EARPLUG PERSONAL ATTENUATION RATING (PAR) IN NOISE-EXPOSED WORKERS: EVOLUTION OVER A FIVE WEEKS FOLLOW-UP

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In Quebec (Canada), the most prevalent and expensive occupational disease is noise-induced hearing loss (NIHL). Noise reduction at the source or during the propagation path is not always possible and is often costly, resulting in a frequent use of hearing protection devices (HPDs), such as earplugs, to prevent workers from NIHL. Multiple studies have shown that workers are not protected to the level expected by the labelled attenuation given by the HPDs manufacturers. One of the causes for this discrepancy is the lack of training about HPDs insertion. This study aims to document the noise-exposed worker's ability to adequately insert three different earplug models over a 5-week follow-up. To date, eighteen workers exposed to a high continuous noise level completed a questionnaire about their noise exposure history and HPDs experience. They were then group trained to insert the earplugs. A calibrated 3M™ E-A-Rfit™ Dual-Ear Validation System was used to measure the personal attenuation rating (PAR) and train them individually for proper insertion during five weeks. During each fit test procedure, the earplug insertion was adapted by the worker until a PAR≥10 was obtained, and the worker wore the tested earplug model in the noisy workplace for a week. Workers followed this PAR measurement procedure and tested roll-down foam model for two weeks, push-to-fit model for two weeks, and premolded model for one week. All the quantitative data were analysed using SAS. Different levels of analyses were conducted. Results about the workers' experience to insert the three different earplug models and the number of PAR trials will be presented considering the worker HPD experience and training prior to and during the study.

1. Introduction

In Quebec province (Canada), the noise-induced hearing loss (NIHL) is the occupational disease with the highest average cost per lesion [1], and 360 000 workers are exposed daily to hazardous noise levels that could lead to hearing disorders [2, 3]. This NIHL risk is directly related to the exposure time and the noise level exposure. Noise reduction at the source or during the propagation path would be the most effective solution to avoid NIHL [4], however it is not always possible and often costly in time and money. Many organizations turn to hearing protection devices (HPD), even if this solution is not completely satisfactory [4]. This study focusses on earplugs, since they are the most commonly used protectors by workers and their proper placement is more difficult to achieve, resulting in a less reliable protection than earmuffs [5,6].

A common method for selecting HPD is based on (i) the use of single number rating called "Noise Reduction Ratio" (NRR) quantifying the global attenuation of the HPD together with (ii) a measurement of the equivalent sound level (A-or C-weighted) at the workplace [7]. The NRR being measured in laboratory for a group of naïve participants [7], it is known to substantially overestimate the attenuation achieved in field conditions and it is thus derated for HPD selection as described in [7]. If derating lowers the level of expected attenuation, it doesn't eliminate the risk of NIHL since the effective attenuation provided by the HPD is still unknown. If the acoustic seal of the HPD is not obtained, the attenuation will be close to zero and thus even lower than the derated value. Indeed, to be adequately protected, the worker has to fit the HPD properly in his ears, and the complexity of this fit will vary from one worker to the other and from one HPD to the other.

A growing number of studies have reported the importance of the worker's training in order to achieve proper HPD positioning. For example, Samelli et al. (2015) studied control and trained groups, of which only the later reached an attenuation close to that announced by the manufacturer [8]. Nodoushan et al. (2014) found a better attenuation in trained participants using 25 dB NRR earplugs than untrained participants using 30 dB NRR earplugs, and concluded that training is the key to an efficient earplug use, rather than the choice of the earplug model (n=150) [9]. The Canadian standard on HPD [7] thus insists on providing the workers with a proper training most probably leading to better fit and protection for a given HPD (sections 11.2 and 11.3 of [7]). It also acknowledges the value of field attenuation estimation systems (FAES) [7]. These systems, recently standardized in the ANSI/ASA S12.71 [10], are based on the field-microphone in real ear technique (F-MIRE) and allow for assessing the attenuation achieved by an individual with a given HPD [11, 12]. This attenuation is quantified by a single-number value called "personal attenuation rating" (PAR). Murphy et al. (2016) studied noise-exposed workers and found an improvement when a short individual training and PAR measurements were performed [13]. Smith et al. (2014) studied workers whose fit-test was initially poor and found a significant improvement in fit-test results after training, which were maintained for at least 6 months [14]. Aside from these two studies, most other studies focusing on the training of good earplug use were limited to naïve subjects in laboratory, generally in a single session and without prolonged noise exposure experience. Those studies have focused on the PAR changes before and after training or immediately after versus many months after the training. Moreover, to our knowledge, none have considered the number of fit-test trials in individual trainings as an indicator of the workers' ability to put on the HPD. Also, if some studies used questionnaires about HPD comfort, they did not follow workers daily in the first days nor did they correlate subjective functional comfort measurements – such as ease to put in place – to PAR results.

