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1aNS4. Comparison of subjective and objective methods for the measurements of hearing protector devices attenuation and occlusion effect

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With the increase popularity of individual fit testing and miniaturization of electronic components, the Field-Microphone-In-Real-Ear approach (F-MIRE) is becoming more appealing and well suited for estimating hearing protection devices (HPD) attenuation both in laboratory and in "real world" occupational conditions. The approach utilizes two miniature microphones to simultaneously measure the sound pressure levels in the ear canal under the hearing protector, as well as outside of the protector. In this study, experiments on several human subjects were carried out in order to examine the various factors relating the subjective and objective attenuation values. The subjects were first instrumented on both ears with miniature microphones outside and underneath the protector. They were then asked to go through a series of subjective hearing threshold measurements followed by objective microphone recordings using high level diffuse field broadband noises. Earmuffs, earplugs and double-protection were tested for each subject and attenuation values were compared. Additionally, an objective scheme to measure the occlusion effect was developed and tested using subjects' voice as the excitation and the same microphone setup. Results obtained for the attenuation values as well as the occlusion effect levels are presented and discussed.

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INTRODUCTION

Comprehensive reviews of measurement methods commonly used to evaluate the attenuation performance of hearing protection devices (HPD) can be found in the literature[1]–[5]. These methods are usually 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 a HPD. On the other hand, 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, it is commonly referred as the microphone-in-the-real-ear (MIRE) technique[1]. When combined with an additional microphone located outside of the protector, the technique is termed field-MIRE (F-MIRE).

The F-MIRE procedure has been successfully used for custom molded earplugs[6], [7]. In these studies, it is shown that attenuation values comparable to REAT measurements can be obtained 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, premolded) has been presented and discussed recently[8]. This approach can also be used with earmuff-type protectors utilizing, also, external and interior microphones to measure the unprotected and protected sound field[9]–[14]. One advantage of the F-MIRE approach lies in the fact 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. A study by Kotarbinska et al[15] has shown the potential of the F-MIRE approach for earmuffs in industrial settings. More recently, attenuation data for earplugs and earmuffs measured with F-MIRE over entire workshift periods in various working environments were reported by Nélisse et al[16]. The increase popularity of individual fit testing and miniaturization of various electronic components has made the MIRE and F-MIRE approaches increasingly attractive. However, there are few studies in the literature focusing on the relationships that exist between the subjective (REAT) and objective (MIRE/F-MIRE) methods in order to, firstly, better understand how the different approaches compare to each other and, secondly, to improve the interpretation of attenuation data obtained with both the objective and subjective techniques.

This paper presents a study aimed at establishing the aforementioned relationships between the subjective (REAT) and objective (MIRE/F-MIRE) methods. This main objective is accomplished through a series a measurements on human subjects equipped with miniature microphones and wearing various HPDs in a laboratory environment. The first part of the paper focuses on explaining the different methods (subjective and objective) proposed to measure HPDs attenuation values. Additionally, one also exploits the fact that human subjects are instrumented with miniature microphones to propose an approach designed to measure an objective occlusion effect by using the same microphone setup used for attenuation measurement. The second part of the paper presents examples of attenuation and occlusion effect results obtained for one subject. The extension to the ensemble of subjects is briefly discussed in the conclusion part.

METHODS

Basic Equations

Let's consider a subject in the open ear and/or occluded conditions as shown in figure 1. If one assumes that the bone conduction sound path is negligible, the subjective insertion loss (noted REAT and defined as the difference between the auditory thresholds measured on the occluded and open ear) that a subject would report is related to the objective insertion loss IL through the physiological noise PN [7]:

$$REAT = \underbrace{P_t - P_t'}_{IL} + PN \quad . \tag{1}$$

By using the sound pressure locations shown in figure 1, equation (1) can be rewritten as:

$$REAT = \underbrace{P'_{ext} - P'_{c}}_{NR^*} + \underbrace{P_t - P_0}_{TFOE} - \underbrace{P'_{ext} - P_0}_{TF_{ext}} + \underbrace{P'_c - P'_t}_{TF_{canal}} + PN \qquad (2)$$

where P_0 is the sound pressure at the center of the head in the absence of the subject's head. The last four terms of equation (2) represent what was called above the "correction" factors relating the subjective measurements (REAT) to the objective noise reduction (NR*).

