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Measurement of Hearing Protection Devices Performance in the Workplace during Full-Shift Working Operations

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Objectives: The effectiveness of hearing protection devices (HPDs), when used in workplace conditions, has been shown over the years to be usually lower than the labeled values obtained under well-controlled laboratory conditions. Causes for such discrepancies have been listed and discussed by many authors. This study is an attempt to understand the issues in greater details and quantify some of these factors by looking at the performance of hearing protectors as a function of time during full work shift conditions.

Methods: A non-invasive field microphone in the real ear (F-MIRE)-based method has been developed for measuring the effectiveness of different HPDs as a function of time in the workplace. Details of the test procedures, the equipment used, and the post-processing operations are presented and discussed. The methodology was developed in such a way that a complete time and frequency representation are possible. The system was used on a total of 24 workers in eight different companies. Work shifts of up to 9-h long were recorded. Various types of earmuffs and one type of molded earplugs were tested.

Results: Attenuation data reported as a function of time showed, for most workers tested, considerable fluctuations over entire work shift periods. Parts of these fluctuations are attributed to variations in the low-frequency content in the noise (in particular for earmuffs) as well as poor insertion and/or fitting of earplugs. Lower performances than laboratory-based ones were once again observed for most cases tested but also, important left and right ear differences were obtained for many individuals. When reported as a function of frequency, the attenuation results suggested that the few approximations used to relate the measurements to subjective real-ear-attenuation-at-threshold (REAT) data were realistic.

Conclusions: The use of individualized attenuation data and performance ratings for HPDs as well as a good knowledge of the ambient noise in the workplace are key ingredients when evaluating the performance of hearing protectors in field conditions.

Keywords: hearing protection; MIRE; noise exposure; subjective rating

INTRODUCTION

Most regulations require employers to provide employees with proper protection against the effects of exposure to excessive noise levels. Protective measures may be provided either through engineering [e.g. noise reduction (NR) at the source] or through administrative controls (e.g. exposure controls). Unfortunately, these control measures often fail, for practical or economical reasons, to reduce the noise below the acceptable limits. Hearing protection devices

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(HPDs) have then to be offered by employers and used by the workers. The effective performance of HPDs not only depends on attenuation levels of the device but also on how well and how long it is worn. In terms of attenuation, HPDs are typically characterized by ratings such as the noise reduction rating (NRR) in the USA. These ratings are notably used to estimate the workers effective exposure when the HPDs are worn by subtracting the rating from a measured sound field level or exposure. Ratings calculations rely on attenuation measurements performed under well-controlled laboratory conditions prescribed in various standards [e.g. ANSI S3.19 (ANSI, 1974) or ISO 4869-1 (ISO, 1990)]. For obvious reasons, these laboratory conditions differ considerably from typical workplace environments. Consequences are that discrepancies between the labeled attenuation rating data and field measurement data have been observed and reported over the years (Behar, 1985; Casali and Park 1991; Berger *et al.*, 1996; Giardano and Durkt, 1996; Neitzel and Seixas, 2005) for all types of HPDs.

Multiple reasons have been put forward to explain the aforementioned discrepancies between the so-called 'laboratory' and 'field' data. Berger (1980) listed some of the causes of poor HPD sealing: (i) comfort, (ii) utilization, (iii) fit, (iv) compatibility, (v) readjustment, (vi) deterioration, and (vii) abuse. The lack of comfort, often cited as one of the main factor affecting the attenuation, may lead to a misuse or intermittent use of HPDs in order to increase their comfort or to improve communication. In a study over a population of printing workers (Morata *et al.*, 2001), it was found that only 64% of the 124 workers in the study indicated that they were wearing their hearing protectors. Of this group, only 20% indicated wearing their HPDs all the time. The most significant reasons mentioned for not wearing the protectors included interference with communication, interference with job performance, comfort issues and self-perception of hearing condition. The intermittent or irregular use of an HPD is one of the most important factors influencing the effective protection obtained by a worker. As an example, using a 5 dB exchange rate, a worker wearing an HPD labeled at 25 dB would see his effective protection dropped to ~17 dB if the HPD is not worn for 30 min over an 8-h shift. A good illustration can be found in a study held in the construction industry (Neitzel and Seixas, 2005). In particular, it is mentioned that 'when the measured HPD attenuation levels and use time data were combined, the effective protection afforded by HPDs was <3 dB, a negligible amount given the high exposure levels associated with construction work'. Comparable results (Lusk *et al.*, 1998), obtained on 400 workers also from the construction industry, showed HPDs utilization rate ranging from 18 to 46% depending on the task performed. In a report from the Health & Safety Executive (HSE) in the UK (Hughson *et al.*, 2002), the results on workers' attitude toward hearing protection were obtained using questionnaires filled by 280 employees in 19 companies. Only 132 of these 280 employees said that they were using their HPD all the time, while only 112 were wearing theirs occasionally. Of the 180 employees, 30 said not wearing their HPD at all [which is in accordance with the results presented in another paper (Berger, 2000)]. As in the work of Morata *et al.* (2001) discussed previously, the main reasons presented to explain the misuse of hearing protectors are interference with communications, interference with job performance, comfort issues and self-perception of hearing condition. Additionally, the authors pointed out certain workers' negative attitudes, which can have an influence on the usage of HPDs. In a study on circumaural protectors (Chung *et al.*, 1983), personal noise dosimeters were used to measure exposures inside and outside of earmuffs and the authors concluded that a major factor affecting the attenuation of earmuffs was fit. The relation between comfort and intermittent use of HPDs has been discussed by Arezes and Miguel (2002). The authors suggested using a questionnaire completed by 20 workers that protectors with lower labeled attenuation but with higher acceptability tended to be more efficient than protectors with higher labeled attenuation but lower acceptability. They have also shown significant positive correlation between the comfort index and the time of usage of protectors.

