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NOISE CONTROL FOR A BETTER ENVIRONMENT

A simple low-invasive method to assess sound pressure levels at the eardrum using dual-microphone measurements in the open or occluded ear

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ABSTRACT

The assessment of the noise exposure for a given individual is commonly performed using measurement techniques such as sound level meters (SLM) combined with estimated of exposure time or the use of portable noise dosimeters (PND). SLM and PND-based approaches only provide information about the ambient noise levels and fail to account for wearer's placement effects and inter-individual differences in the wearers' morphologies (e.g. head and ear geometries). While the damage risk criteria of existing noise standards refer to free-field measurements, it is commonly accepted that the risk of hearing loss is more directly related to the levels at the tympanic membrane. In-ear noise dosimetry (IEND) is a promising approach that provides continuous monitoring of an individual's noise exposure directly inside the ear. However, current IEND systems do not allow direct collection of eardrum data, as their featuring in-ear microphone is typically maintained at a certain distance from the membrane. This paper presents a simple method aimed at converting the measured SPLs to the eardrum, thus forming the basis for individual in-situ calibration of IEND. The method, based on a dual-microphone approach, and prototypes developed to conduct improved IEND measurements in the open or occluded ear are presented.

Keywords: Dosimetry, ear canal, intraauricular measurements
I-INCE Classification of Subject Number: 78

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1. INTRODUCTION

The evaluation of noise exposure is a vital component of a comprehensive hearing conservation program. Indeed, a reliable method to measure noise exposure levels in the workplace is essential to properly identify, propose and evaluate corrective solutions and to support prevention efforts. Moreover, such method is needed to help in the selection and fitting of appropriate hearing protection devices (HPDs) to protect the hearing of overexposed workers. Personal noise exposure measurements aim to assess the noise exposure of a given individual, usually a worker, to ensure compliance with the occupational exposure limits of a particular legislation. The conventional way of monitoring noise exposure of individuals (eg. $L_{ex,8h}$) is to use either sound-level meters (SLM) or personal noise dosimeters (PND), the latter being more interesting when the acoustical environment varies significantly over time as they can can track sound exposure near the ears of the individual (they are typically worn on the shoulder). When hearing protection devices (HPDs) are worn, things become more complicated as an estimate of the attenuation provided by the protector is needed. In such a case, the effective noise exposure of the worker, that is the exposure levels “under” the protector, are estimated using a combination of the noise exposure levels $L_{ex,8h}$ and the attenuation provided by the HPD using calculation procedures found in standards or guidelines[1]. Yet, while the $L_{ex,8h}$ is only an estimation of the actual daily ambient noise exposure, it is well known that HPD attenuation values in the workplace not only regularly differ from laboratory-derived data, but may also fluctuate considerably over an individual’s workshift [2].

Recent efforts have been put into developing systems that can measure noise exposure directly inside the ear (see for example [3–8]) using earpieces instrumented with miniature microphones. Thanks to their design, these systems can automatically account for HPD attenuation as well as for the wearer's positioning and to the individual shape of each individual's ears. One particular drawback of current in-ear noise dosimeters (IENDs) is that the in-ear microphone used for monitoring is typically maintained at a certain distance from the tympanic membrane for obvious comfort and safety reasons. Therefore, the sound pressure levels (SPLs) measured with this microphone need to be converted into eardrum SPLs using correction factors. Although group average correction factors or experimental values measured on a manikin [7] can be used, individual correction factors should prove to be more accurate as a wide variety of earcanal shapes and geometries are found in practice. The present paper proposes a simple, non-invasive method that aims at assessing the SPLs at the eardrum using dual-microphone measurements in the open or occluded earcanal. First, the acoustics of the earcanal is briefly described in order to define the target correction factors. Second, the method and prototypes developed to conduct IEND measurements are presented. Finally, results are presented to illustrate the importance of the individual correction factors on in-ear noise exposure measurements.