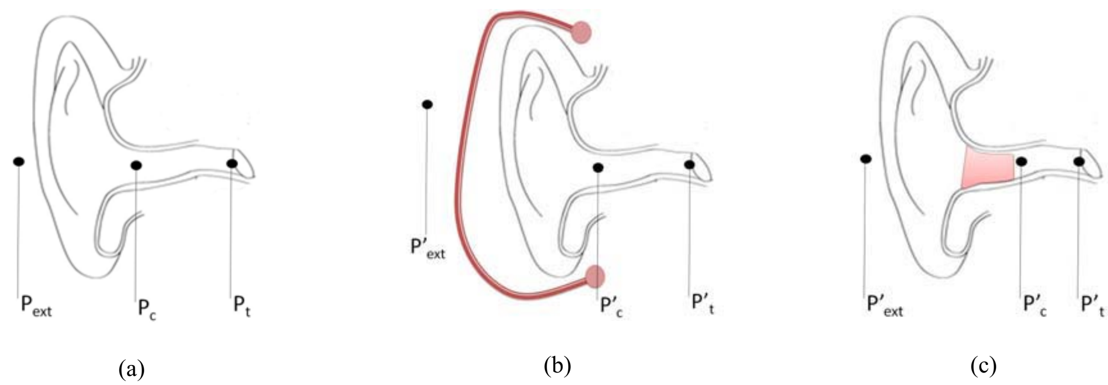


FIGURE 1. Schematic views of the (a) open ear, (b) occluded ear with earmuff, (c) occluded ear with earplug together with sound pressure locations.

Testing Procedures

In order to study the "correction" factors described in equation (2) or, in other words, to investigate if some simple relationships between REAT, IL and NR* can be derived from an individual standpoint or in a statistical way, a test procedure in different steps was developed. The subjects were first instrumented by the experimenter with three Knowles miniature microphones per ear (see example in figure 2). One microphone was positioned in the ear canal approximately halfway between the entrance and the eardrum (open ear and occluded ear with earmuffs) or few millimeters from the plug (occluded ear with earplugs). A second microphone was positioned at the ear canal entrance (open ear and occluded ear with earmuffs) or right in front of the plug (occluded ear with earplugs). Finally, a third microphone was used to measure the exterior sound field (P'_{ext} & P_{ext}). It was placed near the ear lobe (open ear & occluded ear with earplugs) or on the upper part of the cup (occluded ear with earmuffs)[17]. Additionally, a 1-in. B&K microphone was placed approximately 30cm above the head of the subject and used as a control microphone. The tests were conducted in a semi-anechoic room equipped with four uncorrelated speakers/sources generating a diffuse field that meeting the requirements of the ISO 8253-2 and ANSI S12.6 standards for REAT audiometric testing[18], [19]. Each subject was asked to sit still in the test room and was tested under four conditions of ear protection: i) open ear; ii) earmuffs; iii) earplugs; iv) double protection. The HPDs were positioned by the experimenter.

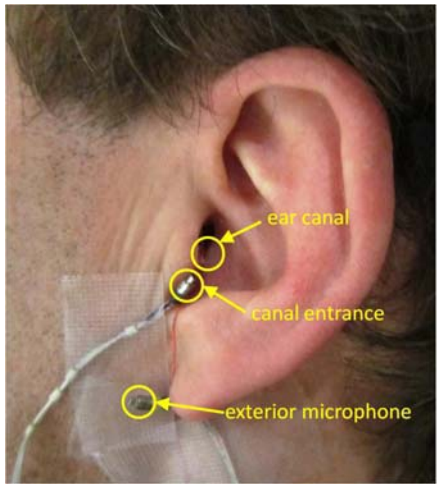


FIGURE 2. Example of miniature microphone locations in the open ear case.

For each ear protection condition, the following tests were sequentially conducted:

- Step 1. Threshold measurements were made using REATMaster which runs on National Instruments hardware in the LABVIEW environment. Threshold levels as a function of frequency were recorded.
- Step 2. A pink noise (90 dB at the center of the head in the absence of the head) was generated and 20sec time recordings were made for each microphone.
- Step 3. Band limited noises were generated (7 octave bands ranging from 125 to 8000 Hz, 85 dB/band) and 20sec time recordings were made for each microphone and each frequency band.
- Step 4. The subject was asked to vocalize numbers randomly and continuously by adjusting his speech level using a feedback system. To do so, the control microphone was placed 30cm in front of the subject's mouth and the overall level at this microphone was displayed on a screen. The subject was then asked to adjust his speech level to attain specific targets. Tests were conducted for three target levels: 60, 70 and 80 dB. For each target level, 30sec time recordings were made for each microphone when speech levels were stabilized around the target values.