In order to better understand what is happening in 'real-world' conditions (e.g. positioning of HPD, dynamic motion of the head, etc.), some authors have tried to reproduce these conditions in a laboratory environment (Casali and Park 1990a,b). Another study (Lemstad and Kluge, 2004) has been carried out to investigate how much spectacles influence the attenuation of earmuffs. It is found that safety glasses can introduce significant reduction in the attenuation of earmuffs, depending on the spectacles and the subject under test. An attempt was made (Lenzuni, 2009) to estimate and quantify the variability of the attenuation due to several factors (biological diversity, positioning, acoustic field and ageing) based on laboratory measurements and observations. Once cumulated, an overall variability in the attenuation of $\sigma = 4.8$ dB is proposed by the author.

Comprehensive reviews of measurement methods commonly used to evaluate the field performance of HPDs have been proposed (Berger, 1986; Hager, 2006; Berger *et al.*, 2007; Gaudreau *et al.*, 2008; Kusy, 2008). These methods can generally be divided into two categories: subjective and objective methods. The most commonly used subjective method is based on the real-ear-attenuation-at-threshold (REAT) method where the difference between the auditory thresholds measured on the occluded and unoccluded ear is used to obtain the attenuation of an HPD. For field measurements, the REAT method usually requires having a quiet environment, typically a portable audiometric test booth. The subjects are then removed from their working environment and tested under the test booth conditions. REAT-based field methods have been successfully used to produce data that can be compared to standard laboratory REAT results in order to evaluate the field performance of HPDs (Murphy *et al.*, 1999; Franks *et al.*, 2003; Neitzel *et al.*, 2006). Other studies, while few in numbers, have shown that subjective procedures based on the loudness balance (Soli *et al.*, 2005) and the bone conduction loudness balance (Rimmer and Ellenbecker, 1997a,b) can be used to measure the field performance of HPDs with some success. These procedures suffer less from background noise contamination than REAT measurements as the testing is conducted at higher sound levels but are affected by workers' hearing thresholds.

Objective methods essentially rely on miniature microphones measurements to obtain attenuation data. When only one microphone is used inside the ear canal to measure an insertion loss (IL), it is commonly referred as the microphone in the real ear (MIRE) technique (Berger, 1986). When this interior microphone is combined with an additional one located outside of the protector, a set-up more suited for field measurements, the technique is termed field MIRE (F-MIRE). The F-MIRE procedure has been successfully used for custom-molded earplugs (Voix, 2006; Voix and Laville, 2009). In their works, the authors have shown that attenuation values comparable to REAT measurements can be obtained by measuring simultaneously the sound pressure levels outside and under the hearing protector as long as some correction factors are used to account for quantitative differences between F-MIRE and REAT. Application of F-MIRE to other type of earplugs (foam and premolded) has been presented and discussed recently (Berger *et al.*, 2008).

The F-MIRE approach can also be used with earmuff-type protectors utilizing, also, external and interior microphones to measure the unprotected and protected sound field. One of the first studies to fully exploit the F-MIRE approach on circumaural protectors was conducted on mining workers performing normal work duties (Durkt, 1993). The unprotected and protected noise signals were recorded by using two frequency-modulation radio systems. Comparisons of attenuation ratings measured on a total of 107 individual tests and 11 protectors with standard NRR values are presented. The F-MIRE approach offers the advantage that it can be conducted in high industrial noise levels and during normal working conditions. Moreover, it provides the capability to carry out measurements in a continuous manner over time while workers perform their regular work duties. Some studies based on F-MIRE principles have used dosimetry to assess the performance of earmuff-type HPDs (Chung *et al.*, 1983; Goff and Blank, 1984; Burks and Michael, 2003). It has been found that field attenuation values are generally well below the labeled NRR values. Similar results based on the dual-microphone F-MIRE approach for muff-type HPDs have also been reported by, additionally, looking at the frequency content of the noise (Giardano and Durkt, 1996). In that study, a total of 23 models of HPDs and 545 machines (20 different machine types) were evaluated in field conditions for a total 1265 HPD evaluations. NR values for each HPD model are presented as a function of the metric C-A, a characteristic of the spectrum of the machine noise. Again, it is concluded that laboratory-derived NRR fails to predict HPDs field performances. More recently, an F-MIRE-based study has been conducted on various workers wearing earmuffs (Kotarbinska *et al.*, 2007). Four microphones were used (two per ear) and were connected to a four-channel third-octave analyzer. Results are presented as $L_{A,eq}$, $L_{A,max}$, and $L_{C,peak}$ outside and under the earmuff cups. However, to our knowledge, no correction factors were used to take into account the effect of the transfer function of the open ear (TFOE). Differences between left and right ears are observed and many workers were found to be exposed to levels higher than the exposure limit value. The main reasons given for the lack of expected protection are bad cushion fitting by incorrect usage or wearing spectacles at the same time and bad condition of earmuffs due to prolonged usage.