2. BASIC ACOUSTICS OF THE EARCANAL

The proposed approach relies on a basic understanding of the acoustics of the earcanal. The key physical concepts are presented by using acoustic simulations and experimental data collected on human subjects. These data are used to illustrate the main principles behind the proposed method.

2.1 Open earcanal

Figure 1 illustrates the open ear, marked with three positions in the earcanal for sound pressure level (L_p) measurements or calculations: at the eardrum (L_{p_E}); at some distance in the earcanal (L_{p_M}); near the earcanal entrance (L_{p_R}), also noted as a reference location. The main idea is to derive correction factors to convert measurements in the earcanal (L_{p_M}) to the eardrum (L_{p_E}) while avoiding the practical and safety issues inherent to eardrum measurements

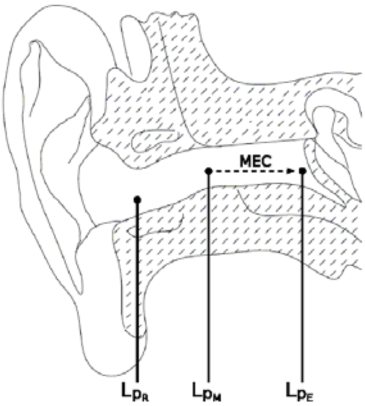

Figure 1: Locations for SPL measurements/calculations. The MEC (Microphone-to-Eardrum Correction) is the correction factor used to convert L_{p_M} to L_{p_E}.

2.1.1 Analytical model

A simple analytical model of the open earcanal was developed using the transfer matrix method (TMM)[9]. The horn represented by the earcanal was modelled as a series of conical transmission –line dissipative elements, where the matrices of each element are given by Mapes-Riordan[10]. The lumped-parameter model of Shaw and Stinson[11] was used to model the tympanic membrane as the earcanal's terminating impedance. The model was validated using experimental data obtained in a real earcanal, as explained in the next section. Precise dimensions of the earcanal of a human subject (hereafter referred to as "reference subject") were obtained from magnetic resonance imaging (MRI) and the reconstructed geometry[12]. The approach proposed by Stinson and Lawton[13] was then used to derive the cross-sectional profile of the reference subject's earcanal to be fed to the analytical model. Example of validation results are presented later in the paper.

2.1.2 Open-ear measurements on human subjects

Open-ear measurements were performed in a reverberant room equipped with four loudspeakers (one loudspeaker in every room corner). Ten human participants were instrumented using a miniature microphone connected to an ER-7C probe tube (Etymotic Research, Elk Grove Village, IL). The tests were supervised by a Canadian-registered audiologist and the protocol was approved by the *Comité d'éthique pour la recherche*, ÉTS's internal review board. White noise was generated through the four loudspeakers and the acoustic pressure was measured at approximately every 2~mm from eardrum to earcanal entrance (ECE) in each subject's left ear. Thus, for each participant, a number of measurements were made along the earcanal, which also gave an estimate of the length of the canal tested (e.g. 12 measurements correspond to an earcanal length of 22~mm). The lengths of the 10 earcanals tested were found to range from 22 to 28~mm.

2.1.2 Comparison between model and measurements

Figure 2 and figure 3 show two comparisons between results obtained with the analytical model and from real-ear measurements. The two figures show that the model is able to capture correctly the main physical aspects of the system. Firstly, the first two natural resonances of the earcanal are clearly seen in figure 2 (at ~3-4 kHz and ~10 kHz). Secondly, when the measurement microphone is further inserted inside the earcanal (figure 3), a standing-wave due to the wave reflected by the eardrum is formed. It results in a maximum in the response that can be seen higher in frequency as the distance from the tympanic membrane decreases. The frequency at which this maximum occurs is noted f_{peak} in figure 3.

