Real-world attenuation of custom-moulded earplugs: results from industrial in situ F-MIRE measurements.

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Abstract:
The attenuation provided by hearing protection devices (HPDs) is traditionally determined under laboratory conditions by means of a standardised method titled REAT (Real Ear Attenuation at Threshold). This performance is often overestimated compared to what has been measured so far in industrial reality. Concerning the earmuff, the formable earplug and preformed earplug type of HPD, there are numerous data related to the discrepancy between, on one hand, the laboratory measured attenuation which is labelled by the manufacturers and, on the other hand, the in situ estimated attenuation. But, few exist concerning custom-moulded earplug (CMEP) type protection devices. This paper presents the practical application of measurements intended to estimate the attenuation of this type of protection device while it is being worn by users during execution of their task. Three manufacturers of hearing protectors took part in this initiative; this participation involved the manufacturing of custom-moulded earplugs with a miniature microphone inserted. The measurements were carried out on 63 employees in nine industrial sites with diverse activities. The estimate of this in situ attenuation, in this study called level reduction (LR), was obtained from the difference between the noise exposure level measured close to the ear of the employee and the residual noise level measured under the earplug.
The CMEP level reduction estimated in situ highlighted significant variability characteristics. The results of the measurements confirm the overestimation of the values indicated by the manufacturers. From 3 to 5 dB at high frequencies, the discrepancy can reach 8–10 dB at medium and low frequencies. The study also confirms that CMEPs which have been tested here, like other earplugs types, are unsuited to attenuate low frequencies.

Keywords:
In situ measurement; F-MIRE method; Real attenuation; HPD; Custom moulded earplugs

1. Introduction

European directive 2003/10/EC [1] defines the regulatory framework relative to the protection of workers exposed to noise. Besides laying down prevention action thresholds of 80 and 85 dB(A), this directive introduced exposure limit values (ELV). For the daily noise exposure level (LEX,d) the limit value is 87 dB(A), and for the peak sound pressure level (Lp,C) the value has been set at 140 dB(C). These limits encompass the wearing of hearing protection devices (HPD).

Respect of this regulation implies knowledge of two data. On the one hand, the noise exposure level at the workplace (LA), measured in conformity with Standard EN ISO 9612 [2]; on the other hand, the attenuation afforded by wearing the HPD. This attenuation is measured in conformity with the method, called Real Ear Attenuation at Threshold (REAT), described in Standard EN 24869-1 [3]. REAT attenuation is the mean of the results obtained thanks to 16 subjects. The standard explicitly says that REAT must be considered as a maximum value which is never reached in situ. Moreover, REAT comes from a small statistics although in situ values are often analyzed as individual results. In few studies [4] and [5] it has been shown that REAT measurements might also underestimate the personal attenuation rating (PAR).

In each octave band frequency between 63 and 8000 Hz, the residual noise level under the protection device L'_A is the difference between LA and the REAT value [6].

Schematically, L'_A is obtained by means of the following equation:

$$L'_A = L_A - \text{REAT}$$

It turns out that the REAT values indicated to a large extent by manufacturers in the user handbooks of their protection devices is different of the real attenuation which can be obtained in situ as it appears in our previous bibliographical review [7]. Consequently, respect of the ELV assumes, when calculating L'_A, taking into account the sound attenuation values closest to reality rather than those indicated by the manufacturers.

Very diverse techniques have been employed by many researchers to try to compare, as accurately as possible, the performance labelled by the manufacturers and the real in situ attenuation of many HPD. For example, even in the late 70s, Padilla [8], applied a REAT method, with specific equipment in industrial field conditions, measuring earplugs performance on workers; Edwards et al. [9] carried out REAT tests on workers in a audiometric van in different plants; Royster [10] evaluated the effectiveness of earplugs in preventing temporary threshold shifts of 70 workers. Later, Chung et al. [11], Goff and Blank [12] used dosimetric methods in order to establish the performance of circumaural HPD. Over 80s and 90s, numerous experimenters repeated REAT tests, varying parameters such methods, type of HPD, number of subjects/workers, sometimes simulating industrial activities at laboratory, sometimes at workplace. This has been reported by Berger et al. [13] in his international review of hearing protector attenuation. More recently, alternative methods have been used by Franks et al. [14] or Bockstael et al. [15] and MIRE technique [16] has been implemented by Voix and Laville [17], Berger et al. [18] or Neitzel et al. [19].

In most cases, the research has been applied to the types of protection devices most commonly used in industry (earmuffs, pre-formed and formable earplugs). The real efficiency of custom-moulded earplugs (CMEPs) has been studied little and always during pseudo in situ investigations either undertaken in the laboratory with a view to simulating industrial situations or on the ground but over short periods of time and never during task execution. At our knowledge, only Nélisse et al. [20] carried out tests on workers equipped with their own CMEP at their workplace during their tasks on long periods.

The present paper reports on employing a measurement method at workplaces intended to measure the sound attenuation of CMEPs while they are being worn by employees for significantly longer periods.

2. Materials and method

2.1. Method

The method developed and tested is based on comparing sound pressure levels measured simultaneously; the noise exposure level and the residual level under the protection device. In the case of CMEP, measurement of the noise level under the device requires the use of a very small sensor: either a miniature microphone or a microphone probe tube to access a measurement point closest to the eardrum. There are two possibilities to equip a CMEP, and these are illustrated in Fig. 1.

