

DESIGN AND LABORATORY VALIDATION OF AN IN-EAR NOISE DOSIMETRY DEVICE

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The assessment of noise exposure is a major component of any hearing conservation program. It is usually conducted using either sound level meters (SLM) or personal noise dosimeters (PND). Some significant problems arise when performing noise exposure measurements using SLMs or PNDs. First, these devices do not usually account precisely for the variations of the actual noise exposure experienced by a given worker over the work shift. Additionally, the attenuation provided by the hearing protector that is worn is only taken into account very approximately. To address these issues, the purpose of this study is to implement a precise and reliable in-ear noise dosimetry system based on low computational algorithms that can be used in a wide variety of environments and work conditions. The adopted methodology focuses on the implementation and validation of a real-time measurement system. The proposed system utilizes a set of two miniature microphones placed inside and outside the ear canal. Besides, two types of in-ear prototypes were developed: one for the unoccluded ear and one for the ear occluded with a passive earplug. The validation of the in-ear devices prototypes and algorithm implementation was done using data collected during a study on human subjects. Both developed hardware and software elements make it possible to determine correction factors enabling the conversion of the measured in-ear noise exposure levels to their equivalent free-field values. Furthermore, the implemented algorithms can detect and exclude wearer-induced disturbances (speech, microphonics, etc.) making it possible to assess noise exposure with and without the energy contribution from these self-generated noises. This paper presents a successful implementation and validation of an in-ear noise dosimetry system, with unique features and capabilities, that could lead to the improvement of methods and systems for personal noise exposure assessments in the workplace.

Keywords: acoustics, in-ear noise dosimetry, hearing-protection, occupational health and safety, acoustics, instrumentation, real-time algorithms implementation.

1. Introduction

The methods proposed by Bonnet et al. [1–4] are the basis for the work presented in this paper. The approach consists in measuring the noise levels in the earcanal of individuals in typical workplace conditions either with unprotected ears or ears protected by earplugs or earmuffs. It uses two miniature microphones located respectively inside and outside the earcanal to account for individual characteristics (shape and length of the earcanal) when estimating acoustical correction factors to convert the measured in-ear sound pressure levels (SPL) to equivalent free-field values. This approach was validated through human subject measurements processed with Matlab (MathWorks, Natick, MA, USA) algorithms. The results made it possible to establish a relationship between the SPL values read within the earcanal and the values at the eardrum itself, called Microphone-to-Eardrum Correction (MEC). Secondly, a low computational algorithm [4] was developed to perform in-ear noise dosimetry measurements under an earplug while excluding the noise contributions induced by the wearer such as speech, shocks on the earpiece, whistling, etc.

The purpose of this paper is to present how the above methods can be implemented in real time and be effectively used by workers wearing the intended portable dosimetry system. This would allow for "on-the-fly" monitoring of the effective noise exposure received by a given individual. The present method and system make it possible to evaluate the contribution of speech and other noises generated by the user with respect to the well-defined risk of auditory trauma. In practical terms, the prototypes can be used as a measurement tool alternative to better assess noise exposure and support prevention efforts in workplaces. Two different prototypes were designed for this project: an Open Ear Device (OED) and a Closed Earpiece (CEP). The paper gives an overview of their hardware concept, design and construction, time development evolution, software development as well as strategies to test and validate them. The first part of the validation tests is related to the individual correction factor MEC, which is to be used in both developed prototypes (OED and CEP). The final validation relates to the detection of wearer-induced disturbances (WID), which should be detected and removed from the in-ear noise contributions caused by the wearer's environment. This WID detection algorithm applies to the CEP device specifically, since the impact of WIDs is expected to be more important inside a protected ear due, notably, to the occlusion effect. This paper is organized as follows: the system implementation is first presented, followed by a presentation of the various prototypes designed during the project. The software and algorithm implementation is then discussed. Finally, since the methods developed in this study were initially validated using Matlab algorithms [1,3,4], the newly developed real-time algorithms obtained with Python (Python Software Foundation, Wilmington, DE, USA) software are compared to Matlab's results as a means of validation.