Results obtained with step 1 allowed obtaining the subjective attenuation values (REAT) by subtracting the threshold values obtained with the open ear and occluded conditions. Steps 2 and 3 allowed obtaining similar results, that is, insertion loss (IL) values or noise reduction (NR) values depending on which microphones and ear protection conditions were used. Step 2 was used for its simplicity while step 3 was used to generate enough acoustic energy in each band in order to make sure levels above the noise floor were attained in occluded conditions (in particular for double protection). Both approaches were tested so comparisons can be made afterwards in order to evaluate which of the two is more suitable for attenuation measurements. The last step (step 4) was designed as a simple objective test to measure the occlusion effect. In our opinion, it mimics well what is experienced by workers when expressing their discomfort related to the occlusion effect as the test includes both the bone conduction as well as the airborne paths when they speak.

All time recordings were analyzed and post-processed using in-house Matlab scripts. Various auto- and cross-power spectra could be obtained in narrow, third-octave or octave bands for all microphones, ear protection conditions and tests combinations. It allowed obtaining all the REAT, IL and NR[*] values needed for comparison purposes as well as the occlusion effect values.

Human Subjects and HPD Used

When this paper was written, only few subjects had been tested. However, it is planned to ask a total of 60 subjects with normal hearing (hearing thresholds ≤ 25 dB HL from 250 to 8000 Hz) to take part to the test sessions. Each subject is asked to best tested with at least one pair of earmuffs, one pair of earplugs and with the corresponding double protection. Three types of earmuffs and three types of earplugs were selected. The selected earmuffs were different in construction (dual-cup vs single shell), sizes and labeled ratings (NRR=20, 23 and 30 dB). As for earplugs, classic foam, push-ins no-roll foam and custom molded earplugs were selected.

RESULTS

As the tests on human subjects were not completed yet when this paper was written, no statistical analyses were realized. Therefore, only examples of results for one subject are presented in this section. For this subject, 3M Peltor Optime 105 earmuffs and E-A-R classic foam earplugs were used.

Attenuation Values

Attenuation values obtained with step 1 (REAT) and step 3 (IL and NR^*) test procedures described above are shown in figure 3 for three ear protection conditions: (a) earmuffs, (b) earplugs and (c) double protection. The results illustrate well the differences between the NR^* and IL expressed by the TFOE, TF_{ext} and TF_{canal} terms in equation (2). It is expected the TF_{ext} and TF_{canal} terms to depend on the type of HPD[17], [20] as well as ear canal geometry. Analysis of results obtained with the entire set of subjects should help to shed some light on these factors and, expectedly, to propose some simple estimates to relate the IL and the NR^* values. Differences observed between the REAT and IL values (especially for the double protection) are currently under investigation.