Position Figure 1

The first option (Fig. 1a) allows the use of the same sensor for all the subjects. However, this requires compensation of the frequency response of the probe. Indeed, the frequency response of the probe depends greatly on its length, which is different for each ear.
The second option (Fig. 1b) needs to drill a second vent (the first one being for insertion of the attenuating filter) to pass the wires through the earplug before to solder them to the connector which ensures the electrical contact between the miniature microphone and its preamplifier. This vent is slightly smaller drilled than the diameter of the wires insuring airtight. Such operation has to be made in the laboratory in advance before to carry out the in situ measurements. That also involves the use of a different microphone for the ear of each different equipped subject at the same moment. This requires correction of the frequency response of the different microphones used. However, this is easy to verify and correct. Consequently, this option was chosen.
The external level is measured and recorded simultaneously by means of a microphone of the same type as that inserted into the earplug. This measurement is made as close as possible to the ear, as indicated in Fig. 2. Comparing the difference between the two measurements yields an estimation of the in situ attenuation.

2.2. Materials
The different elements comprising the acquisition/recording system are indicated in Fig. 2. The sensors used are electret microphones (1 and 4). These sensors deliver signals pre-amplified by two conditioners (3); the signals are then acquired in a portable two-channel digital recorder (2). The assembly, very light and compact (7), allows the employee to be equipped while leaving freedom of movement and no hindrance to task execution. The autonomy of the recorder allows recording periods of close to two and a half hours.

Position Figure 2

2.3. Implementation
First at laboratory, we pass the wire throw the custom moulded ear-plug and we sold the wire to the connector. The calibration of the acquisition system allows the recording level to be adjusted for the subsequent processing. To do this, the signal of a sound level calibrator Bruel&Kjaer, type 4231 (94 dB at 1 kHz) is recorded by the miniature microphones on the acquisition system described in Section 2.2. The adjustment between the miniature microphone and the calibrator is ensured by a specific adaptor in respect of the volume of the calibrator’s cavity. That is carried out on each of the two channels just prior to each measuring session. After that, the miniature microphone is inserted in the CMEP in order to have its grid just at the end of the side of the ear plug to be turned toward the tympanum.
A measurement campaign was undertaken between March and June 2008 in nine enterprises with varied activities including steel production, forging, metallurgy, boiler making, mechanical engineering, pneumatics and glass making. The measurements were taken in the nine sites on a sample group of 63 employees. Voluntary participation in the experimentation was required. Three CMEP manufacturers (noted CMEP1, CMEP2 and CMEP3) offered their support for the tests by supplying earplugs: 29 for CMEP1, 41 for CMEP2 and 8 for CMEP3.
All the CMEP used were manufactured according to the same conformation with full occupation of the concha and retention of the upper hook (corresponding to the cymba

conchae). The CMEP was fitted in place (cf. Fig. 2) by the experimenter, retained by an over-ear clip, and the connecting cables of the microphones were attached to the skin of the employee by means of adhesive tape, thus ensuring that the assembly remained in place during the entire recording period.

The test workers were under constant observation throughout the recording. Their actions and gestures were noted on detailed forms, allowing, during the data sorting phase, elimination of the measurement phases with no direct connection to a real work situation.

During several recording sessions, the external noise level was measured simultaneously by means of a dosimeter (6) whose microphone (5) was placed on the shoulder of the subject. This measurement, taken with equipment in conformity with Standard IEC 61252 [21] and in accordance with a method recommended by the manufacturer, allowed verification of that taken with the external miniature microphone close to the ear.

Prior to the in situ campaign, a laboratory experiment was carried out. This allowed testing of the equipment, the strategic and logistic conditions of use, and validation of the data processing. This simulation consisted in placing a person, equipped with a CMEP with the aforementioned instruments fitted, in a noise exposure situation inside a large-size semi-anechoic chamber (490 m3). The noise exposure was performed by placing the test subject in an acoustic field generated by a sound source (Lp > 104 dB at 1 m) in the chamber. The subject walked up and down in this acoustic field, alternatively going further from and coming closer to the source to vary the sound levels picked up and recorded by the two miniature microphones. During these movements, lasting some 10 min, the subject took on different attitudes (immobile, walking, mouth open, and mouth closed) and emitted different physiological noises (coughing, speaking, clearing the throat, and sneezing) which were rigorously observed. The recording and processing of this simulation illustrate the different steps described in Section 2.4.

2.4. Data processing

The data processing included three phases: data structuring, sorting and enhancement. The experimentation in the acoustic chamber described above allowed validation of these three phases.

2.4.1. Structuring

The temporal signals recorded were firstly segmented in contiguous 200 ms intervals and filtered in one-third octave bands from 50 Hz up to 10 kHz. This operation was performed for the external channel (level Lp,ext) and for the internal channel (level Lp,int).

Fig. 3 illustrates this first processing. The raw levels to which A weighting was applied (LA,ext and LA,int) were set up for the total recording duration.

Position Figure 3

The difference between the two channels corresponds to the attenuation contributed by wearing the earplug. It was termed LR (level reduction) to avoid any confusion with the sound attenuation established in the laboratory. These definitions allow the establishment of the equation:

$$LR = L_{A,ext} - L_{A,int}$$

2.4.2. Selection of the useful signals

Reading the raw results highlighted phenomena of various kinds that could be grouped into four categories depending on their origin:

- case 1: activity not directly linked to the task;
- case 2: sensor overload;
- case 3: lack of signal dynamic;
- case 4: physiological noise.

In every case, the difference between the levels measured by the two microphones reflected neither the reality of the workplace nor the real noise exposure level.

