a range of more than 10 dBA, suggesting that subjects should be fit tested with multiple donnings. Failure to wear the earplug was an important factor in determining the miners' noise exposure, accounting for 64.6% of their doses at ear on average and ranging from 33.3 to 93.4% across these subjects. Nearly half (45.5%) of the coal miners might not receive adequate protection with their earplugs. 35.2% of miners never wore any hearing protectors in the high noise environment and were in very high risk of hearing loss. Thus, an important portion of miners were exposed to excessive noise although the earplugs were provided.

Keywords: *Variability, Fit test, Earplugs, Noise exposure, Fraction, Failure to wear*

INTRODUCTION

Noise induced hearing loss (NIHL) is a serious problem in the mining industry in US. Between 70% and 90% of miners have enough NIHL to be classified as a disability [1]. The problem is severe in all areas of mining, including surface, preparation plants and underground. Coal mine operators rely largely on hearing protection devices (HPDs) such as earplugs or earmuffs to protect miners from noise exposures [2]. The HPD attenuation is highly dependent on individual-specific fit [3]. Rather than relying on the noise reduction rating (NRR) of Environmental Protection Agency that cannot accurately predict the noise protection of HPD provided to workers in the field, individual HPD fit tests should be conducted to estimate

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the noise protection of a HPD provided to the wearer while working [4].This paper reports on coal mine worker fit test for hearing protection with earplugs, as well as the effectiveness of noise attenuation that the earplugs provided under actual use conditions during coal mining.

Noise insertion loss (IL) and noise reduction (NR) are two primary approaches to describing the noise protection of a HPD. Noise insertion loss is the difference between the sound pressure levels (SPLs) measured at the same ear location with and without the HPD. In IL measurement, the SPL of the noise signal source must remain constant before and after the HPD is worn. Otherwise, the values of IL would be affected by changes in ambient noise levels. Measuring IL is not practical for field work because the noise level usually fluctuates. NR is the difference between the SPLs simultaneously measured at two different locations, with one microphone measuring the ambient SPL and the other measuring the SPL under the HPD, as given by the equation:

$$NR = SPL_{amb} - SPL_{with} \ldots (1)$$

Where: SPL_{amb} = "ambient" sound level measured near the head (e.g., above the collar bone)

SPL_{with} = sound level measured proximal to (inside) the HPD at the opening to the ear canal for earmuff or at the ear canal for earplug with the HPD present

In NR measurement, two microphones simultaneously record SPL_{with} and SPL_{amb}. Since the measurements are simultaneous, it does not matter if the ambient noise level is varying, making it feasible for field use. The relationship between IL and NR is:

$$IL = NR + TFOE \ldots (2)$$

Where:

TFOE is the transfer function of the open ear, the amplification relative to the undisturbed sound field caused by ear canal and pinna resonances and the effect of head presence [5].

The microphone-in-real-ear (MIRE) is a technique accurate enough to determine NR values of HPDs [6]. When the MIRE technique is used a microphone is placed either on the entrance to ear canal (for earmuffs) or at the ear canal (for earplugs) and the other microphone measures the ambient noise level while a loud noise signal is presented [7]. MIRE is a physical measurement that is quick and easy to implement. The NR value of a wearer's HPD at each frequency is collected at the same time while MIRE is implemented. In addition, MIRE does not require a quiet environment because the noise signal level is usually well above (more than 10 dB) the background noise level. MIRE was used to determine NR values in this study.

A coal miner's ear often experiences different angles of noise source exposure during their normal coal mining work. It was unclear whether different angle of noise signal source in a fit test could substantially affect the noise reduction of a coal miner's earplug. This issue was addressed in this study. In assessing workplace noise exposures, the overall A-weighted noise level is the most relevant metric of exposure. Therefore, the focus in this article is to determine the overall deviation in A-weighted noise level due to the presence of the earplugs. In addition, from the practical point of view, it is convenient to conduct single, instead of multiple, fit tests. Thus, a study is necessary to examine if the single trial of fit test can represent multiple performances with earplug refittings. If not, it would indicate multiple fit test measurements should be taken.