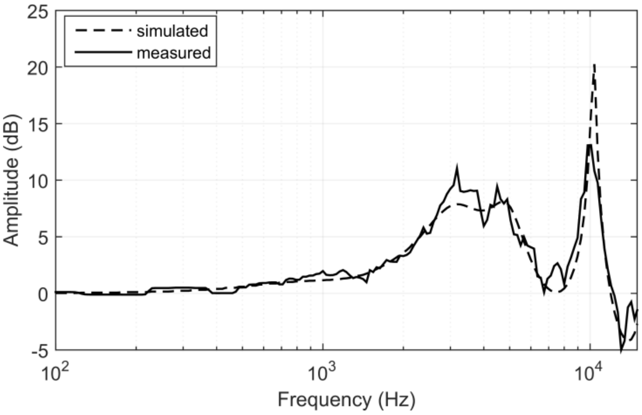

Figure 2: Sound pressure level transformation from earcanl entrance to eardrum for the reference subject.

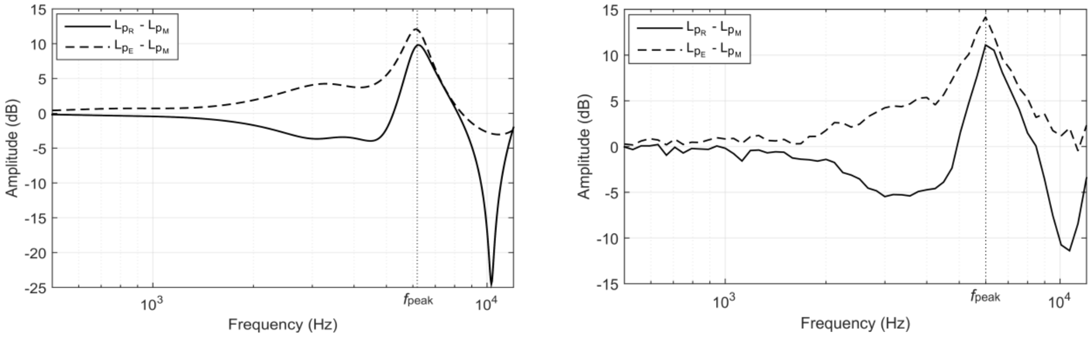

Figure 3: SPL differences $L_{p_R} - L_{p_M}$ and $L_{p_E} - L_{p_M}$ for the reference subject. The left panel shows the analytical model's results while the right panel shows the test results. The measurement microphone M was located at 20 mm from the eardrum and was 9 mm away from the ECE microphone (R). The frequency f_{peak} is associated with the standing-wave mínimum.

2.1.2 Identifying the individual correction factor MEC

One recalls that the objective here is to estimate the correction factors to convert SPL measurements in the earcanal (L_{p_M}) to the eardrum (L_{p_E}) without actually measuring directly at the eardrum. Such correction factors are noted MEC as:

$$\mathrm{MEC} = L_{p_E} - L_{p_M} \qquad (1)$$

One key result of figure 3 is that f_{peak} may be identified from either $\mathrm{L}_{\mathrm{p}_\mathrm{R}} - \mathrm{L}_{\mathrm{p}_\mathrm{M}}$ or $\mathrm{L}_{\mathrm{p}_\mathrm{E}} - \mathrm{L}_{\mathrm{p}_\mathrm{M}}$. Therefore, performing measurements directly at the eardrum is not required to determine f_{peak}.

The MECs measured on the 10 subjects at 8, 10 and 12 mm from the ECE are shown in figure 4, where the associated curves were rearranged so that all maxima coincide. The results show that most MECs exhibit a very similar shape. Consequently, an approximate MEC shape was built as the average of all 30 curves shown in figure 4. The resulting curve curve, further referred to as “MEC filter”, is shown in figure 5. If the frequency f_{peak} is known individually, the curve in figure 5 can be used to obtain an estimate MEC for each individual. As shown earlier, the identification of f_{peak} can be done relatively easily using the measured SPL difference $L_{p_R} - L_{p_M}$.