While it is well documented that field attenuations are generally lower than laboratory measured ones and that field methods have been developed to assess the performance of HPDs in real industrial conditions, few studies have looked in details at the effective daily protection as a function of time during regular work shifts. This paper presents the results and findings of an F-MIRE-based study that focused primarily at measuring the effective attenuation obtained by workers by recording continuously, over entire work shifts, the protected and unprotected sound pressure using miniature microphones connected to portable recorders. The paper focuses mainly on presenting the developed method and demonstrating its potential in the workplace rather than offering a complete analysis of data obtained from large number of HPDs, subjects, and working environments. The remainder of the paper provides first a description of the methodology and the data acquisition system as well a short presentation of the workplace environments that were visited for testing. The most relevant results are finally presented followed by discussion.

METHODS

Basic procedure

The proposed method is based on the F-MIRE technique. Two types of protectors were used: earmuffs and custom-molded earplugs. The custom earplugs were provided by Sonomax Technologies Inc. (Sonomax, 2011). As illustrated in Fig. 1, these earplugs are designed to allow for a miniature microphone to be inserted in the plug looking into the ear canal through a tube thus measuring the protected sound pressure. This 'interior' microphone is combined to form a dual element with another microphone (noted the 'exterior'). The second microphone is used to measure the exterior (unprotected) sound field. Similarly, the earmuffs used in the study were modified in a way that the same dual element can be used to measure the exterior and interior sound pressure signals. A small hole was drilled in the cup of the earmuffs and a tube was inserted through it (see Fig. 1). The tube was cut to a fixed length of

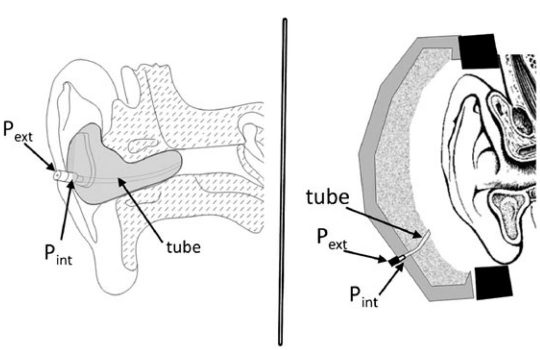

Fig. 1. Representation of the installation of the exterior (noted 'ext') and interior (noted 'int') microphones on molded earplugs (left side) and earmuffs (right side).

20 mm in order to pass through the foam inside the cup. The dual-element microphone was then connected to the inner tube, using threaded element, the interior microphone then looking directly into the volume under the cup. While this type of arrangement requires modifying the earmuffs, tests were carried out to check for proper acoustic sealing. Also, it eliminates the need to have wires running between the earmuffs cushion and the subject's skin and it facilitates the placement of the interior microphone as it is always at a fixed position under the cup. The dual-element microphone was connected to a two-channel recorder and uncompressed pulse-code modulation (PCM) files were continuously recorded. The unprotected and protected time signals were then post-processed to obtain various indicators relative to the performance of the HPD.

Equipment

One of the main objectives of the study was to be able to 'instrument' a worker such that at least 8-h work shifts could be recorded for each ear. Therefore, the acquisition system was required to be light, comfortable, and rugged in order to be able to be worn in diverse working conditions without altering workers' habits. Recording the entire time signals (as opposed to measuring only the sound pressure levels) leads to large datasets but gives much more flexibility in terms of signal analysis. Omni directional Knowles miniature microphones of type FG-23742 and FG-23652 (Knowles, 2011) were assembled to form the dual-element microphone. The recorder was an Edirol R-09 (Roland, 2011) a two-channel digital recorder with 16 bits resolution, 44.1 kHz sampling frequency, and the capability of saving uncompressed data on secure digital memory cards. Total weight of the recorder and the batteries did not exceed 170 g. A complete measurement system for one ear consisted then in the dual-element microphone installed on the HPD and a small portable bag containing a battery pack for microphone power supply and the digital recorder. Each worker was then asked to wear two of these systems on their belt during their entire shifts (see Fig. 2). To calibrate the microphones on-site, 10-s segment of tones generated by a Brüel & Kjaer type 4231 reference source were recorded for each microphone before and after each recording sessions. These calibration recordings were then used during data post-processing to correct the microphone measurements.