If health and safety practitioners are able to judge the wearing status (i.e., wearing or failure to wear) of coal miners' earplugs during the course of their normal work just by examining the NR data of their earplugs after the work shift, they will be able to learn the real-time NR of coal miners' earplugs while they were worn, determining the real-time protection effectiveness. Also, the judgment method helps determine when the earplugs were worn and when not. Thus, practitioners can develop a better hearing conservation program incorporating more effective enforcement or training elements with the earplug wearing status judgment method. This study attempted to develop a valid method judging coal miners' earplug wearing status (i.e. on or off the ear).

The National Institute for Occupational Safety and Health (NIOSH) Noise Exposure Standard [8] suggested that if the ambient noise dose (usually measured on the top of the shoulder with more noise exposure) during an eight-hour work shift is equal to or exceeds 100, a worker's noise exposure is considered hazardous regardless of the noise dose his (her) ear actually received. In fact, noise reading taken at the ear position provides better estimate of a worker's noise exposure, although the reading is somewhat conservative (overestimated). However, due to technical difficulties very few studies were done to determine ear dose level of coal miners who wear HPDs (especially those underground coal miners wearing earplugs) during their full-shift work. Coal miners' noise exposure at the ear with earplugs was explored in current study, not only the ambient noise dose measured on the shoulder.

When noise levels are excessive coal miners are at the risk of NIHL. An appropriate earplug can protect them but only if they wear it when needed. Moreover, if coal miners wear an earplug they may don and doff it alternatively during their normal work for various reasons such as communication, comfort, etc. The effective noise protection will be reduced if the earplug is not worn enough. It is necessary to study coal miners' earplug wearing behavior to examine whether they don the earplug when environmental noise is loud enough and doff it if the noise level is low. Additionally, the study determined how much the fraction of noise doses was due to failure to wear the protector by coal miners during their normal workdays.

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Fig 1. Earplug with microphone

MATERIALS AND METHODS

Human subjects

A coal preparation plant and two underground coal mines in West Virginia in 2009 were chosen for the study. A total of 11 male coal miners with age between 22 to 51 years' old at these facilities served as paid volunteer participants. Each subject signed a consent form before participating in the study. All subjects were protected under the conditions of a West Virginia University Human Subjects Internal Review Board approved protocol. The subjects included preparation-plant operators, underground continuous miners, shuttle-car operators, and roof bolters. All were known to be exposed to relatively high levels of noise (i.e. above 85 dBA). Only those coal miners who said they wore an earplug at least sometimes while working were selected to participate in the study. Six miners who should wear a HPD but never did so were excluded from the study, including continuous miners, roof bolters, and shuttle car. Because of the widespread proliferation of the continuous mining equipment, any noise study of the underground coal mining industry should have its focal point in continuous mining sections. The noisiest location in an underground coal mine is at the working face where continuous miners, roof bolters and shuttle car operators work together [9]. Coal preparation plants are also highly noisy where the noise easily reaches 90 dBA, the exposure limit of Mine Safety and Health Administration (MSHA) [10].

The tested earplugs

These eleven human subjects usually wore earplugs during their job. The investigators provided each of them a modified E-A-R PVC foam earplug to wear during determinations of values of both non-working noise reduction testing (NR_{fit}) and normal work (NR_{work}). E-A-R foam earplugs are one of the most common earplugs used in workplaces in America. The original earplug of this type has a NRR of 29 dBA. All the miners who wore earplugs in the study had previous experience wearing the E-A-R plugs. The modified E-A-R earplug with its microphone was a product of doseBuster Inc. in USA. The doseBuster personnel punched a hole through the center of each earplug along its long axis so that a 0.23cm diameter plastic tube could be passed through the center of the foam plug (Fig. 1). The microphone was tightly screwed into the plastic tube, allowing the microphone to sample noise inside the ear canal proximal to the ear plug. The study by doseBuster, Inc [11] showed that the acoustic attenuation characteristics of the E-A-R earplug fitted with this microphone were not changed from the unmodified earplug.