A sorting of the recording files was done taking account of the notes written in the observation forms. For the first case, the phases corresponding to break periods or to conversations noted in the observation forms were eliminated from the files.
At each step of the signal sorting process, the periods retained were placed side by side, resulting in a reduction in the initial duration of the recording:

Initial duration	t_1 to t_2	t_2 to t_3	t_3 to t_4	t_4 to t_5	t_5 to t_6
Sorting	retained	eliminated	retained	eliminated	retained

Final duration	t_1 to t_2	t_3 to t_4	t_5 to t_6

Overload phenomena (case no. 2) are easily detectable and removable. They occurred rarely (1% in time), for the external microphone, at workplaces with high level impulse noise as those found in metallurgy. These easily detectable overloaded phases were deleted from the recording files. After elimination of the overloaded levels, the same variables LA,ext and LA,int lead to a slightly reduced retained time interval.
In the third case, it was less easy to detect the parts of recorded time which are perturbed by a lack of signal dynamic. In the case of insufficient dynamic, very low level signals could be confused with the electrical noise of the recording. Records with insufficient dynamic were observed in situ on the internal microphone when the exposure level was momentarily low.
Finally, in the fourth case, the occurrence of a physiological noise (e.g. cough, sneeze, throat clearance, speech; phenomena defined in Fig. 3) produced an internal pressure level greater than the external pressure level. Other rarer phenomena (yawning, swallowing, and rapid breathing) could artificially vary the difference between the two pressure levels.
In the latter two cases, unwanted periods could be detected by observing the coherence of the signals. For a given frequency f, the coherence is the square of the cross spectrum of signals x and y (internal pressure and external pressure respectively) normalised by the autospectrum of each signal, such that:

$$C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)} \qquad (1)$$

Observation of the correlation between the external pressure level and the internal pressure level highlighted the coherence, which varies from 0 to 1, and allowed qualification of the signals frequency by frequency. Only signals with a certain coherence were retained. A threshold is defined later in the paper and in Fig. 4.

Position Figure 4

However, the useful frequency bandwidth and the high number of time samples complicated the detailed analysis of this variable. It is indeed not easy to accurately set a coherence threshold for each frequency.
Consequently, the selection of time periods was obtained by observing the average coherence over the entire useful frequency band by means of the following equation:

$$\overline{C_{xy}} = \frac{1}{f_{max} - f_{min}} \int_{f_{min}}^{f_{max}} C_{xy}(f)df \qquad (2)$$

This average coherence was calculated for each pressure level (every 200 ms).

Fig. 4 shows, in black, the value of the average coherence function corresponding to the evolution of the two pressure levels. Most often, this lies between 0.7 and 0.85. It sometimes dropped in the periods where the internal pressure was greater than the external pressure (aforementioned physiological noises). Deleting signals whose average coherence was below 0.65 resulted in eliminating physiological noises and low dynamic signals.
New curves were obtained; these are given in Fig. 5. The retained time corresponds to a discontinuous period (8.7 min) shorter than the duration of the preceding figure.

Position Figure 5

Following these processing steps, fragments (visible in Fig. 5, during the sixth minute for example) where external pressure levels lower than the corresponding internal pressure levels still occurred. These periods corresponded to times of speech when the worker was having short conversations with colleagues. During these periods, the average coherence remained high. Thus, these phenomena did not affect the coherence sufficiently for them to be eliminated on this criterion alone.
An elimination threshold for these phases was set such that the internal pressure level (Lp,int) being higher than the external pressure level (Lp,ext) augmented by the physiological noise (PN) [22]. The latter was predominant at low frequencies, as the table below shows.

Frequencies (Hz)	100	125 to 315	400	>400
PN threshold (dB)	4	3	2	0

Applying this correction resulted in deleting short conversations, as indicated in Fig. 6 where the retained time (8.2 min) has again reduced. The same figure shows the level reduction, i.e. the difference between the two levels corrected for all the undesirable phenomena.

Position Figure 6

2.4.3. Data enhancement
Data enhancement led to the definition of a pseudo-attenuation, pREAT, made up of the LR modified by means of corrective terms. Studies [15], [17] and [18] have shown that to establish a realistic comparison of the LR and the REAT attenuation value of the HPD, corrections must be applied to the sound levels measured that take into account of the following terms:
• the transfer function of the open ear;
• the physiological noise;
• the modification of the acoustical field due to the presence of the worker in this acoustical field;
• the resonance effect of the probe tube;
• the resonance effect of the part of the ear canal between the earplug and the eardrum (occluded canal).
One can notice that, in this processing, the different terms have not the same weight. On one hand, we consider:
• the PN correction as a minor correction, only involved in the lower frequency bands;
• the term linked to the diffraction effect created by the presence of the worker (its head and torso) in the acoustical field brings also a light modification to the data.
On the other hand, the TFOE correction (such as exposed in ISO 11904-1) strongly modifies the original data.
Those latter three effects are known and quantified. The probe tube does not exist in our measuring system. The resonance of the canal lying between the earplug and the eardrum is not taken into account in our data enhancement.

The processing performed allowed the application of other corrective terms, which are presented below by means of the Voix equation [17]:

$$pREAT = LR + \left\{ TFOE + 20\log_{10}\left(\frac{p_{mes}}{p'_2}\right) + 20\log_{10}\left(\frac{p'_2}{p'_3}\right) + 20\log_{10}\left(\frac{p}{p_{ref}}\right) + PN \right\} \quad (3)$$

where pREAT is the reconstituted acoustical pseudo attenuation of the CMEP; LR is the level reduction provided by the CMEP during the in situ measuring; TFOE is the transfer function of the open ear, described in Standard ISO 11904-1 [16], which states the spectral values in one-third octaves; $20\log_{10}(p_{mes}/p'_2)$ is the corrective term relative to the resonance effect of the microphone probe; zero in the present case as no probe is used; $20\log_{10}(p'_2/p'_3)$ is the term relative to the resonance of the occluded canal; ignored in the present case (and discussed in Section 4, below); 20 log10(p/pref) is the term linked to the diffraction created by the presence of the subject in the acoustic field. This term was measured on a real ear in a reverberating chamber with the equipment used in situ; PN is the term to compensate for physiological noise. This term is from Berger measurements[22]

3. Results

3.1. Measurement of the external level, (Lp,ext)
The comparison between the in situ measurement obtained with the external microphone and the measurement obtained with the dosimeter microphone shows a low divergence of between −1.7 and +1.1 dB, with an average close to −0.7 dB.