The purpose of this study is to document the noise-exposed workers' ability to adequately insert three different earplug models over a 5-weeks follow-up. More specifically, the impact of the workers' experience and training before and during the 5-weeks follow-up on the fit quality of the different earplug models is analysed. The first days of HPD use are considered as beneficial experience for the noise-exposed worker, in complement to the initial training on earplug insertion. Here, both PAR and number of PAR trials needed to obtain a proper fit are used as indicators of the worker's ability to put the earplug adequately in place. This ability to fit the earplug is compared to daily questionnaires about perceived functional comfort by the workers.

2. Methods

2.1 Participants

Participants were recruited in autumn 2018 in a manufacturing organization in Quebec (Canada). Following our inclusion criteria, all participants were 18 years and older, French speaking (able to read and answer the questionnaires), exposed to a continuous noise in an indoor environment and were used to wear earplugs before taking part in the study. Participants did not have antecedents of ear or neurological pathologies and did not have an important amount of earwax in their earcanals. So far, 144 printing workers have attended the project presentation, 71 have shown an interest in taking part in the study and 18 eligible workers have completed their participation (final sample for this paper). The study has received ethic committee approval from ÉTS (École de technologie supérieure). The recruitment and participation is ongoing and results for a larger sample will be presented during the oral presentation.

The sample is constituted of 1 woman and 17 men (49.61 ± 8.36 years old). Most of participants had at least a high school degree ($n=14$; 78%). Out of 18, 12 (67%) wore roll-down foam earplugs regularly, 7 (39%) used custom earplugs regularly and 3 (17%) used premolded or push-to-fit earplugs regularly. Eleven workers out of 18 said having received a training about noise exposure hazard at work in the last two years ($n=6$; 55%) or $\geq$ 3 years ($n=8$; 45%). This training was provided mostly by the actual employer ($n=8$; 44%).

2.2 Measurement protocol and tested earplugs

Workers participated to a 5-weeks test campaign in which they were asked to wear three different earplug models in the following order (see Figure 1): week 1→3M^{TM} E-A-R^{TM} Classic uncorded (called "roll-down foam" in this study), week 2→ 3M^{TM} E-A-R^{TM} Push-ins^{TM} corded (called "push-to-fit" in this study), week 3→ 3M^{TM} E-A-R^{TM} Ultrafit^{TM} corded (called "premolded" in this study) , week 4→ repeat roll-down foam and finally, week 5→ repeat push-to-fit. Workers were individually trained at the beginning of each test week using a calibrated 3M™ E-A-Rfit™ Dual-Ear Validation System, as described in the next sections. They then wore the earplugs for a week in their noisy workplace. Hence, each participant was seen twice for fit-testing the roll-down foam and the push-to-fit earplugs. During the 5-weeks follow-up, workers reported wearing the earplugs for a mean of 7,0 hours per day, 4 days a week.