Instruments used to measure SPL_{amb} and SPL_{with}

A pair of dosimeters (Larson Davis Spark 705+, Depew, NY) and a National Instrument real-time analyzer (Data Wi-Fi Acquisition Hardware, Austin, TX) was employed, respectively, at different times to measure SPL values for fit tests on the coal miners. In both cases, the analyzer was used to generate a pink noise signal (80 Hz- 12500 Hz) with the noise level of approximately 80 dB at each $1/3^{rd}$ octave band frequency. The analyzer was also used in the fit test because it not only measured overall A-weighted SPLs, but also frequency- specific SPLs, whereas the dosimeter could only report the overall A-weighted SPLs integrated for all the noise frequencies or noise dose. When the analyzer was used for the fit tests, each of two microphones (doseBuster, USA) was connected to one of the two channels of the analyzer to simultaneously sense the noise levels proximal to the ear under the earplug (SPL_{with}) and the ambient noise level (SPL_{amb}). An integrated 15-second sampling time was used to reduce the potential variability of the measured SPLs. The analyzer was only used in the fit tests. The dosimeters were used both in the fit tests and the worksite noise sampling.

The dosimeters were all modified by the manufacturer to use the doseBusters microphones while still meeting intrinsic safety requirements for coal mines. They were operated using Blaze® software (Larson Davis, Depew, NY) for set-up, calibration, and data downloading. When a pair of dosimeters was used to determine NR_{fit} or NR_{work} values, one microphone that was placed at the middle point of the top shoulder of the most exposed ear measured the ambient noise levels (SPL_{amb}) and the other measured the noise levels proximal to the earplug (SPL_{with}) received by ear. All SPL values measured by a given dosimeter were logged into that dosimeter's memory along with the date and time. These logged SPLs on each pair of dosimeters were retrieved later and matched using their logged dates and times to calculate NR_{fit} or NR_{work} values using Equation 1. In the fit tests the dosimeters were set to measure second-by-second SPL value. Each fit test with the dosimeters included 15 seconds of data logging, with a total of 15 A-weighted SPLs on each dosimeter. For all determinations of NR_{work} each miner wore the dosimeters and his earplugs during most or all of his entire shift. The lunch time was excluded from the noise sampling.

Just before and after the fit test experiments, all microphones used in the study were calibrated against a standard pure tone noise signal of 114 dB at 1000 Hz generated by a Norsonic calibrator (Norsonic, AS, Norway, type 1251). The calibration results were always within 114± 0.4 dB, indicating the microphone was valid to take measurements. The analyzer and dosimeter were compared to each other prior to the study by measuring the noise levels when both were challenged with various noise levels side by side in a diffuse sound field generated by a customer-made chamber. The noise with dominant frequency of each one-third octave band center frequency between 125 Hz – 8000 Hz that was at least 10 dB higher than other frequencies was made by the analyzer and presented one after another while the analyzer and the dosimeter were compared for their SPL response. The differences were found to be no greater than 1 dB at each frequency. Because both instruments used the same type of microphones throughout the fit tests, the NR_{fit} values achieved by these two types of instruments was considered the same in the study.

For all tests the subject donned the tested earplugs in his "usual manner" without any help or instruction from the investigator. The same subjects were tested for both fit test NR and worksite noise sampling.

Fit test procedures

When determining NR_{fit} values, the analyzer and a pair of dosimeters were used in a different randomized order for each subject for these tests. All tests for a given subject were completed before testing the next subject. The subject sat on a chair with the tested ear 60cm from the speaker. A fixed order of orientations of the tested ear from the speaker of 90°, 0°, and 180° were used for each subject when the analyzer or a pair of dosimeters were used for tests. To change orientations the subject simply rotated the chair to each orientation when asked. The investigator waited about 2 minutes for the earplug to fully expand before taking the first measurements. Specifically, the step by step procedure was as follows:

For the analyzer NR_{fit} measurements:

(1) The subject was fit tested for his earplug at each of the orientations in the order of 90°, 0°, and 180° while not attempting to adjust his fitting.

(2) He refitted his earplug and Step (1) was repeated.

(3) He refitted the earplug again and was fit tested with the tested ear only at 90°.

(4) He refitted his earplug and Step (3) was repeated.