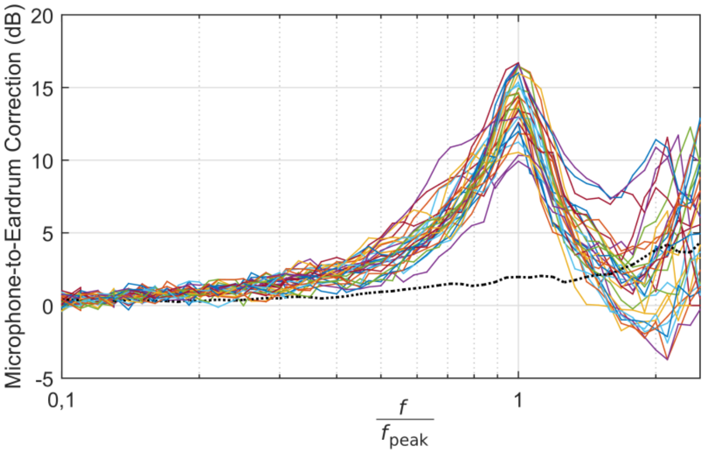

Figure 4: MEC measured on the 10 participants at 8, 10 and 12 mm from the ECE. The black dotted lin indicates the standard deviation (N=30)

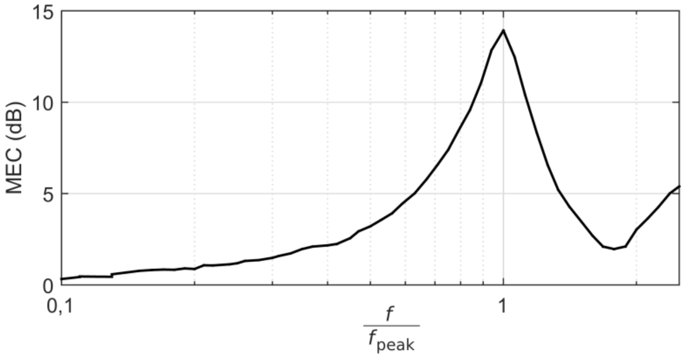

Figure 5: MEC filter obtained by averaing the 30 curves presented in figure 4.

The analytical model was used to assess the working range of the identification process (earcanal length, exact location of the measurement microphone in the earcanal, etc.). These aspects are discussed by Bonnet et al[14]. Results from real-ear measurements also showed that a frequency resolution of at least one twelth octave band was required for accurate detection of f_{peak}.

To examine the precision and working frequency range of the proposed method, the results from probe-microphone measurements made in the open ear were used. For each subject, the SPL measured at 8 mm past the ECE (L_{p_M}) was subtracted from the SPL collected near the ECE (L_{p_R}). The resulting spectrum difference was used to convert L_{p_M} to the eardrum using the proposed MEC filter and the pre-established frequency f_{peak}. This result was then compared to the spectrum directly measured close to the tympanic membrane. For the 10 participants tested, it was found that the estimated SPL spectrum at the eardrum fell within 5 dB of its target measured values, over the entire frequency range up to 10 kHz. An example for one participant is shown in figure 6. As can be seen on the figure, large differences are obtained between the eardrum and earcanal measurements, especially above 1 kHz. The proposed approach showed to be able to accurately correct for these differences. The approach was also successfully tested for earmuff-covered ears.

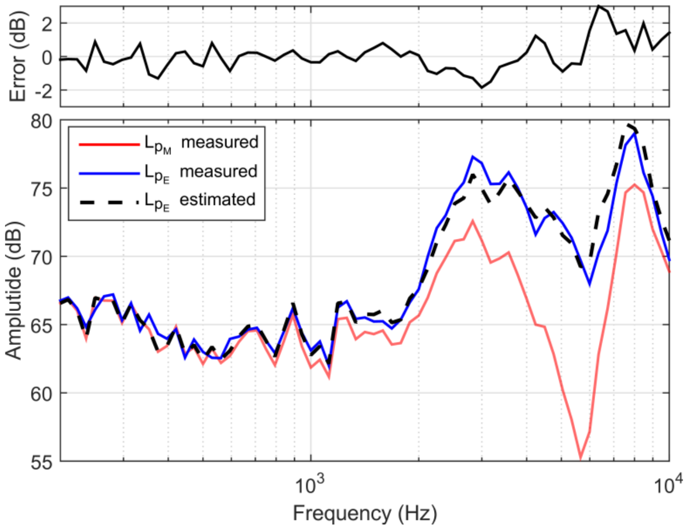

Figure 6: SPL spectra on one subject: measured at 8 mm past the ECE (red line); measured close to the eardrum (blue line); estimated at the eardrum using the proposed approach (dotted line).