Sites and subjects selection

A total of eight facilities participated in this study. It was intended to have a diversity of workplaces, not only in terms of work activity but also in terms of sound field (frequency and temporal contents and noise levels). Table 1 summarizes the main characteristics of the eight participating facilities. Facility no. 8 was a special case where test durations were limited by the employer to ~30 min because of severe noise levels (>110 dB(A)). Also, a set of three pairs of new earmuffs were used for all the workers in this facility. For three workers, the cups were installed on a safety helmet (Workers no. 22, 26, and 27). Three sets of the measurement system described above were brought at each facility so that three workers could be tested simultaneously. The workers participated on a voluntary basis and were not given any monetary inducements. Prior to their regular shift, the workers were given an overview of the study as well as the procedures for the tests and the day. Interested participants signed a consent form and were told they could stop their participation at any time and for any reason. Of the 24 participants, 19 were males. Age of the participants ranged from 23 to 60 years old with an average of 41 and a median of 39.5 years old. The earmuffs worn by the workers were sent to our facilities few days before the testing for installation of the tube in the cups. At the end of tests, new unmodified earmuffs were given to the participants.

Processing of the data

For a given subject, a group of four PCM files was available for post-processing. The interior and exterior microphone time signals were analyzed using

Fig. 2. Examples of workers equipped with two sets (one per ear) of measurement systems. This figure appears in color online.

Table 1. Overview of the visited facilities and hearing protectors and workers tested

No.	Company type	No. tested workers	HPD type	Brand	Approximate time per worker	Age range (years)
1	Food transformation	2	Molded earplugs	Sonomax	8 h	40–50
2	Petrochemicals	2	Molded earplugs	Sonomax	8 h	50–60
3	Wood furniture	2	Earmuffs	Oris Mustang EM-4155	3 h	30–40
4	Aluminum transformation	3	Molded earplugs	Sonomax	8 h	1 × 55–60 2 × 25–30
5	Motorized products assembly	3	Molded earplugs	Sonomax	8 h	45–50
6	Wood transformation	3	Earmuffs	Peltor H7A	9 h	25–50
7	Aeronautics	3	Earmuffs	Peltor H7A	9 h	25–30 35–40 45–50
8	Power production—generator	6	Earmuffs	Bilsom Thunder T3 and T3H	30 min	N/A

third-octave bands. The autopower (PSD) and cross-power (CSD) spectral density functions were calculated for various time frames with a time step Δt The PSD and CSD were used to calculate indicators such as sound pressure levels and overall sound pressure levels, spectral balance, and attenuation values. Attenuation values M were computed using the transfer function between the exterior (e) and interior (i) microphones and were defined as:

$$M(t,f) = -20\log_{10}\left(\left|\sqrt{\frac{G_{\mathrm{ei}}G_{\mathrm{ii}}}{G_{\mathrm{ee}}G^{*}_{\mathrm{ei}}}}\right|\right), \quad (1)$$

where G_{ee} and G_{ii} are the PSD of, respectively, the exterior and interior microphones and where G_{ei} is the CSD between the exterior and interior microphones. PSD and CSD functions are frequency and time dependant. The attenuation values can be compared to laboratory data using the Assumed Protection Value (APV) (ANSI, 2007) defined as:

$$\mathrm{APV}_x(f) = m(f) - \alpha_x s(f), \quad (2)$$

where f is the frequency and m and s are, respectively, the mean and standard deviation of the laboratory-derived attenuation values. The constant α_x is related to the desired protection rate x. The F-MIRE attenuation values can be directly compared to the $\mathrm{APV_x}$ values provided that some correction factors, discussed later, are used on the measured data.

The attenuation values M can be used to define a single attenuation index, noted AI, by:

$$\mathrm{AI}(t) = O^{A}_{\mathrm{ext}}(t) - 10\log_{10}\left(\sum_{i=1}^{N_f} 10^{0.1\left(L^{A}_{ext}(t,f_i) - M(t,f_i)\right)}\right), \quad (3)$$

where $O^{A}_{\mathrm{ext}}(t)$ and $L^{A}_{ext}(t,f)$ are, respectively, the exterior A-weighted overall and spectrum levels and N_{f} is the number of frequency bands. This attenuation rating is constructed in a similar way than the single number rating defined in an ISO standard (ISO, 1994) with the exception that the proposed rating AI can be subtracted directly from A-weighted noise levels to obtain an estimate of the noise experienced by users of HPDs.

For the purpose of comparisons with laboratory-derived values, an additional attenuation index, noted $\mathrm{AI}^{x}_{\mathrm{lab}}$, is defined as:

$$\mathrm{AI}^{x}_{\mathrm{lab}}(t) = O^{A}_{\mathrm{ext}}(t) - 10\log_{10}\left(\sum_{i=1}^{N_f} 10^{0.1\left(L^{A}_{\mathrm{ext}}(t,f_i) - \mathrm{APV}_x(f_i)\right)}\right). \quad (4)$$

This index is constructed the same way as the AI index by simply replacing the measured attenuation values by the APV values. The APV values were computed using publicly available manufacturers' data.