As a result, the subject refitted his earplug four times during the analyzer measurements.

For the two-dosimeter system NR_{fit} measurements:

(1) The subject was fit tested for his earplug at a fixed orientation order of 90°, 0°, and 180° while keeping the same fitting.

(2) He refitted the earplug and was fit tested with the tested ear only at 90°.

Hence, for each subject the analyzer was used to determine NR_{fit} values 4 times at 90°, 2 times at 0° and 2 times at 180°; a pair of dosimeters was used to determine NR_{fit} values 2 times at 90°, once at 0° and once at 180°. There were totally 6 different fittings and 12 tests.

Study orientation effect and examine if single trial of fit test can represent multiple performances

For the study of orientation effect on NR_{fit}, the average NR_{fit} values with the same earplug fitting but at different orientations (i.e., 90°, 0° and 180°) were compared with each other. The same fitting with different orientations excluded the refitting effect and allowed the examination of orientation effect only. To study if a single trial of fit test can represent multiple performances with different earplug fittings and different orientations, the NR_{fit} values of all measurements were examined on an individual subject to determine if they maintained constant throughout the measurements. If the NR_{fit} were found to be constant, then a single trial of fit test was sufficient; otherwise, the average NR_{fit} value of all measurements should be used as the fit test result for an individual coal miner, considering that workplace exposures are likely to come from different orientations and that coal miners usually refit their earplugs during their work.

Worksite noise sampling studies

Each of the same miners whose SPL_{amb} and SPL_{with} had been determined for NR_{fit} values in a mine office wore the same earplug and a pair of dosimeters for SPL_{amb} and SPL_{with} measurement for the determination of NR_{work} during the normal coal mining work of his 8-hr work shift on the same day. The noise dosimeter was set so that an equivalent noise level (L_{eq}) was computed for an average SPL value over one minute. The L_{eq} values were computed by the dosimeter with a 0 dBA threshold and 3-dB exchange rate, meaning that all the sound energy were used. This way, the minute-by-minute SPL was obtained and logged by the dosimeter. Afterwards, the data was retrieved and analyzed. The minute-by-minute NR_{work} values were determined. In addition, the noise dose was computed by the authors based on minute-by-minute SPL values.

When asked at the end of the shift, the miners stated that their work shifts had been normal. The investigators unobtrusively observed each subject's use of earplug while his noise exposure was sampled. This allowed the investigators to associate observed use of earplugs to observed real-time NR value for each individual minute. The authors employed this data to develop a method to judge earplugs when a miner was wearing his earplugs and when not during unobserved minutes. Using this method, the minutes when each miner wore his earplugs were determined.

Noise dose calculation

According to NIOSH [8], when the noise is sampled and calculated for the noise dose, only the sound pressure levels (SPLs) from 80 to 140 dBA is integrated. The level of 140 dBA is the ceiling level that should never be exceeded in the workplace due to its very hazardous sound energy. Below 80 dBA, the NIHL is minimal. Therefore, in the study only the average SPL over any minute that was between 80-140 dBA was integrated for the dose calculation for both the ambient noise dose and the noise dose at ear (ear dose). The noise dose calculation method on a particular coal miner was calculated using NIOSH recommended exposure as:

$$D_{total} = \sum_{i=1}^{n} \left(\frac{T_{Observed_i}}{T_{Allowed_i}}\right) * 100$$

Where:

D_{total} is the total noise dose

The $T_{Observed_i}$ indicated the total time of exposure at a specific noise level;

$T_{Observed_1} = T_{Observed_2} = \ldots = T_{Observed_i} \cdots = T_{Observed_n} = 1$ minute; n was the n[th] sampling time period, which was the last minute

The $T_{Allowed_i}$ indicated the exposure duration for which noise at this level becomes hazardous.

$$T_{Allowedi} = \left(\frac{480}{2^{(Li-85)/3}}\right)$$

L_i = measured A-weighted sound level SPL by a dosimeter.