General information about the workers' noisy workstation and earplug use before the study were compiled on the first day (user profile questionnaire). The daily questionnaire allowed the worker to express any concerns about difficulties to put the earplugs in place and more detailed questions about earplug insertion were asked at the end of each test week (weekly questionnaire). The specific questions about functional comfort used in this study were derived from more complete questionnaires covering the four dimensions of comfort used in our broader study, and were defined according to the holistic definition of comfort proposed by Doutres et al. (submitted work), [15].
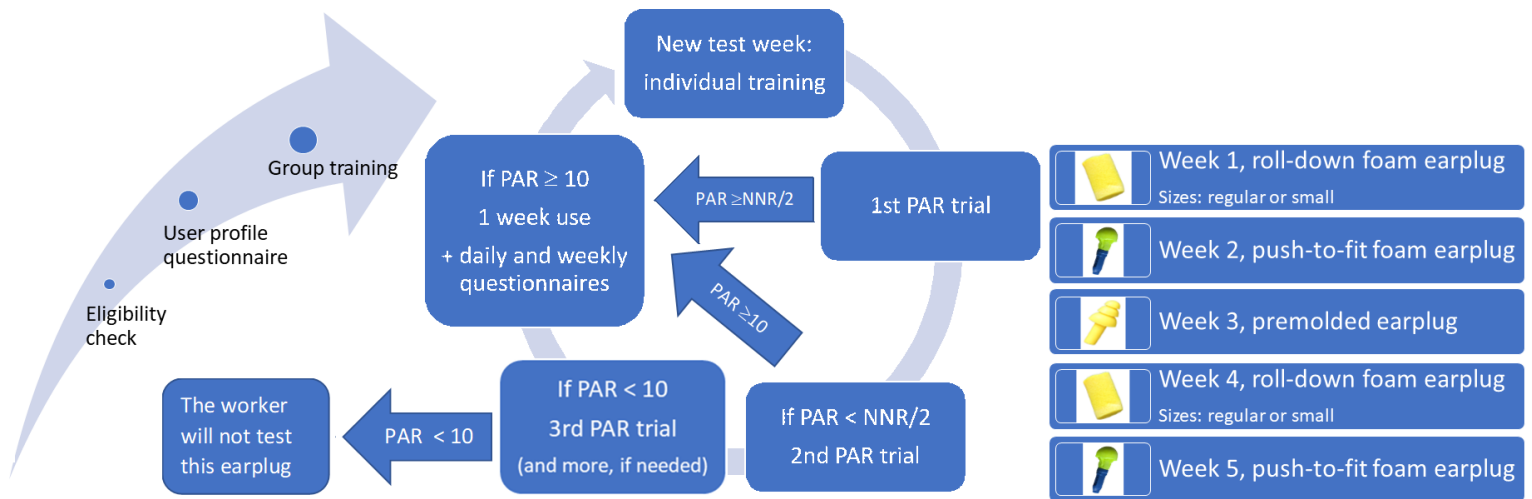
Figure 1: Description of the test weeks and tested earplug models

2.3 Training about HPDs insertion

2.3.1 Group training

Workers were group-trained by an audiologist once before beginning the first test week for one 20 minutes session. The group training included a reminder of the following steps of the study, the presentation of a short INRS video about the use of different earplug families [16]. Instructions were given in three modalities: written, video with demonstration, and verbal reminder before FAES (details in 2.3.2).

2.3.2 Individual training and PAR measurement

Each test week was beginning with an individual training using the FAES (see Figure 1). The audiologist first reminded the worker how to put the earplug in place, when to replace it and how to check if there was a proper fit. Then, the worker put the surrogate earplugs in place himself (or herself) for a first PAR trial. If both ears had an initial PAR of minimally 50% of the manufacturer's NRR value (the highest derating suggested in Table 2 of [7]), the worker was considered adequately protected and the individual training was over. If not, the worker was asked to adjust the earplugs for a second PAR trial, still aiming for 50% of the NRR. A floor PAR value of 10 was accepted, because the PAR data from the FAES includes a security factor. If the second trial reached at least a PAR of 10 for each ear, the training was over. If this floor value could not be obtained, a third placement was attempted by the audiologist: if this PAR trial was adequate, the worker was asked to replicate the adequate placement to ensure he was able to put it back in place (third trial, and more if needed). This is similar to the method described by Federman & Duhon (2016), where the participants learned successfully to replicate the adequate placement (and similar PAR) after feeling the correct insertion by an expert [17]. Finally, if both ears did not reach a PAR $\geq$ 10 for all trials (fitted by the worker), the earplug model was considered unsuitable for this participant's ear(s).