2.2 Earcanal occluded by an earplug

When insert-type HPDs are worn, IEND measurements are usually performed inside the occluded earcanal, between the inner end of the occluding HPD and the eardrum. When such a “dosimetric earplug" is used, the impedance seen at the measuring position in the direction of the middle ear is independent of the earplug. In other words, the MEC that exists in the presence of external noise is the same as in the open earcanal case[15,16] provided that sound arrives primarily through the HPD and that bone conduction (BC) can be neglected. Therefore, the approach presented in the previous sections can be used to estimate the MEC in the case of earplugs, that is by measuring the difference $L_{p_R} - L_{p_M}$ to identify f_{peak} and using the MEC filter. Four options can be used for the measurements of the spectrum $L_{p_R} - L_{p_M}$ in presence of an earplug. One is to perform the measurements in the open ear, as explained before, and to apply the MEC to the case of the earplug, as long as the exact same measurement locations are used. This approach is unrealistic in practice as it would require separate sets of measurement (open ear and occluded ear) and would be greatly sensitive to microphone placement. The three other options are illustrated in figure 7. In option (a), L_{p_R} is measured at the earplug’s outer end. This option is also seen unpractical as the identification of f_{peak} would be considerably “polluted” by the complex attenuation response of the earplug. A clean peak detection would then be improbable. Option (b) is rather promising in theory, but is very difficult to implement in practice, as it requires the use of two microphones separated by a certain distance under the earplug, without creating any pain of discomfort. Option (c) was chosen here as it allows using an external microphone and easily bypassing the attenuation via a controllable leakage path, in the form of a small cylindrical tube. The analytical model presented earlier was used to investigate the effect of this controllable leak, whose the effect combined with that of the residual part of the earcanal may be assimilated to a Helmoltz resonator. It allowed showing under which conditions (tube dimensions, insertion depth, etc.) such arrangement is valid to correctly identify f_{peak} and, by extension, the MEC to be determined [14]. Results from such acoustic simulations also confirmed the independence of f_{peak} with regards to the tube's dimensions (length and diameter), as illustrated in figure 8. The decrease in amplitude visible between 200 and 400 Hz corresponds to the natural resonance of the Helmholtz resonator.

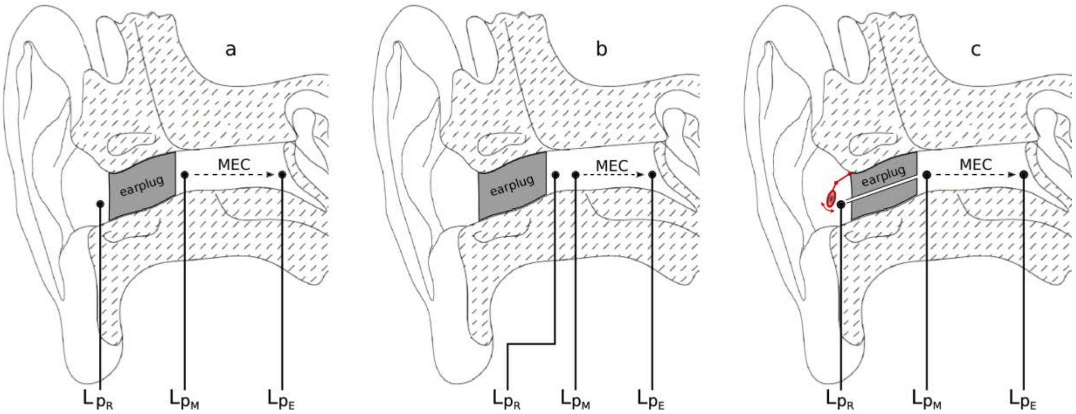

Figure 7: Measurement options for the estimation of f_{peak} under an earplug. (a) $L_{p_R}$is measured at the earplug's outer end; (b) L_{p_R} is measuresd at the earplug's inner end; (c) L_{p_R} is measured at the earplug's outer end but a controlable leak (tube) is used to bypass the attenuation of the earplug.