For SPL < 80 dBA, $T_{allowed}$ is infinity

Both the ambient noise dose at the shoulder crest and also the ear dose were calculated using above formulas. The ear dose consisted of protected noise dose when an earplug was used and unprotected dose when the earplug was not used. To calculate the noise dose due to failure to wear the earplug, only these time periods a miner did not wear his earplug were used. In case that the full-shift noise sampling could not be taken, the projected full-shift (8 h) noise dose was extrapolated from the noise sampling result with the following equation:

$$\text{Dose } 8\text{-}hr = \text{Dose}_{Observed} \left(\frac{480 \text{ minutes}}{T_{sampling}}\right)$$

Where:

$\text{Dose}_{8\text{-}hr}$ = projected full-shift (8 Hrs) noise dose

$\text{Dose}_{observed}$ = actual noise dose from sampling result

$T_{sampling}$ = actual noise sampling minutes

Table 1. Frequency-specific NR_{fit} of the earplugs averaged by all fit test measurements across all subjects

Frequency	Average NR_{fit} (dBA)	std (dBA)
125 Hz	9.9	4.2
160 Hz	10.4	4.3
200 Hz	11.9	4.4
250 Hz	12.2	4.9
315 Hz	12.6	4.6
400 Hz	13.3	5.1
500 Hz	15	5.3
630 Hz	16.1	5.2
800 Hz	17	5.1
1k Hz	18.6	4.8
1.25k Hz	18.2	3.6
1.6k Hz	19.7	3.7
2k Hz	22.2	4.9
2.5k Hz	23.1	5.2
3.15k Hz	23.9	6.5
4k Hz	25.3	5.8
5k Hz	25.2	6.2
6.3k Hz	22.6	8.9
8k Hz	21.7	9.4

The relationship between wearing behavior and ambient noise level

Coal miners' earplug not-worn fraction of time in different range of ambient noise levels were compared to examine if there was any relationship between wearing behavior (wearing or failure to wear) and ambient noise levels. The NIOSH recommended exposure limit (REL) for occupational noise exposure is 8-hr time weighted average 85 dBA (equal to 100 if the exposure is described with noise dose). At or above REL noise induced hearing loss become an important concern. Therefore, two categories of ambient noise levels were chosen as the independent variable for studying the relationship: SPL< 85 dBA and SPL ≥ 85 dBA. The dependent variable was earplug not-worn fraction of time, which was the fraction of exposure time at each specific noise level range, not of the entire work shift exposure time across various noise levels.

RESULTS

Fit test results

Usable data were collected on 11 coal mine subjects who wore earplugs at each of three orientations (i.e., 0°, 90°, and 180°). The results of average frequency-specific NR_{fit} value from all the subjects with all measurements and orientations included are shown in Table 1. The observed average earplug NR_{fit} at the low

Table 2. The overall NR_{fit} value of 12 fit test measurements for each mine subject's earplug

Subject#	Average (dBA)	Range (dBA)	Std (dBA)
1	14.6	(11.4, 17.7)	2.0
2	18	(9.7, 23.1)	3.8
3	21.7	(15.7, 27.5)	3.9
4	13.4	(8.3, 15.2)	2.0
5	20.1	(12.5, 26.3)	3.8
13	13.2	(7.4,16.8)	2.8
15	11.5	(0.2, 18.9)	6.6
17	14.2	(9.2, 19.8)	3.8
19	16.5	(6.2, 21.3)	4.2
20	19.3	(10.2, 23.8)	3.6
21	18.6	(15.6, 23.4)	2.2

frequencies was at or above 10 dBA. At middle and high frequencies, the NR_{fit} exceeded 20 dBA.

The results of the overall NR_{fit} are shown in Table 2. Every subject achieved an average overall NR_{fit} value of more than 10 dBA. The mean value across all subjects was 16.5 dBA, with a standard deviation (std) of 3.3 dBA. Seven of 11 mine subjects had a range greater than 10 dBA, and every subject had an overall NR_{fit} range greater than 6 dBA across all his fit test measurements. Subject 15 even obtained 0 dBA of overall NR_{fit} at one time, and achieved approximately 19 dBA at another fit test measurement.