3.2. Effect of the duration of wearing the CMEP
The time periods of in situ recordings vary between 1h30 and 2h30. The cumulative time of the recording after processing of the data for the 63 subjects is 137h30. Depending on the test worker, the level reduction time graphs show higher or lower variations in this parameter. Nevertheless, we observe onto the records no visible and durable increase or decrease. The efficiency of the tested CMEP, when it is effective, does not seem to be degraded by how long the CMEP is worn.

3.3. Descriptive analysis of the data

3.3.1. Exposure levels
The industrial sites chosen for the measurement campaign allowed the selection of workplaces having noise exposure levels within a range extending from 76.1 to 119.8 dB(A), with an average of 94.7 dB(A), as shown in Fig. 7.

Position Figure 7

3.3.2. Exposure spectra
The studied workplaces are classical noisy industrial workplaces where the noise level generally exceeds 85 dB(A). Some of them are very noisy as the level reaches 110 dB(A) or more. The spectral balance (LC–LA) is the most often comprises between −2 and +3 dB, thus showing the noise spectrum is generally not composed of strong low frequency components. Nevertheless, some of them with predominantly low frequencies have a LC–LA index above 5 dB; one of the latter is notable, with a LC–LA of 9.6 dB for an exposure level of 108.6 dB(A), conditions in which it is particularly difficult to protect the employees.
Fig. 8 shows that all the CEMPs, whatever the manufacturer is, are randomly distributed through the two variables (noise exposure vs. LC–LA).

Position Figure 8

3.3.3. Corrected level reduction, pREAT

The corrected level reduction was calculated by means of Eq. (3). The calculation was performed for 63 subjects. The pREAT value varies from 10 to 12 at 125 Hz, 12–22 at 1 kHz and 25–37 at 8 kHz, all the CMEPs taken together. Each workplace has its own exposure noise spectrum. Furthermore, this spectrum can vary, according to industrial process conditions, during the recording time.

An analysis of the variance, processed through the 63 subjects, 6–12 periods of time, did not show any significant correlation between the attenuation and the sound fields. Considering that this result does not bring any pertinent information, this statistical analysis is not detailed in this paper.

The pREAT values compared to the REAT values indicated by the CMEP manufacturers are detailed in Fig. 9.

Position Figure 9

4. Discussion

The pREAT corrected level reductions are, on the whole, below the REAT values indicated by the manufacturers, the difference for the CMEP3 being particularly high. In this latter case, the sound attenuation labelled by the manufacturer is notably different from that estimated in situ. This divergence is probably attributable to a manufacturing defect, without being able to be sure of it. The results of CMEP3 lead to a low mean but small standard deviation, indicating a slight inter-subject variance. So, several reasons could be at the origin of that phenomenon and caused by either the print's taker or the manufacturing process. First, it is possibly a skill's lack of the technician who makes the impressions of the workers ear-canal. Second, it could be possible that material used while making the imprints or material used for the transfer from the print to the earplug are not suitable to this kind of process. A last reason could be a general fault due to bad workmanship in finishing the CMEP.

Nevertheless, the pREAT estimates for the CMEP1s and the CMEP2s, namely a little over 87% of the protection devices tested, have attenuation spectra whose profiles converge with others already observed in previous studies [20], [23], [24] and [25].

The results stemming from the measurements on the CMEP1s and CMEP2s indicate a relatively good reliability of the sound attenuation values indicated by the manufacturers in the highest part of the spectrum, i.e. the easiest frequencies to attenuate.

The discrepancy between REAT values and pREAT values is close to 3 dB in the high frequencies, an acceptable difference given the warning contained in the introduction to the standard describing methods for calculating L'_A (EN ISO 4869-2 [6]) and in the appendix on the uncertainty attached to measuring sound attenuation in accordance with the REAT method (EN 24869-1).

On the other hand, these results confirm the lack of efficiency of earplugs at low and medium frequencies. For frequencies between 125 and 1 000 Hz, the difference between REAT values and pREAT values varies from 5 to 10 dB(A). These results are comparable with those, few in number, indicated in our bibliographic review [7].

A few remaining unresolved questions could possibly reduce the credibility of these results: the potential effect of the presence of a miniature microphone in the CMEP; taking into account the amplified resonance effect of the occluded canal; the limited number of manufacturers taking part in the experiments may also warrant caution.

This latter point would be easily settled if the publication of the present results encourages other manufacturers to compare the real performance of their products with those already tested.