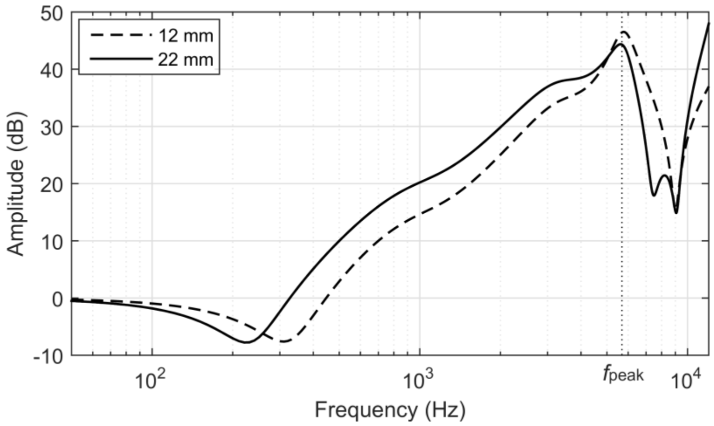

Figure 8: SPL difference $L_{p_R} - L_{p_M}$ for two tube lengths (12 mm and 22 mm) using option C. The reference subject's earcanal dimensions were used in the calculations. The measurement microphone is located 8 mm away from the ECE and the tube's inner diameter is 1 mm.

3. MEASURING DEVICES

Two prototypes based on the principles exposed in the previous sections were developed and tested on human subjects. These two prototypes are presented in the next section, followed by results obtained with such instrumentation on human test-subjects.

3.1 Prototypes presentation

3.1.1 Dosimetric earpiece

A dosimetric earpiece designed for usage in an unoccluded ear (unprotected ear or ear under an earmuff) is presented in figure 9. This earpiece was designed to be almost acoustically transparent.

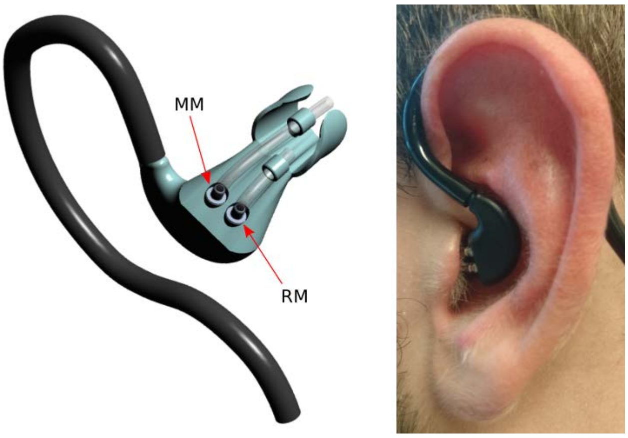

Figure 9: Illustration of the dosimetric earpiece. Left panel: 3D model showing the earpiece, instrumented with a measurement microphone (MM) and a reference microphone (RM). The distance between the tips of the two probe-microphones is 8~mm. The RM’s location is intended for measurements near the ECE. The earpiece was designed to allow a maximum insertion depth of approximately 8~mm. Right panel: picture showing the earpiece worn in the ear.

3.1.2 Dosimetric earplug

A dosimetric earplug, featuring also two microphones, is presented in figure 10. This earplug was designed so that the measurement microphone (MM) be located at approximately 8~mm past the ECE (at the inner end of the earplug). The reference microphone (RM) is located near the vent's inlet, and is used to perform the identification procedure described before. The system features a vent, in the form of a tube 13.8~mm long and 0.8~mm in diameter, and a manually operable lever to close the vent at the end of the identification procedure and recover the earplug's nominal attenuation. In the up position, the lever keeps the vent open, while pushing the lever down allows sealing the vent. This prototype can support various types of eartips, and is shown as worn inside the ear by figure 11.