ANOVA showed that overall NR_{fit} values for different subject were significantly different (P<0.0001), indicating that the subject had a significant effect on the overall NR_{fit}. The difference in mean overall NR_{fit} value among these three orientations was less than 2 dBA (Table 3). ANOVA showed that orientation significantly (P=0.003) affected the overall NR_{fit}. LSD Post Hoc Tests showed that the 90^0 and 0^0 were significantly different (P = 0.001); the 90^0 and 180^0 orientation were significantly different (P = 0.0001), and the 0^0 and 180^0 were not significantly different (P = 0.35).

Worksite noise sampling study results

Complete full-shift sampling was not achieved for most of the subjects, primarily because of work shift interruptions caused by machine maintenance, Mine Safety and Health Administration inspectors, and to some extent, by sampling instrument malfunctions. The actual noise sampling durations ranged from 135 to 461 minutes, with an average of 355 minutes. Seven out of 11 subjects' sampling times exceeding 360 minutes. On-site observation durations of these coal miners' task performance during their normal work ranged from 119 to 298 minutes, with an average observation time of 203 minutes. The investigator observed that the mine subjects took their HPDs off and put them back on alternatively at work. The duration between re-donning varied from one subject to another. The coal miners usually did not talk in the loud noisy environment.

The judgment of earplug wearing status

Figure 2 and Table 4 show a typical example of the observed NR_{work} values from a mine subject (Subject 15) when his earplug was off or on his ear, alternatively. As shown, NR_{work} values ranged from slightly negative to slightly positive when the earplug was not worn. When the earplug was worn the NR_{work} values also ranged from negative to positive, making it less than clear from the sound level readings when earplugs were worn and when not. For that reason, a "wearing status judgment method" was developed based on the NR_{work} values and their corresponding periods when the subjects were observed to wear or not to wear their earplugs. To make the judgments, the particular minute being judged was included in a series of five continuous minutes (one NR_{work} for each minute) with two minutes prior to the current minute and the two following. The earplug was judged to be off for this particular minute if the following two conditions could be met: (1) at least three of the five NR_{work} values from the five contiguous minutes were each less than $1/3^{rd}$ of median NR_{work} as calculated from all the NR_{work} data for this particular subject, and (2) the NR_{work} of the "judged" minute was less than $1/3^{rd}$ of the median. Otherwise, the earplug was judged to be worn for the judged minute.

Table 4 show an example application of the judgment method to the minute by minute earplug wearing status of Subject 15 for an observed period. For

Table 3. Overall earplug NR_{fit} value comparison among all three orientations with the same fitting. (overall NR_{fit} was averaged across all subjects)

# of subjects	Parameter	0°	90°	180°	All orientation Avg
11	Mean (dBA)	16.2	17.6	15.8	16.5
	std (dBA)	3.9	3.7	4.2	3.3

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Table 4. Judgment method example of earplug wearing status ("off" or "on") for observed periods for Subject 15.

Time elapse (min)	NR (dBA)	1/3 median (dBA)	Observed	Judged
197	0.4	5.7	off	off
198	-4.1	5.7	off	off
199	-2.4	5.7	off	off
200	-2.7	5.7	off	off
201	-0.6	5.7	off	off
202	2.6	5.7	off	off
203	23.3	5.7	on	on
204	21.9	5.7	on	on
205	22.2	5.7	on	on
206	22.3	5.7	on	on
207	2.6	5.7	on	on
208	8.5	5.7	on	on
209	2.2	5.7	on	on
210	21.3	5.7	on	on
211	17.2	5.7	on	on
212	12.1	5.7	on	on
213	18.2	5.7	on	on
214	8.2	5.7	on	on
215	4.1	5.7	on	on
216	19.6	5.7	on	on
217	-0.9	5.7	off	off
218	-1.3	5.7	off	off
219	5	5.7	off	off
220	0.5	5.7	off	off
221	2.8	5.7	off	off