For the roll-down foam earplug, the first trial was done using the regular size (also known as "one size fits most" size). According to Smith et al. (1980), people will tend to choose smaller earplugs than their earcanal dimensions and, in those cases, a 1 mm diameter difference may have an important impact on the measured attenuation [18]. In our study, when a proper fit was not obtained with the regular size after a minimum of 2 attempts, the small size was tested.

After the individual training session, the worker was asked to wear the properly fitted earplugs for a week in the noisy workplace, which provided him with further experience of how to put the earplug properly. The exact same procedure was repeated for each 5 follow-up weeks. Week 4 and 5 resulted in a second individual training for the roll-down foam and push-to-fit earplugs three weeks after the first one.

To assess the worker's ability to properly fit each earplug model, the PAR and number of PAR trials were compared between the three earplug models. The impact of the workers' previous experience (years in a noisy workplace and previous regular use of a roll-down foam, push-to-fit or premolded earplug model) and experience during the study (first and second test week with a same earplug model) were investigated. Subjective information collected via questionnaires were compared to objective PAR and number of PAR trials data: perceived difficulties to put an earplug in place (daily questionnaires) and functional use (weekly questionnaire: intuitive insertion, ease of use, insertion time, number of actions required to insert the earplug and compatibility of use with the rhythm of work) were considered.

2.4 Data analyses

PAR data were collected and saved directly into the calibrated FAES. SAS 9.4 © (SAS Institute Inc, Cary, NC, USA) was used to perform all statistical analyses. A p-value <0.05 was considered statistically significant. To take into account the correlation between repeated measurements on the same individual over time, analyses were carried out using Linear Mixed Models with SAS PROC MIXED to analyse different outcomes. Preliminary results are presented below.

3. Results and discussion

Most workers were able to obtain a proper fit after one or two trials for every earplug model. The workers that needed more than 3 trials didn't obtain the minimal PAR of 10, even after up to 7 trials. When referring to depth "calibration" protocol considering the proportion of earplug inserted referring to the "posterior intersection of the concha floor and the earcanal entrance" described in [19], the placement of the roll-down foam earplug was usually standard (50-60% insertion) or better. In the following the PAR mean value and standard deviation of each earplug are calculated by considering the mean PAR obtained for both ears of all workers. Figure 2 shows the mean PAR at their first attempt to put each earplug model, compared to the NRR provided by the manufacturer. Those results include workers for which no adequate fit was obtained (NRR < 10). The mean PAR for the roll-down foam model is for the regular size and include the 4 workers who finally wore the size small; none of the workers had tried the smaller size before taking part in the study. Each mean PAR is below the NRR as pointed out by previous studies [8, 11], with the lowest and most different value obtained in the case of the premolded earplug.
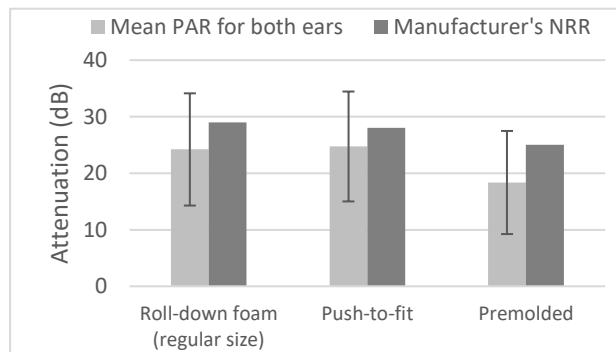

Figure 2: Mean PAR for the first attempt to fit each earplug model (*n*=18), with standard deviation