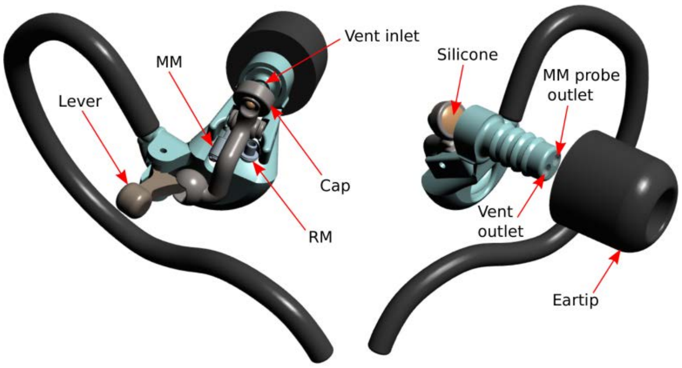

Figure 10: Illustration of the dosimetric earplug. Similar to the dosimetric earpiece, the earplug was designed to allow an insertion depth (distance between earplug's inner end and ECE) of approximately 8~mm, when properly fitted.

Figure 11: Dosimetric earplug, as worn with the vent in open (left) or sealed (right) conditions.

3.2 Prototypes: measurement on human subjects

Tests on 10 participants were performed in a 10 m^2 double-wall audiometric sound booth (Eckel, Morrisburg, ON, Canada). For each test, approximate pseudo-diffuse sound field was created around the participant using white noise played through four loudspeakers. The participants were asked to wear both the dosimetric earpiece and the dosimetric earplug alternatively. The dosimetric earplug was equipped with the high insulation Comply^{TM} Isolation T-400 eartip (Hearing Components, Inc., St Paul, MN), illustrated in figure 11. TheSPL difference $L_{p_R} - L_{p_M}$ obtained on the ten participants with both prototypes is shown in figure 12. Results show that the f_{peak} may be more easily identifiable with the dosimetric earpiece than with the earplug, as the curves in the right figure panel are not as smooth as the ones in the left figure panel. The authors found that the earplug was in fact more sensitive to the acoustic field used due to the distance between the reference microphone and the the vent inlet. Because of design constraints, the RM is indeed slightly off the vent inlet (by approximately 7 mm), as shown in Fig. 10, making the SPL difference between the RM and the MM more sensitive to the acoustic field, resulting in acoustical artefacts in the response. It is believed that a better and more compact design would help reducing these effects, as discussed by Bonnet et al[14]. Nevertheless, the data showed in figure 12 were proved reliable enough to obtain good estimates of f_{peak}, and thus MEC.

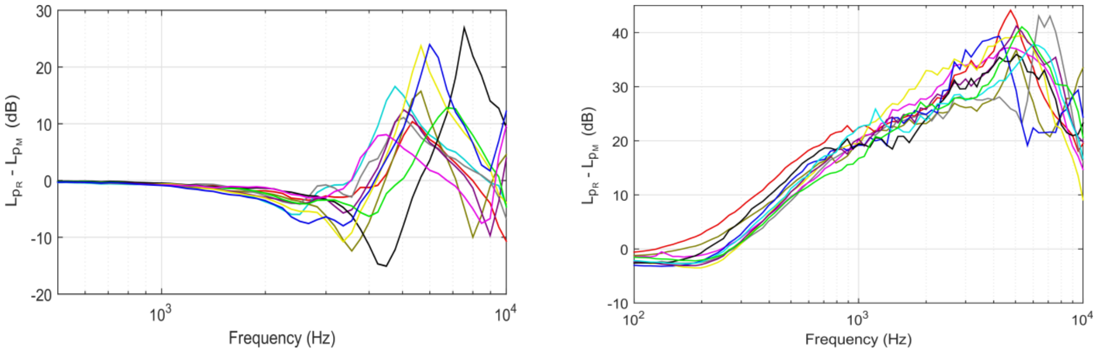

Figure 12: Sound pressure level difference $L_{p_R} - L_{p_M}$ for the 10 participans wearing the dosimetric earpiece (left panel) or the dosimetric earplug (right panel)