Correction factors

The proposed F-MIRE method yields attenuation data derived from NR, a measurement of the difference between the exterior and interior levels. The REAT method yields attenuation data that can be viewed as a subjective IL as it results from the difference between the auditory thresholds measured on the occluded and unoccluded ear. The objective counterpart of the subjective REAT is an objective IL, which is the difference of levels in the ear canal, with and without the protector in place. As such, IL and NR are directly related and corrections factors can be incorporated in the NR calculations to obtain corrected attenuation values, which can be compared to REAT/IL values. The correction factors account, on one hand, for the TFOE, which corresponds to the difference between the sound pressure levels at the eardrum and in the sound field without the presence of the head. They also account for the fact that the sound pressure is measured at the end of the tube and not at the eardrum and also incorporate the effects of frequency response of the tube itself. Estimation of these correction factors is not trivial and can be found in the literature for the custom-molded earplugs used in this study (Voix, 2006). For earmuffs, to the authors' knowledge, there is a lack of study on that matter in the literature. The correction factors due to the tube effect can be estimated in laboratory but to account for the TFOE, values proposed in a standard were used (ISO, 2000). The diffuse field values for open entrance position were employed since the measurement tube is picking up the signals directly under the cup, close to the ear canal entrance. For the remainder of the paper, all presented results derived from the interior microphone signal were corrected.

RESULTS

A first set of results, for a worker from Company no. 6 wearing earmuffs, is presented in Fig. 3. Four indicators are presented as a function of time (time step of 60 s). The first plot at the top shows the exterior levels, in dB(A), for both ears. Similarly, the second plot presents the spectral balance B (the difference, expressed in dB, between the C- and A-weighted overall sound pressure levels) of the exterior sound field at both ears. The third and fourth plots depict the attenuation index AI as calculated

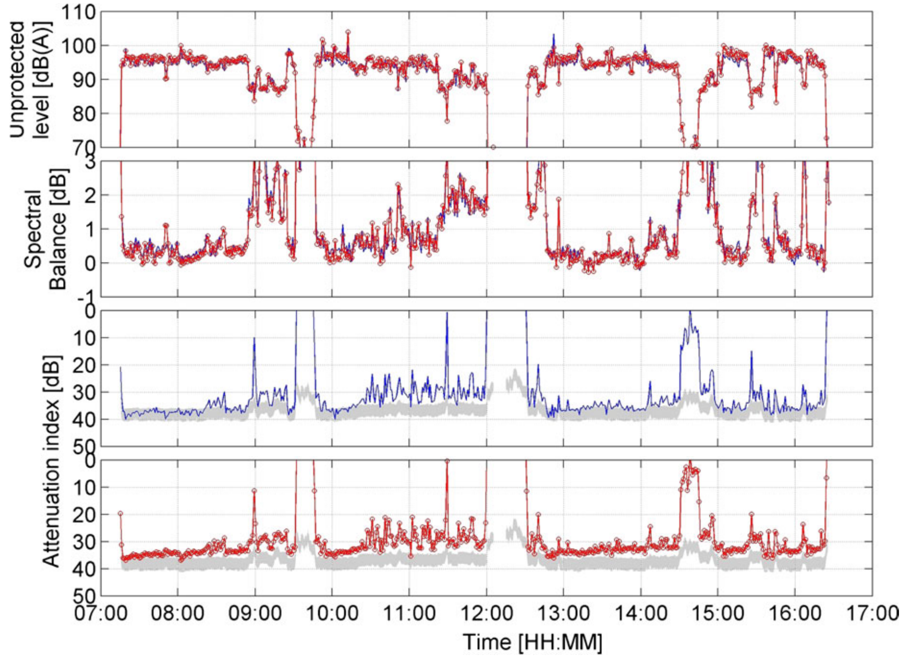

Fig. 3. Unprotected level (first row from top), spectral balance (second row) and attenuation index for left ear (third row) and right ear (fourth row) as a function of time for a worker wearing earmuffs in Facility #6. Solid lines with/without symbols are related to the right/left ears. Gray shaded area: range of values for the index AI^x_{lab} using protection rates of 20 and 80% to set, respectively, the upper and lower limits. This figure appears in color online.

in equation (3) for, respectively, the left and right ears. The gray shaded area represents the range of values for the laboratory-based index AI^x_{lab} by using protection rates of 20% ($\alpha = -0.84$) and 80% ($\alpha = +0.84$) to set, respectively, the upper and lower limits. The morning (9:30–9:45), lunch (12:00–12:30), and afternoon (14:30–14:45) breaks can easily be observed by looking at the exterior levels as the worker went outside the noisy environments for the breaks. The equipment was removed during lunch break to change batteries and memory cards. The worker was exposed most of the time to levels ranging from 90 dB(A) to >100 dB(A). The attenuation index AI is different from the left to the right ear and is constantly below the range of values of the AI^x_{lab} index. As it can be seen at different times, the attenuation index AI is generally inversely proportional to the spectral balance. Between 10:00 and 12:00, important variations of AI are observed as the spectral balance increases considerably and, overall, reductions of AI by as much as 7–10 dB are observed. This is somehow expected as values of spectral balance >1 dB are indication of significant low-frequency content in the ambient noise, frequencies for which the weaknesses of earmuffs can appear.