2. System Implementation

A portable hardware platform dubbed "Auditory Research Platform" (ARP3) recently developed by the NSERC-EERS Industrial Research Chair in In-Ear Technologies (CRITIAS) was used throughout the development. The ARP3 platform is connected to a four-channel sound card and a battery-pack for long-running tests (up to 8 hours of data acquisition and processing). A basic diagram with all hardware parts is depicted in the Fig. 2(a). The ARP3 unit has an Intel ATOM Z3735F processor, 2GB DD3 memory and runs the Windows 10 operating system (OS), specially configured to allow complex and fast algorithms to run flawlessly. The four-channel sound card was added to the platform to connect the data coming from the earpieces (presented later) to the running algorithms. The entire assembly is depicted in Fig. 2(b). Python was chosen for data acquisition and data processing for the final prototype system, and runs smoothly on the ARP3 platform.

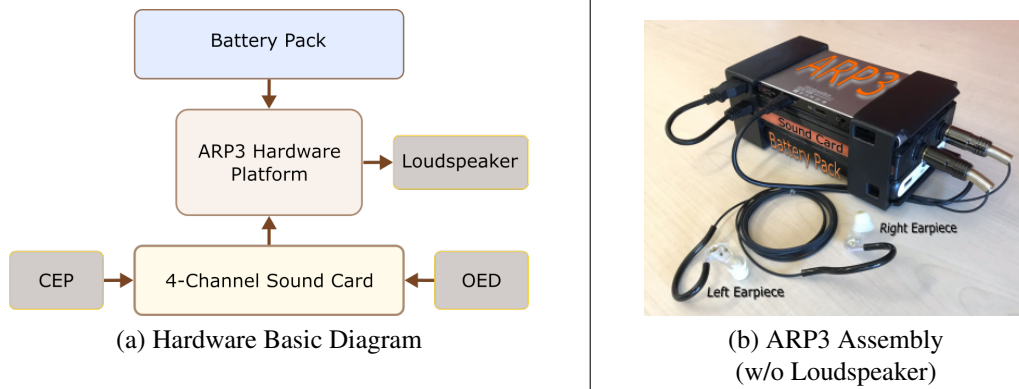


Figure 1: Block diagram (left) and physical assembly (right) of the proposed in-ear dosimetry system

2.1 Earpiece prototypes

To measure the sound pressure levels in the earcanal, two prototypes were developed and manufactured: an acoustic transparent device or open-ear device - OED, and an occluded device or closed earpiece - CEP. Both were first designed using SolidWorks (Dassault Systèmes SOLIDWORKS Corp., Waltham, MA, USA) 3D CAD tool and were produced in-house with the help of a Formlabs (Formlabs Inc., Somerville, MA, USA) 3D resin printer. Once printed, two Knowles (Knowles Corp., Itasca, IL, USA) miniature microphones, model FG23652-P16, were added to each device for SPL measurements in the earcanal. Figure 2 shows different iterations of both prototypes created for this project showing their evolution toward the final design. The OED was the first device to be implemented. Special care was taken to design it to provide the smallest cross-sectional area as possible in the earcanal in order to be as acoustically transparent as possible, as recommended by ISO 11904-1:2002 [5](item 3.7).