It is possible that inserting a miniature microphone, a metal element, into the silicon compound of the earplug has an effect on the acoustic behaviour of the CMEP. What is the

amplitude of this effect and at which frequencies does it occur? Could it be related to the masses of the materials employed?
Complementary tests on a head and torso simulator (HATS) comparing insertion loss (IL) of one CMEP with inserted microphone and another without microphone could give an answer. However, this latter could not be a proof. There is a too large difference between the artificial ear canal of the HATS and the human ear canal, particularly in terms of impedance, in order to decide which effects occurring in the first one could also occur in the other one. That needs complementary investigations by subjective method which will take place in our future works. In this study, as Neitzel et al. [19] did, we assumed this effect was not so important, as long as we insure a perfect seal, by inserting the microphone in an adjusted vent through the plug.
Concerning the term of amplified resonance effect of the occluded ear canal, the equation of Voix and Laville [17] indicates a solution, but it is global. Actually, this term has been achieved by specific measurements on a panel of 20 subjects equipped with the only SONOMAX CMEP. Furthermore, preliminary investigations we achieved on our three CMEPs prior to the in situ measurements showed a huge inter-subject variability of this term. That strong variability, particularly in high frequencies, has also been noticed recently by Voix and Zeidan [26]. Because of such difficulties to accurately estimate this term on each of the three CMEP and because it has been shown by Hammershøi and Møller [27] and Nélisse et al. [20] that its influence is smaller than the TFOE correction, the resonance effect of the occluded ear canal was finally neglected in our processing. The accuracy of our results is certainly affected by neglecting this term, but slightly enough than we can still trust in our results.
Finally, although the accuracy of the results may be open to debate, we consider that the selection process applied to the data constitutes a good compromise between a perfectly rigorous mathematical approach and a simple solution of the problems raised by applying a laboratory measurement method to industrial conditions.
Even if these results tend to demonstrate that the in situ performance of CMEPs is not very different from the performance labelled by the manufacturers, this may not be true in more general conditions. Indeed, this study was carried out on the basis of controlled parameters: dimensional characteristics of the earplugs, fitting by the experimenter, fixing by means of an over-ear clip and of adhesive tape. Since the 1990s, the tendency, clearly observed from CMEP manufacturers to reduce the volume of their earplugs on the pretext of improving comfort runs counter to a good retention in place of the earplug during task execution, especially over long periods. This argument, associated with others (quality of print of concha and ear canal, manufacturing reproducibility, quality of the different resins used, useful life), leads us to believe that our results are somewhat generous to certain CMEP as regards their real performance in the field.
The principle of the personalisation of protection devices cannot be brought into question. The results of this study show that CMEPs are efficient hearing protection devices provided all the manufacturing stages have been mastered and that they remain firmly in place throughout the exposure period. The bibliographic review [7] has shown that they provide less random protection than the other types of earplugs, with low difference between the attenuations indicated by the manufacturers and those estimated in situ. It has been shown [25] that this is only effective provided that the efficiency of the CMEP is checked on the wearer in situ.

5. Conclusion

The method described in this paper uses a couple of miniature microphones and a portable digital recorder in order to estimate the in situ exposure values of a worker who is protected from noise by wearing custom moulded ear plugs (CMEP). Those light and compact components allow carrying out measurements of the noise levels in and out of the occluded ear canal of the worker during his working tasks.

This method has been applied to 3 CMEPs on 63 workers accomplishing their tasks at their workplace during a time period bounded between 1h30 and 2h30.
The discrepancy between the inner and the outer level indicates a level reduction (LR) supplied by wearing the CMEP. The LR value is thus corrected by mean of appropriate terms related to the measurement conditions. That correction leads to a pseudo attenuation (pREAT value) which can be compared to the attenuation (REAT value) labelled by the manufacturer of the CMEP.
Employing the method developed and tested in this study is relatively simple and requires only limited equipment to take the recordings. It does not restrict free movement of the employees to any great extent and allows them to accomplish their tasks without discomfort bothering them. As opposed to the practices employed during standardised laboratory measurements, it allows noise level measurements genuinely representative of an industrial setting to be taken while the employees of the industry are executing their tasks.
It does however remain true that the sound attenuation values stemming from the laboratory measurements using a standardised method overestimate their real in situ efficiency. While protection appears ensured at frequencies above 1000 Hz for a controlled fitting and continuous wearing of the earplug, the overestimation of efficiency at frequencies below this limit can nevertheless reach 10 dB(A).
Account taken of these observations, it could be possible to establish a relationship between REAT value and pREAT value if the known data are expressed in octave bands. However, the results of this study are based on the CMEP of only three manufacturers. It would therefore be premature to give a concrete version complete with figures.

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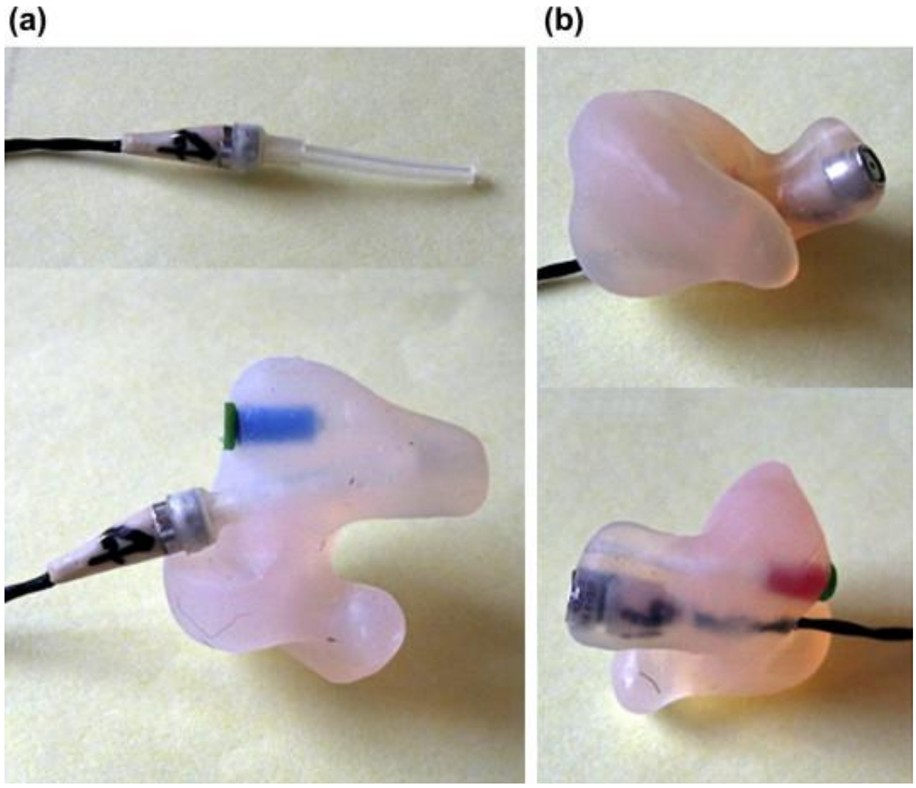