In a similar way as in the previous section, Fig. 4 presents the results for a worker wearing custom molded earplugs (Company no. 4). Interestingly, the ambient noise levels are notably higher at the right ear compared to the left one before lunch break, suggesting that the worker was exposed to a directional source. This can also be observed in the spectral balance for which a much lower value is observed at the right ear. For both ears, the attenuation index AI is lower than the laboratory-based index AI^x_{lab}. Low attenuation values are obtained for the right ear before lunch break while it almost doubles after lunch, suggesting better earplug insertion in the afternoon. In the same vein, the first few minutes of the afternoon shift show high values of AI rapidly declining toward a more constant value. For the left ear, a relatively stable value of attenuation is observed with few variations as a function of the spectral balance. It is worth noting that in some sections (e.g. from 9 h 15 to 10 h 15 in Fig. 4), a decline in the AI values is observed, while no significant variations in the spectral balance are observed. It is rather difficult to point out which specific factor affects the attenuation and, at this point of the analysis, one can only speculate a poor fit of the earplug causing the plug to 'lose' gradually its seal.

A different view of the results just presented above in Fig. 4 is proposed in Fig. 5. Attenuation frequency

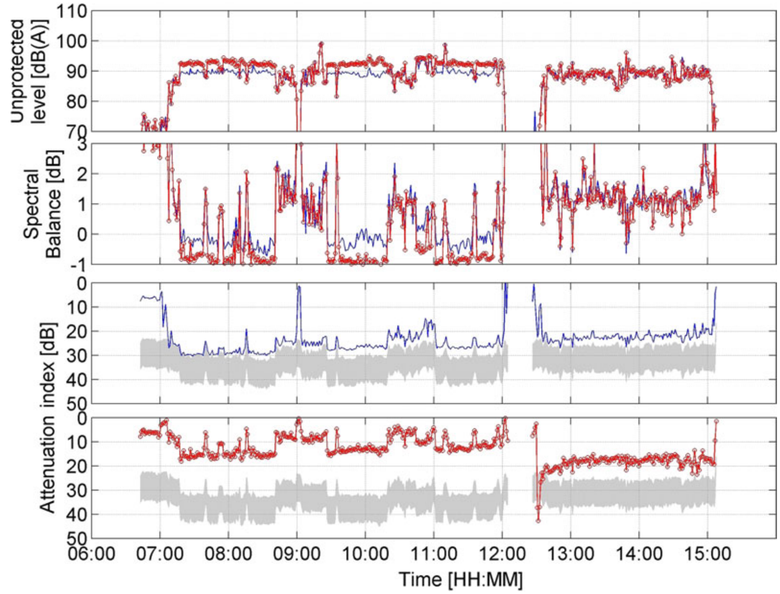

Fig. 4. Unprotected level (first row from top), spectral balance (second row), and attenuation index for left ear (third row) and right ear (fourth row) as a function of time for a worker wearing molded earplugs in Facility #4. Solid lines with/without symbols are related to the right/left ears. Gray shaded area: range of values for the index AI_{lab}^{x} using protection rates of 20 and 80% to set, respectively, the upper and lower limits. This figure appears in color online.

responses are plotted for every 60-s time step. Plots on the left side refer to the left ear and the ones on the right side to the right ear. The upper part shows the attenuation results for all time frames while for the center part, only the values for which the ambient noise was >85 dB(A) were retained and plotted. The mean and standard deviations values associated to this last set of data are plotted in the bottom part and compared to the $APV_{80\%}$, computed using laboratory-based values. The left/right ear differences can easily be observed; the left ear results showing good correlation between the measured and APV values <1000 Hz and some departures >1000 Hz. The morning/afternoon differences observed in Fig. 4 for the right ear can be seen easily in Fig. 5 as two groups of lines are obtained, thus impacting the mean values and increasing the standard deviation. It reveals that the earplug was particularly inefficient in the low-frequency range when, as hypothesized earlier, poorly inserted during the morning part of the work shift.

Special cases were made with some workers in Company no. 8 to look at the effect of safety glasses on earmuffs performance. The attenuation index is shown, as a function of time, for one of the worker in Fig. 6 (5 s. time step). Again, the AI values are shown in comparison with the range of laboratory-based attenuation index values. For this environment, the ambient noise levels were very high (between 110 and 115 dB(A)) and fairly constant over time. The spectral balance was also constant at 1–1.5 dB. The worker was asked to remove his safety glasses between 19:47 and 19:48. The effect can be immediately seen as the AI values increase significantly by as much as 5–8 dB after the glasses were removed. Also, much more fluctuations of AI are observed when the safety glasses were worn. Finally, left/right ear differences are observed in the AI values before as well as after the safety glasses were removed.