The descriptive statistics regarding the PAR data are summarized in Table 1. It must be recalled that workers were non naïve earplug users. The same roll-down earplug model was available in their workplace for years before taking part in the study. Previous experience may explain why all of the subjects (100%) were able to fit the roll-down foam earplug model. Moreover, the mean PAR was not statistically different for the same earplug model (roll-down foam or push-to-fit) when comparing the first and second test week results. However, for the mean number of PAR trials, a significant difference was observed for the push-to-fit earplugs only, showing that the workers put it in place in the second week in less attempts

than in the first week (difference of least squares (LS) means estimate: 0.50; $p < 0.05$; Confidence interval: 0.11 to 0.89). Workers may have benefited from the experience in the noisy workplace during the first week, as they have to take the earplug on and off many times a week and are able to adjust the placement according to their perception of the surrounding noise. Maybe they also perfected an adequate technique (manual dexterity, pulling with the right angle on the outer ear) and benefitted from the first individual training using FAES. Those results are in agreement with those of Smith et al. (2014), suggesting that workers were able to maintain a proper earplug placement 6 months after training [14]. Murphy et al. (2016) however found that only half the trained workers maintained an adequate protection after a year, suggesting that workers tend to eventually forget how to properly place the earplugs [13].

Table 1: PAR measurements for the 3 earplug models over the follow-up

		Roll-down foam	Push-to-fit	Premolded
NRR (manufacturer's data)		29	28	25
% unable to fit this earplug model properly (PAR < 10 for all trials for at least one ear)		0.0 % 0/18	11.1 % 2/18	16,7% 3/18
Mean PAR for both ears ± standard error (group, excluding PAR < 10)	1st week*	28.1 ± 1.2 n = N=18	30.1 ± 1.2 n = 16	25.2 ± 1.3 n = 15
	2nd week*	29.9 ± 1.2 n = 16	31.3 ± 1.3 n = 14	
Number of PAR trials ± standard error	1st week*	1.2 ± 0.1 ** n = 18	1.6 ± 0.1 ** n = 16	1.5 ± 0.2 ** n = 15
	2nd week*	1.4 ± 0.1 n = 16	1.1 ± 0.2 n = 14	
Mean ΔPAR for both ears (first – last trials) ± standard deviation For subjects with more than one trial only	1st week*	3.9 ± 4.9 n = 4	9.8 ± 6.6 n = 5	10.0 ± 10.8 n = 6
	2nd week*	6.4 ± 7.7 n = 5	6.3 ± 12.4 n = 1	

*Week 1 is the 1st roll-down foam test week, week 2 is the 1st push-to-fit test week, week 3 is the 1st premolded test week, week 4 is the 2nd roll-down foam test week and week 5 is the 2nd push-to-fit test week.

** A statistically significant difference is observed between the mean PAR for both ears at week 1, between roll-down foam and premolded (difference of LS means estimate: 2.88; $p < 0.05$; Confidence interval: 0.13 to 5.63) as well as between push-to-fit and premolded (difference of LS means estimate: 4.96; $p < 0.01$; Confidence interval: 2.14 to 7.79).

Considering all earplug data, workers who obtained an adequate fit on the first trial obtained a larger mean PAR for both ears compared to workers who needed a second trial (difference of LS means estimate: 4.72; $p < 0.01$; Confidence interval: 2.20 to 7.23). No significant PAR difference was found between workers who needed two trials and those who needed three trials. This difference may be due to the different pass/fail criterion used for the first (≥NRR/2) and following trials (≥10 dB). However most successful first attempts were done with a PAR exceeding largely the criterion. It is possible that the worker's understanding of the instructions has played a role even if the instructions were given in three modalities as mentioned in sec. 2.3. in order to limit this potential bias. A better hand dexterity could be beneficial to obtain a proper fit, although it would remain the same between trials: more studies on this aspect of earplug fitting would help to understand this potential bias. Because not everyone learns the same way, some workers would benefit of an audiologist fitting to be able to mimic the right fit. Anatomical factors may also explain these differences; a subsequent analysis of the workers earcanal geometries could help answer this question.