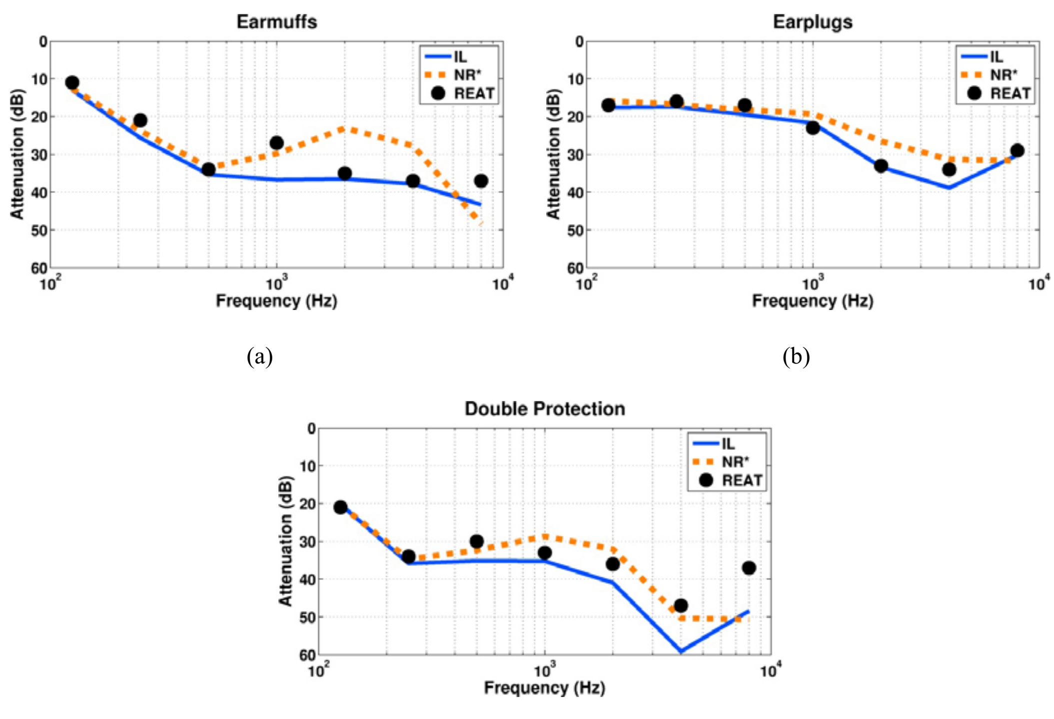
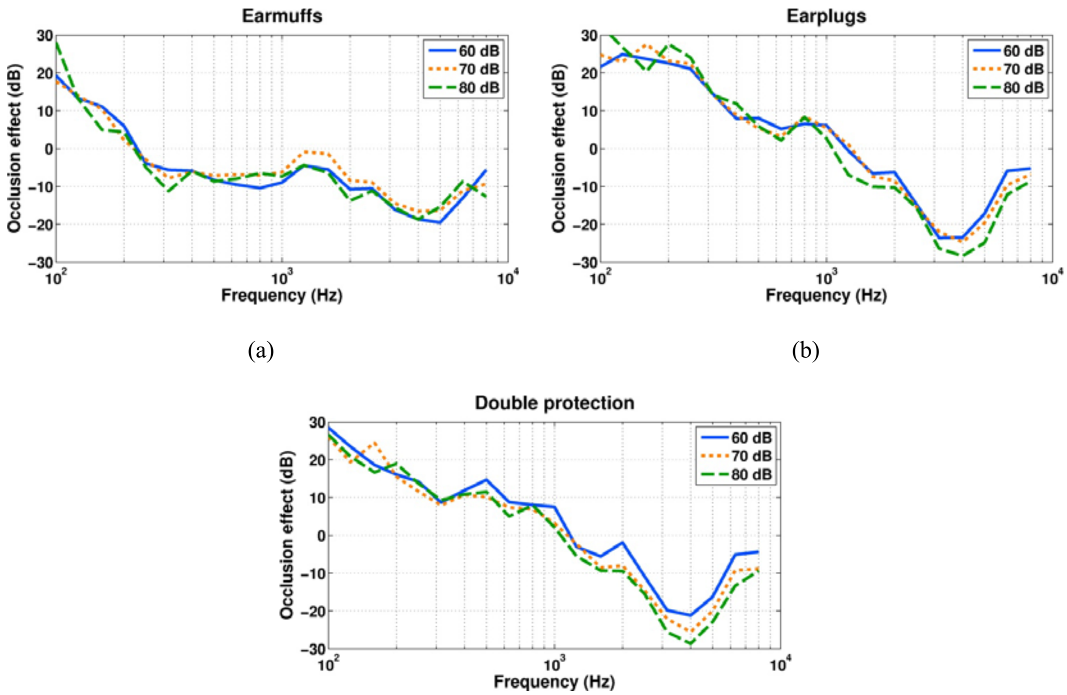


FIGURE 3. Attenuation values (in dB) obtained with subjective and objective procedures for one subject.

Occlusion effect

The occlusion effect, expressed in dB, was calculated as the difference between the sound pressure level in the ear canal in the occluded condition and the one in the open ear condition. Therefore, a positive (negative) value for the occlusion effect indicates that the noise is higher when the ear canal is occluded (open). Occlusion effect values obtained with the step 4 test procedure described above are shown in figure 4 for the three ear protection conditions and three speech levels (60, 70 and 80 dB). Although the test procedures proposed in the present study are different, the results presented here show similar trends and are consistent with those presented by Reinfeldt et al[21] and Stenfelt and Reinfeldt[22].



(c)

FIGURE 4. Occlusion effect (in dB) obtained for one subject and three speech levels (60, 70 and 80 dB).

CONCLUSION

A series of tests were conducted on human subjects to investigate the relationships between subjective and objective measurements of hearing protection devices attenuation. Subjects were instrumented with miniature microphones in the ear canal and were asked to sequentially take part to various tests with and without HPD:

(i) threshold measurements to obtain REAT (subjective) values
(ii) high level pink noise for MIRE/F-MIRE (objective) data calculation

Additionally, one exploited the fact that the subjects were already present and instrumented with microphones to propose a simple testing procedure to measure objectively the occlusion effect based on speech production. Earmuffs, earplugs and corresponding double protection were tested for each subject. Preliminary results on very few subjects show the potential of the simple proposed series of tests to perform a thorough comparison of objective and subjective attenuation data. It should allow proposing approximations relating together the REAT, IL and NR values either from a statistical standpoint (ensemble of subjects) or, conceivably, on an individual basis.

Preliminary occlusion effect results obtained for the few subjects tested were consistent with those found in the literature and showed similar trends. Analysis of the entire set of data and comparison with other existing techniques for occlusion effect measurement should help to determine if a simple and robust procedure can be derived from the tests proposed in this study.

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