A summary of the attenuation results for all workers is presented in Fig. 7. For each worker, the left and right AI mean and standard deviation values were calculated over the entire time for which the worker was exposed to ambient noise >85 dB(A). This exposure time is indicated on the left side of the plot together with labels related to the company (Letter C) and to the worker (Letter W). AI values were sorted, from the lowest at the bottom to the highest at the top, using left ear values. Although sample size is small, a few observations can be made on the results. As noted before, left/right ear differences are observed for most of the workers, more particularly for earplugs. Small AI values, together with substantial standard deviations, are observed for some workers. Two of these workers, wearing earplugs, are essentially showing no significant attenuation. It was found, by frequent visual

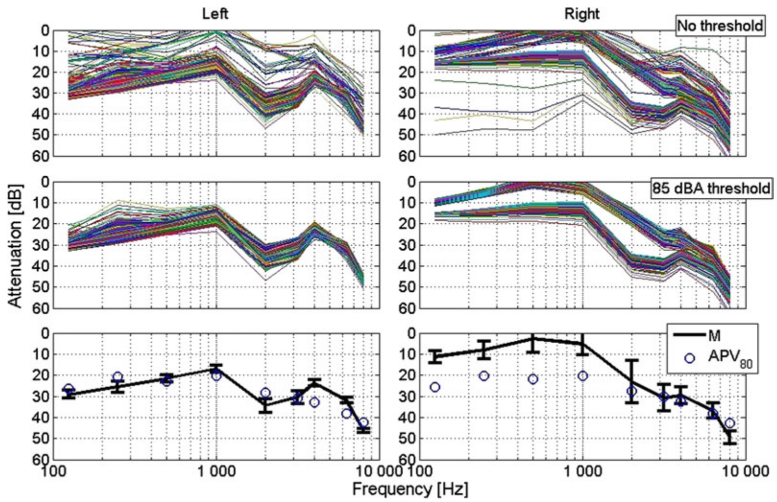

Fig. 5. Attenuation values for both ears as a function of frequency for a worker wearing earplugs in Facility #4. Top row: all 60-s time frames represented. Center row: time frames with ambient noise >85 dB(A) only are retained. Bottom row: mean and standard deviation of the 'thresholded' data and APV_{80} values. This figure appears in color online.

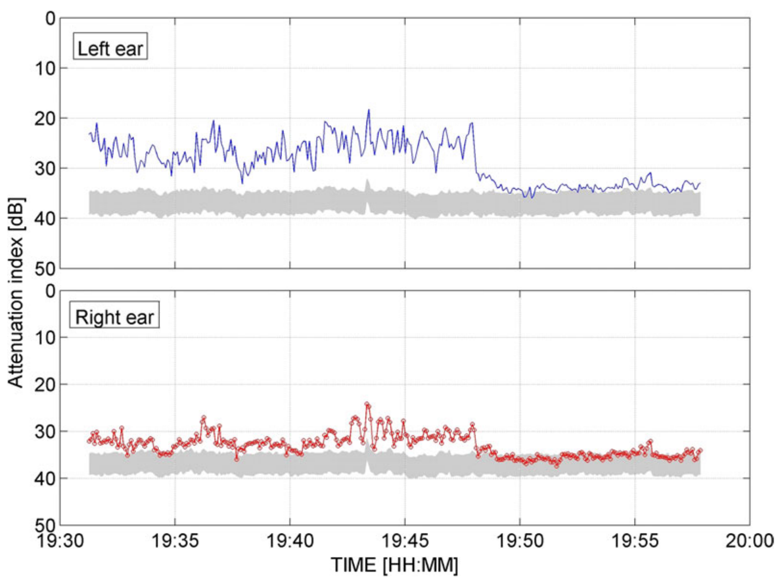

Fig. 6. Attenuation index as a function of time for a worker wearing earmuffs and safety glasses in Facility #8 (the worker was asked to remove his safety glasses between 19:47 and 19:48). Gray shaded area: range of values for the index AI^{x}_{lab} using protection rates of 20 and 80% to set, respectively, the upper and lower limits. This figure appears in color online.

observations during the shift, that these workers had their earplugs regularly removed and poorly inserted. As mentioned earlier, the workers of Facility no. 8 (very high noise levels >110 dB(A) and constant spectral balance ~1.5 dB) were all utilizing the same type of earmuffs and, in some cases, the exact same earmuffs. Even in that scenario, various values of attenuation index are obtained for different workers, ranging from 20 to 40 dB.

DISCUSSION

The subset of results presented in the previous section shows the potential of the proposed approach to better understand the performance of hearing protectors. However, the number of workers and type of HPDs tested in this study are too low to make any generalizations. Still, one can expect some observations and findings of this study to be applicable to

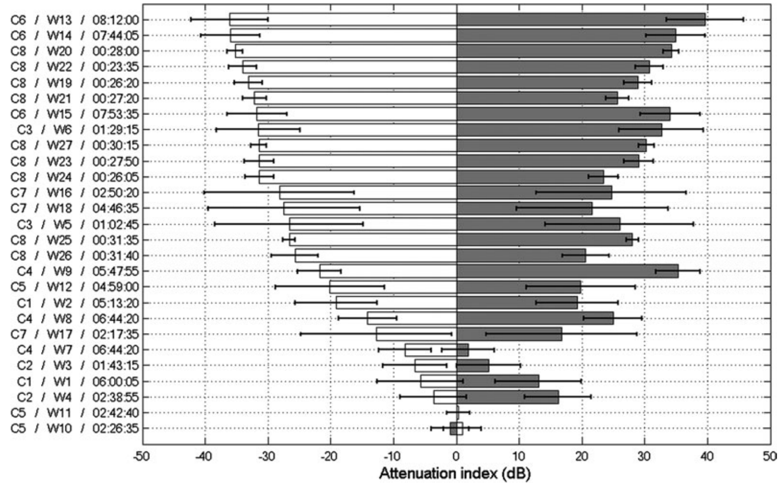

Fig. 7. Mean and standard deviation of the attenuation index for all workers tested (left/right ear on the left/right side). Only values for which the ambient noise was >85 dB(A) were retained for the calculations. The time spent >85 dB(A) and identifications of the facility (Letter 'C') and worker (Letter 'W') are displayed on the left axis.