Fig. 1. Measurement technology. (a) Microphone with probe tube; (b) inserted microphone.

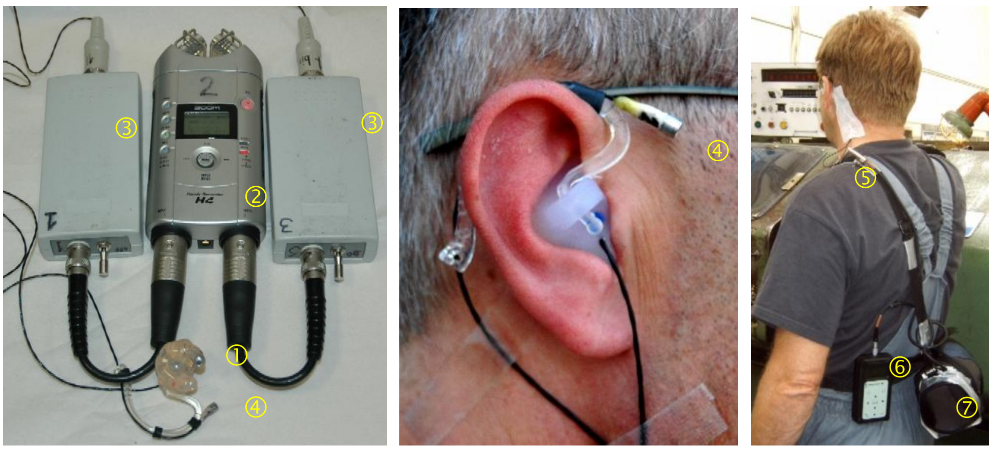

Fig. 2. Measurement devices: (1 and 4) electret microphones; (2) portable two-channel digital recorder; (3) conditioners; (5) microphone dosimeter; (6) dosimeter; (7) bag.

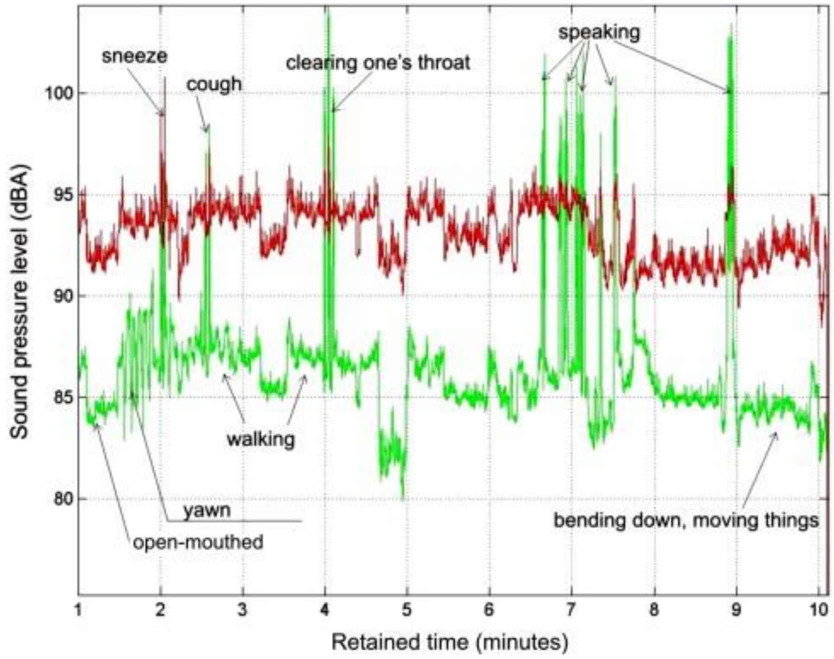

Fig. 3. Retained time of the levels without overloaded signals: external pressure (red), internal pressure (green). Display of different physiological phenomena.