instance, to determine the wearing status for the 202nd sampling minute, one can find that the NR_{work} at the 202nd minute was 2.6 dBA. The series of five contiguous minutes for the 202nd minute was the 200th, 201st, 202nd, 203rd, and 204th minute, in which the 202nd minute was the median minute (judged). The corresponding NR_{work} for these minutes were: -2.7, -0.6, 2.6, 23.3, and 21.9 dBA. Since the median NR of all the sampling NR_{work} data for Subject 15 was 17.2 dBA, one third of the median NR_{work} was thus 5.7 dBA. Based on the two conditions for the judgment as shown above: (1) The corresponding NR for the 200th, 201st, and 202nd minute was each less than the 5.7 dBA, indicating that at least three NR_{work} in the row of the five minutes were less than the 1/3rd of median NR_{work}, and (2) the NR_{work} at the 202nd minute was also less than the 1/3rd of median NR_{work}. Thus the earplug was judged to be off (not worn) in the 202nd minute.

The judgment method was applied to periods when the investigators observed whether or not earplugs were worn, with which the wearing status was compared for

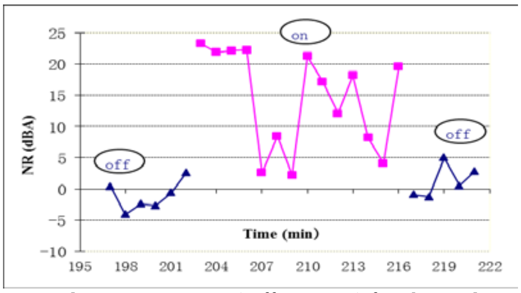

Fig 2. Earplug wearing status ("off" or "on") for observed periods for subject 15 (Judged agreed completely with observed in this example)

the "judged" and the observed actual use of earplug across all the subjects' sampling NR_{work} data. Less than 58 of 2093 minutes were incorrectly judged, an error rate of less than 3%, indicating that the judgment method was accurate enough to determine a coal miner's earplug wearing status for non-observed periods. Therefore, the judgment method was applied to every minute for each subject to determine the earplug wearing status for the unobserved periods.

The relationship between wearing behavior and ambient noise level

The coal miners failed to wear their earplugs 16.1% of time during their exposure period when ambient noise levels were at least 85 dBA. They did not wear them 40.8% of the time during their exposure period when the ambient noise levels were less than 85 dBA. The difference is substantial and statistically significant (P=0.034). The result indicates that these coal miners tended to remove their earplugs when the environment was relatively quiet and wore them when it was noisy.

Noise dose study result

Full-shift (8 hours) dose of the ambient noise and the ear noise exposure was extrapolated, respectively, from the noise sampling result on each subject. Table 5 shows that, every miner was exposed to projected ambient noise doses well above 100, the exposure limit recommended by NIOSH. Eight out of 11 coal miners even had projected ambient noise doses above 500. The average ambient noise dose of the coal miners was 931 with a standard deviation of 504. Five miners (45.5%) had projected ear noise doses above 100 while their earplugs were alternated between on and off during the work. The projected noise doses at the ear varied from the 33 to 560 among these miners, with an average of 153. Finally, the portion of the ear dose due to failure to wear ranged from 33.3 to 93.4% with an average of 64.6% across all the subjects. Additionally, the percentage of time the coal miners failed to wear their HPDs ranged from 6 to 78.3%, with an average of 24.9%.

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DISCUSSION

Fit test result

The overall NR_{fit} difference between any two orientations was less than 2 dBA for the E-A-R earplug. Orientation did not have an important effect on the overall NR_{fit} value of the earplug. In addition, the average overall NR_{fit} at 180^0 was less than that at either of other two orientations. The smaller NR_{fit} observed at 180^0 was most likely because the head and body shielded the tested ear. The effect was more dramatic at the high frequencies than the low frequencies. The E-A-R earplug provided at least 10 dBA of noise reduction, a level considered adequate for the great majority of workplace noise protection [12].

Every mine subject had a highly variable fit test overall NR_{fit} value across all his measurements. Since orientation did not show substantial effect on the over NR_{fit} value, the broad range of overall NR_{fit} value across all the measurements on each individual subject indicated that the overall NR_{fit} varied greatly from one fitting to another on each subject. This broad range can make an important difference regarding the noise protection, because the protection status of a coal miner can vary from being well-protected to being at risk of overexposure to noise, if the fit test result reflected his actual noise reduction during his coal mining work. Given the broad ranges found for the subject, no single fit test can be representative of the mean fit test. Multiple fit test measurements with different fittings were necessary to determine more accurate overall NR_{fit} of their earplugs.