a significant number of workers. As discussed previously, significant left/right ear differences are observed in the attenuation for many workers, even for muff-type protectors. As illustrated in Fig. 4, some results also revealed differences in the ambient sound levels between the left and right ears for some workers. It may suggest directional fields or sources at certain workstation but also raises some questions regarding the position of the exterior microphone capturing the ambient noise. It also brings up the issue of directionality of the attenuation of HPDs, an issue less frequently studied in the past. These two topics are currently under investigations.

Detailed analysis of time data results showed important variations of the attenuation index as a function of time as illustrated in Fig. 7 by the large standard deviations found for most workers. Some of the variations can be explained by the fluctuations in the frequency content of the ambient noise, estimated here by the spectral balance. This effect was generally found more pronounced for earmuffs for which lower attenuations are usually found at low frequency. After listening to the recordings, variations in the attenuation index values were also found to be due, in many occurrences, to the removal or poor placement/insertion of the protectors (for short or long periods of time) or to the presence of worker's own voice. The presence of self-voice in the protected signals for well-inserted earplugs tends to increase the low-frequency content, thus reducing the attenuation index. Automatic detection of such time events (or any other particular event) would require the use of more advanced signal processing and is also currently under investigation.

Although limited to a set of few workers and HPDs, an attempt has been made to look at the effect of safety glasses and helmets. As discussed earlier (see for example Fig. 6), the effect of safety glasses has shown to be significant for some workers. On the other hand, no differences in the attenuation were observed in few cases when the glasses were removed. No information was collected or was available regarding the workers (hair, morphology, etc.) and the glasses so that it is considered impossible, within the scope of this study, to quantify or generalize this effect on the performance of HPDs. Similar results were also obtained for safety helmets. In one instance, rapid variations in the attenuation index as a function of time were found suggesting that the earmuffs (cups mounted on a helmet) were slightly moving while the worker was walking/working thus lessening the seal around the outer ear. In another case (same cups but different helmet), the attenuation values were found to be fairly stable and constant with time suggesting a better fit of the combo helmet/cups.

Analysis of the attenuation frequency response results let us believe that reasonable approximations were used for the correction factors for earmuffs. For such protectors with high attenuation, values comparable to laboratory data were obtained for all frequency bands with some exceptions for frequencies >2000 Hz where significant discrepancies were observed for some earmuffs. Correction factors for earmuffs consist mainly of two parts. The first part is related to the fact that the protected microphone is connected to a small tube looking into the cup.

The transfer function of the tube is measured in a free-field environment using white-noise source and shows a resonance ~3400 Hz. When placed through the cup, this transfer function is most probably modified as the tube is looking at a small volume containing absorbing material as well as the ear canal entrance. The measurement of this transfer function in 'working' conditions is currently under investigation. The second part of the correction factors is related to the protected microphone, which is not exactly located at the eardrum as well as to the TFOE for which a diffuse ield approximation is used. While the approximations used in this study seem to lead to reasonable results, these aspects have been little studied in the past for occluded ears and thorough validations in more controlled environments are needed and under investigations.

CONCLUSIONS

The present study is an attempt to examine in more details some of the causes of discrepancies observed between field- and laboratory-based attenuation data of hearing protectors by examining the time evolution of the performance during full work shift activities. A non-invasive field-efficient F-MIRE-based procedure was developed and applied in various facilities on several workers wearing earmuffs or molded earplugs. The results presented in the paper show the potential of the method for analyzing and understanding different factors affecting the performance as a function of time as well as frequency. Unsurprisingly, field attenuations were found to depart considerably from laboratory-based ones for most workers tested. Important variations of the attenuation as a function of time were observed for earplugs as well as earmuffs, for which the low-frequency content in the ambient noise was found to influence greatly the performance. Significant inter-subject differences were found for workers wearing the same type of protectors. Additionally, substantial left and right ear differences were also observed for many workers. These results reinforce the idea that individualized performance data and ratings, together with a good knowledge of the sound field frequency content in the workplace, would provide a better representation of the effective exposure obtained by workers. As a matter of fact, the concept of measuring the performance on an individual basis is gaining more and more grounds with many manufacturers of HPDs. The method proposed in this study is clearly a step in this direction. A better understanding of the different factors relating the measured F-MIRE quantities to subjective REAT data and free-field conditions as well as the development and the use of more advance signal processing algorithms (e.g. for the detections of speech or other specific events in time) would greatly enhance the proposed method.

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