Regarding the impact of the workers' previous experience, no statistically significant correlation was found between the mean measured PAR and work experience (in years), as well as between previous experience using regularly roll-down foam, push-to-fit or premolded earplug families and specific earplug models. The same conclusion goes for the number of PAR trials. It is possible that the group training offered before the 5-weeks tests was sufficient for the workers to learn how to put the different HPD

models. It is also possible that there is an impact of work experience in a noisy workplace in the first weeks or months, but this impact was not measured since all workers had many years of experience. To answer that question, a sample with more work experience diversity would be needed.

Workers were asked daily about difficulties to put the earplug in place and a statistically significant difference was found regarding the mean answer on the very first test day between the roll-down foam and the push-to-fit earplugs (difference of LS means estimate: -1.37; $p < 0.01$; Confidence interval: -2.29 to -0.45) and between the roll-down foam and the premolded (difference of LS means estimate: -1.57; $p < 0.01$; Confidence interval: -2.50 to -0.63) models. These differences were still significant on the second and third days wearing the earplugs. The Classic model was associated to less difficulty to put in place, but this result may be biased due to its accessibility in the workplace for many years. Interestingly, no significant difference was found between the earplug models on the fourth day of the first week, as well as on all the days of the second week of test, showing that difficulties to put the tested earplug models in place were overcome by the workers after a 4 days use. Most previous studies did not follow up noise-exposed workers, but rather studied naïve participants or trained workers in a single session. These data suggest that workers benefit from their earplug use experience in a noisy environment to achieve a quick proper placement.

When functional attributes of comfort are compared between earplug models, the only statistically significant result was that the insertion required fewer actions for the push-to-fit as compared to the roll-down foam earplugs (difference of LS means estimate: -0.70; $p < 0.05$; Confidence interval: -1.40 to -0.01). When all earplug models are analyzed together, the PAR value is correlated to subjective assessment via the weekly questionnaires for the questions relative to: intuitive insertion (difference of LS means estimate: -1.76; $p < 0.05$; Confidence interval: -3.10 to -0.41), ease of use (difference of LS means estimate: 3.55; $p < 0.01$; Confidence interval: 1.46 to 5.63) and compatible use with the rhythm of work (difference of LS means estimate: 2.34; $p < 0.01$; Confidence interval: 1.14 to 3.54). An earplug with a more intuitive insertion would, contrary to what could be expected, be associated to a poor PAR. On the contrary, an earplug considered easy to use or adapted to the rhythm of work is associated to a better (larger) PAR. No significant correlation was found between PAR and the daily questionnaire, neither with weekly questions about insertion time and number of actions required to insert the earplug.

4. Conclusions

This study has documented the workers' ability to insert different earplug models adequately, considering the worker's experience and training during a 5-weeks follow-up. Eighteen trained workers used three different earplug models in a noisy workplace. When comparing the number of PAR trials on the first and second test week of roll-down foam and push-to-fit earplugs, a significant lower number of trials was measured for the push-to-fit earplugs, showing an impact of the use experience during the first week. However, no statistically significant impact of previous experience of the workers (earplug use or use of a specific earplug model) was found on the PAR or on the number of trials needed for a proper placement, possibly due to the fact that roll-down foam earplugs were already widely used by the workers but also available to them for years. When comparing subjective functional comfort as assessed by questionnaires, the difficulty to put the different earplugs in place was significantly different for the first three days, after which no statistically significant difference was observed between the earplug models. Globally, a higher ease of use as perceived by the worker was correlated to a higher PAR (considering all earplug models). In addition to training itself, the workers seemed to learn proper fitting by using the earplug in their noisy workplace for a few days. Other interesting results about training will probably come from the broader field study. Some limits of this work are the important experience with the roll-down foam earplugs before entering the study (due to its availability in the workplace), diversity of workers' manual dexterity, missing data in the questionnaires and diversity of noisy workplace environment. Future work about individual ear geometry and its impact on the different earplug model fitting is planned.

Acknowledgments

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