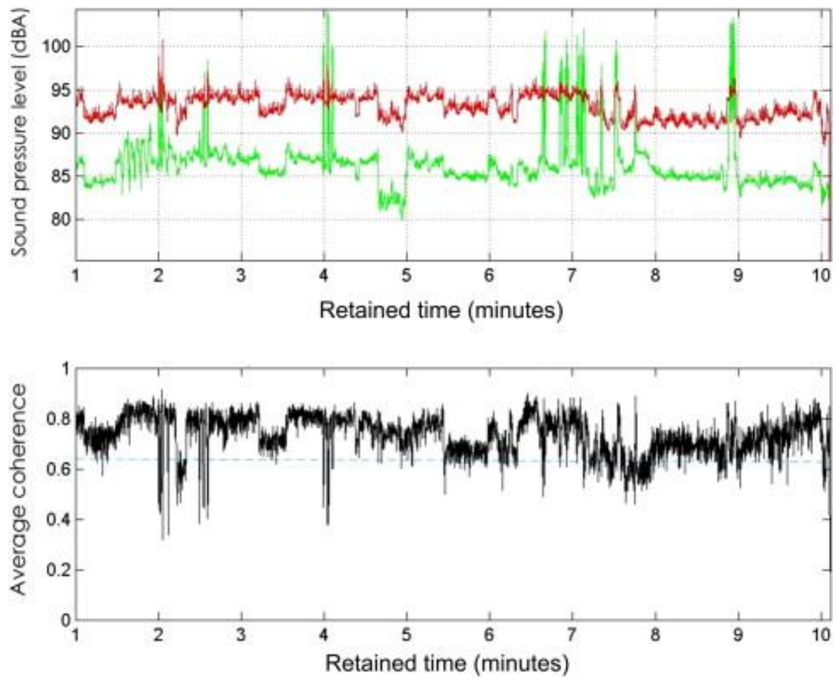

Fig. 4. Retained time of the levels without overloaded signals: external pressure (red), internal pressure (green), compared to the average coherence (black). Dotted blue line is the acceptable threshold of average coherence. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

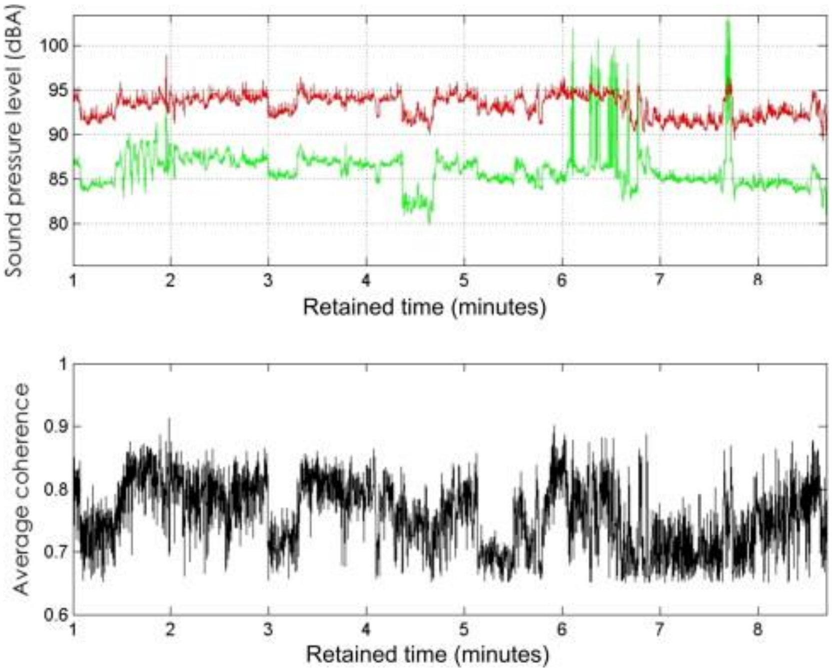

Fig. 5. Retained time of the levels without overloaded signals: external pressure (red), internal pressure (green) and elimination of low coherence periods compared to the average coherence (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

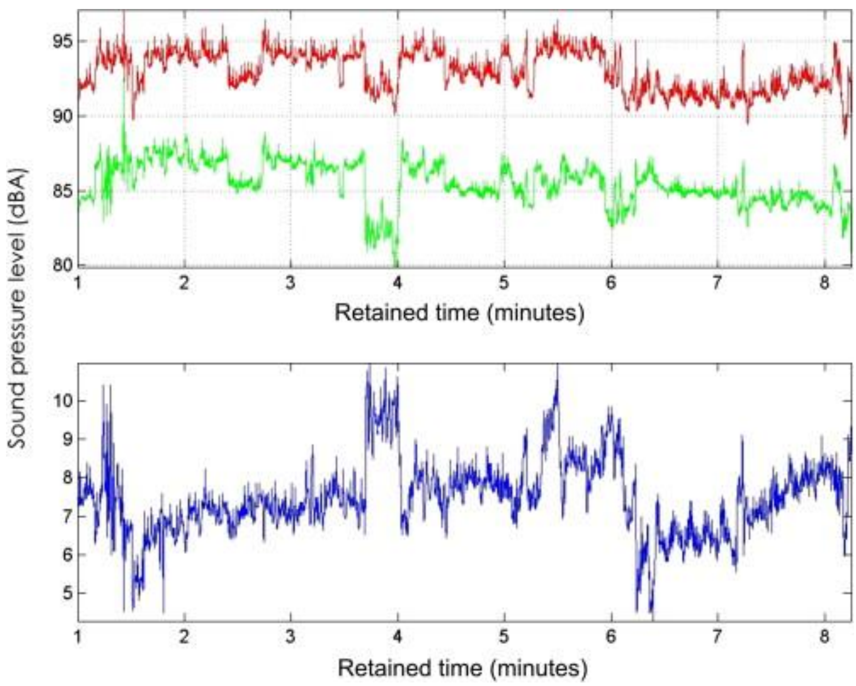

Fig. 6. Retained time of the corrected levels: external pressure (red), internal pressure (green) and level reduction afforded when wearing the HPD (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

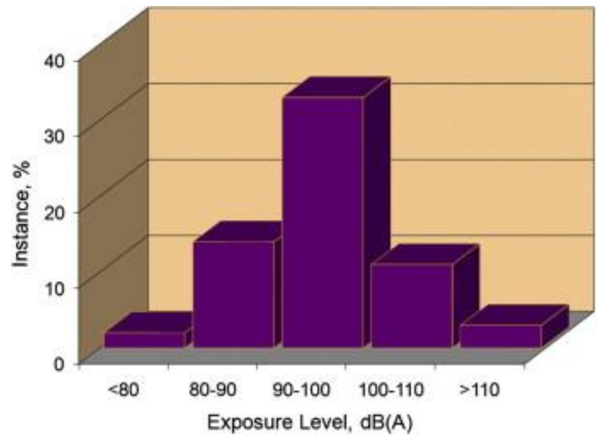

Fig. 7. Exposure level of the studied workplaces.