4. DISCUSSION

The proposed method showed, both for the unoccluded and for the ear occluded by an earplug, that SPLs measured in the earcanal can be successfully transformed to the eardrum using simple dual-microphone measurements. Such conversion being quite sensitive to the distance that separates the measurement microphone from the eardrum, the method relies on a good control of the positioning of the measuring device. An open ear device would most probably tend to move in real field conditions, as it is designed to be fairly acoustically transparent and does not occlude the earcanal. Such variations could affect the precision and variability of the results. To palliate this problem when continuously monitoring the noise exposure in real time, it is suggested that the proposed method be repeated frequently using the surrounding noise as the exciting sound source for the identification process. Such a task could be run automatically and would allow accurate determination of the correction factors if the device moves without any intervention from the wearer.

In the same way, the proposed approach with an earplug relies on the proper knowledge of the HPD's insertion depth. This implies that the f_{peak} identification process needs to be ideally repeated whenever the earplug is removed and re-inserted. Additionally, the MEC is not valid when the device is removed from the ear, a common situation as many workers are sometimes tempted to remove their HPDs for various reasons[17]. Further development is hence needed for a method that detects when the device is removed. When the dosimetric earplug is correctly worn inside the ear, the MEC's identification is viable under two conditions: 1) the eartip should be fitted well enough so that the vent, when open, is the primary transmission path towards the earcanal; 2) the attenuation of the earplug, when the vent is closed, should not exceed the BC limit[18]. In the latter case, the proposed MEC would not be appropriate, as the BC path would become significant and the eardrum SPL would not accurately represent all the sound energy ultimately transmitted to the inner ear.

For the two configurations discussed in this paper (occluded and unoccluded ear), the proposed method is based on an airborne external sound excitation, and is not valid for noises emitted by the wearer (speech, internal noise, movements, etc.). Further work is needed to investigate what would be the correction factors in the presence of such internal noise disturbances.

The proposed approach may have important repercussions for hearing research and the prevention of NIHL. Using the suggested individual correction factors, noise dosimetry measurements may finally establish the actual SPLs and frequency contents received at the eardrum by a given individual. It should enable the large collection of individual datasets, thus improving our knowledge of noise-induced hearing loss in the workplace especially if audiometric data are collected in parallel.

Besides in-ear dosimetry, the authors believed that the proposed approach and prototypes could to be very useful for laboratory and research work for which in-ear measurements at the tympanic membrane are needed (eg. hearing protection, occlusion effect, hearing aids). Measuring directly at the eardrum using probe tubes can be a laborious task, particularly due to the lack of visibility when inserting the probe and for safety and comfort issues of the participants. Conduction such careful measurements also require a good level of expertise. The proposed method and devices allow much simpler and safer measurement procedures and lead to robust estimates of the SPL at the tympanic membrane. The authors assumed that more research and development on the proposed method would open up opportunities for in-ear measurements in various fields.

5. CONCLUSION

A method based on dual-microphone measurements was presented to perform the individual identification of correction factors for in-ear noise dosimeters. Using data collected on human test-subjects, combined to simple modeling tools, a measurement procedure was proposed, and preliminary results were presented using instrumentation developed for this study. Results suggest that the proposed approach can be successfully used to transform in-ear measurements to eardrum in open (unprotected) ears, ears occluded with earplugs or earmuff-covered ears. The proposed method and prototypes provide a simple and safe in-ear measurement procedure that laboratory and field research activities could benefit. In the long term, it is believed that data collected using the proposed method, combined with proper audiometric testing, could serve as a basis to redefine current occupational noise exposure legislation and damage risk criteria.

6. ACKNOWLEDGEMENTS

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