Worksite noise sampling

The results (Table 5) indicated that these coal miners were highly overexposed to the coal mining noise and were at high risk of NIHL because each of their ambient noise doses was well above 100. 45.5% of the miners had projected ear noise doses above 100 while their earplugs were alternated between on and off during the work. These data suggest that the usage of their earplugs might not be adequate to protect them from NIHL. In addition, the result indicated that coal miners' ear dose due to failure to wear their earplugs varied from one subject to another (std = 23.2). Most of the coal miners (82%) had a percentage of ear doses due to failure to wear that exceeded 50%, indicating that failure to wear was an important factor affecting their noise protection. Furthermore, some coal miners were observed to wear their earplugs most of the time while some others wore them much less.

However, the result might have been affected by the investigators' presence. The investigators made observations on the subjects for identifying the mine subject's earplug usage behavior. Although each subject had been told to wear his earplugs as what he usually

Table 5. Noise dose sampling result for each mine subject

Subj#	Job title	Sampling minutes	Actual dose% sampled		Projected dose% (8hr)		Faction of ear dose due to not- worn	% min not-worn
			Ambient	Ear	Ambient	Ear		
1	operator	460	1485	537	1550	560	84.2%	20.0
2	operator	407	791	28	933	33	39.3%	6.0
3	operator	461	693	32	722	33	81.3%	8.7
4	operator	397	1196	247	1446	299	78.5%	19.6
5	operator	336	1128	25	1611	36	51.0%	6.3
13	shuttle car	193	129	54	321	134	33.3%	23.8
15	roof bolter	230	215	106	449	221	93.4%	78.3
17	roof bolter	135	59	32	210	114	90.6%	64.4
19	continuous miner	437	1274	61	1399	67	54.1%	7.6
20	roof bolter	401	602	82	721	98	53.7%	21.7
21	roof bolter	444	810	81	876	88	71.6%	18.0
Average		355	762	117	931	153	64.6%	24.9
Std		116	483	153	504	158	23.2%	24.1

would during the work, the investigators' presence might still have caused him to wear his earplugs more often, because a study subject may want to look good under the watchful eye of the investigator [9]. In addition, only those coal miners who sometimes or usually wore the HPD in their work were allowed to participate in the study. Those who should wear their HPDs in high noise environment but did not do so were excluded from the study. Therefore, the conclusion drawn in the study is limited to those coal miners who at least sometimes wore their HPDs during their work. It should be noted that 6 miners (35.2%) who should wear HPDs in the high noise workplace but never did so were excluded from the study. Considering the ambient noise exposure dose that was well above REL found on current mine subjects, one should be concerned that these miners excluded from the study had similar work environment and therefore were at very high risk of NIHL. Furthermore, there were relative few (11) subjects who participated in this study, which might affect the reliability of the research results. The current study just started to show some feasible approaches to exploring the research questions raised. More extensive studies are needed.

CONCLUSION

The orientation was not important for the fit test of earplug. Every coal miner was able to achieve an average NR of more than 10 dBA across all the fit test measurements. However, each subject's fit test result was highly variable across the different fitting measurements, indicating signal fit test is not adequate, and multiple fit test measurements should be taken in order to determine the coal miner's more accurate earplug noise protection. The wearing status judgment method was correct over 97% of the time. The coal miners generally wore their earplugs when the ambient noise levels were high (i.e., at least 85 dBA) and wore them much less when noise levels were below 85 dBA. The coal miners were exposed to excessive noise in their workplace and were at high risk of noise-induced hearing loss. Failure to wear the earplug was an important factor in determining the miners' noise exposure, accounting for 64.6% of their doses on average. Nearly half (45.5%) of the coal miners might not receive adequate protection with their earplugs from noise-induced hearing loss. 35.2% of miners never wore any HPD in high noise environment and were in very high risk of NIHL.

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