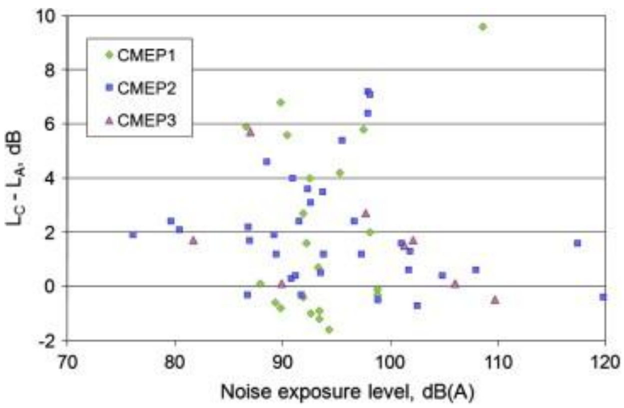

Fig. 8. Noise exposure level of the workplaces studied as a function of L_C–L_A value for the 3 CMEP.

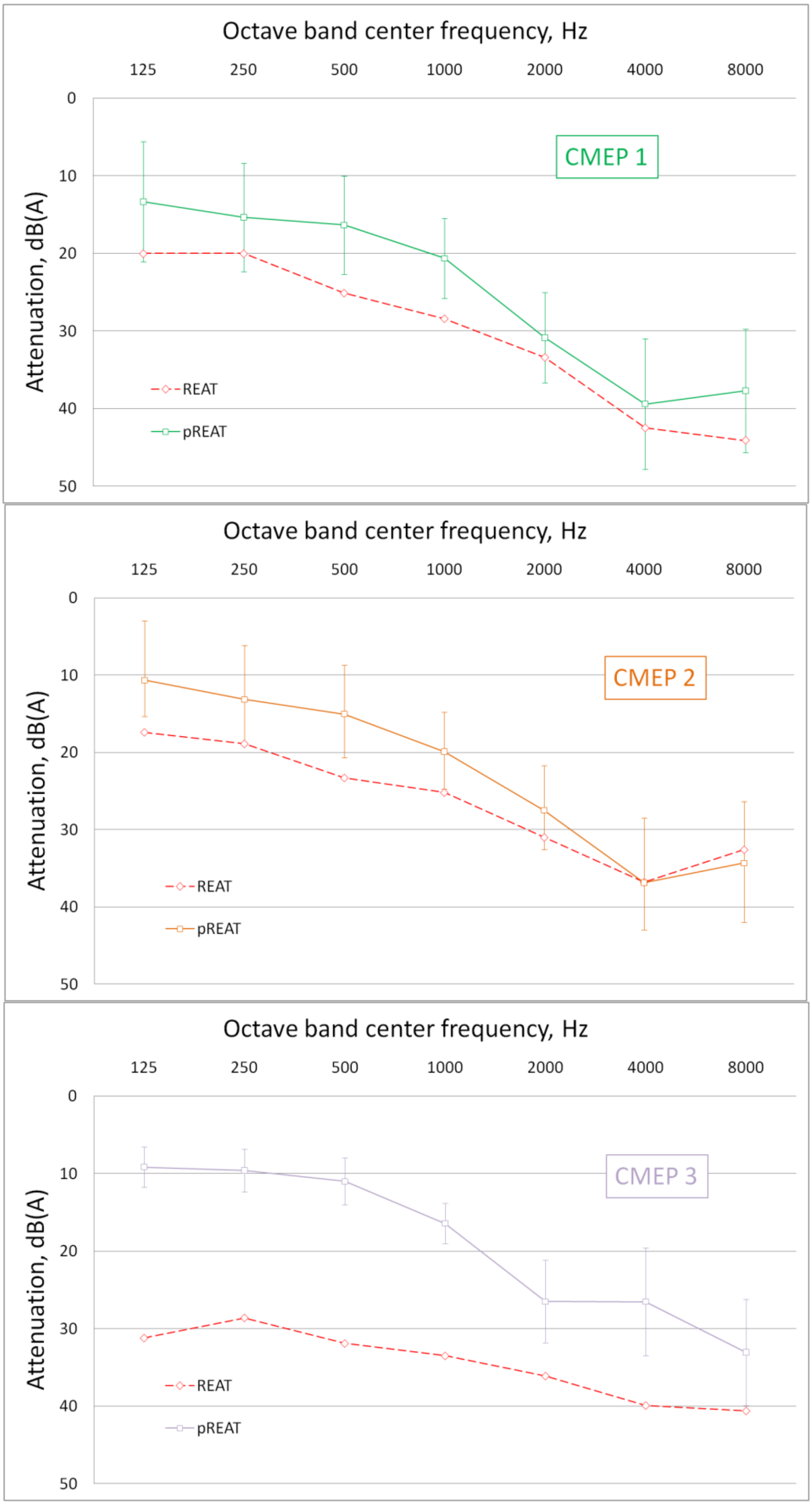

Fig. 9. Corrected level reduction (pREAT) compared to the REAT indicated by the manufacturers for the 3 CMEP.