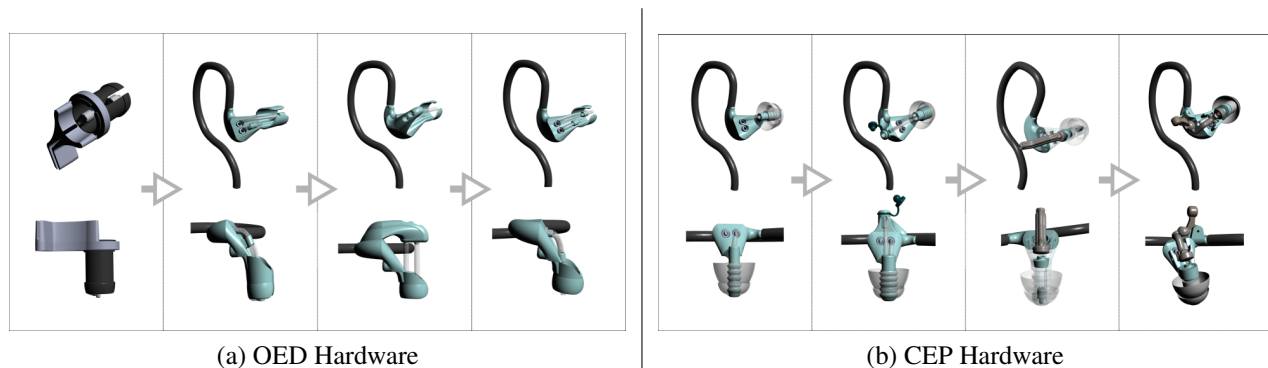


Figure 2: Evolution of the OED and CEP devices over design iterations

The mechanical development started with defining the earcanal geometry [6] and a three-dimensional (3D) geometry extracted from a magnetic resonance imaging (MRI) conducted on a human subject in a recent study [7]. This 3D pinna scan was useful because it helped to find suitable geometry parameters to improve the design concept and support modelling of the in-ear devices. An interaction study of the 3D model of the device inside the pinna geometry model was conducted. It proved an important step toward obtaining a feasible and practical solution. Instead of placing the microphones directly inside the device as in the first approach, it was decided to enclose them in the device's main body for added protection to the electrical wires and thus, this created a more robust device. This modification also helped reduce the cross-sectional area, a feature needed to achieve an almost acoustically transparent solution. Fig. 3 shows the OED prototype assembly and how it will be worn by the user.

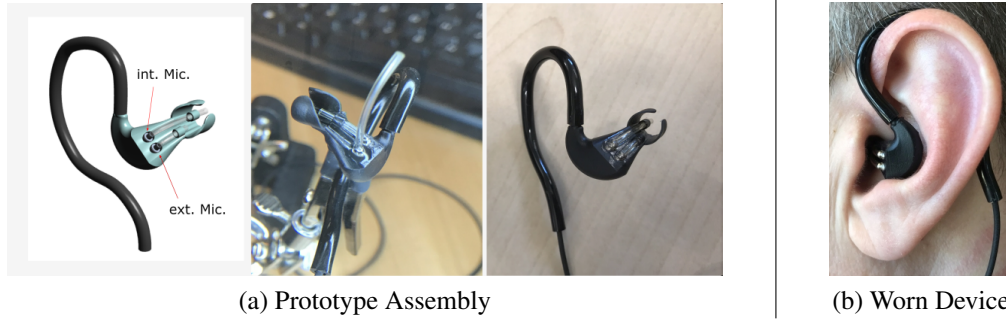


Figure 3: 3D rendering and pictures of the OED prototype showing the various components, assembly and overall design

The initial CEP design used the same mechanical main body of the OED. The difference is in the eartip part, which is very similar to certain conventional off-the-shelf earpieces. Two microphones were also used for this assembly and at first, only one sound-guiding tube was considered to conduct the sound from the earcanal to the respective internal microphone.



Figure 4: 3D rendering and pictures of the CEP prototype showing the various components, assembly and overall design

This earpiece can support various types of eartips, from double-flanged silicone eartips to high insulation eartips. CEP details are shown in Fig. 4.

2.2 Software Development

Real-time data acquisition and analysis is an essential requirement for this project. The ARP3 hardware platform runs on Windows 10 OS and the software code was developed using Python 3.7. The algorithms were based on equations from ANSI S12.19 [8], but were adapted to incorporate the occluded ear correction factors. The core element responsible for the signal acquisition from the sound card is the PyAudio library [9]. Some libraries were also added to this project like NumPy [10] (a fundamental package for scientific computing with Python), Python Acoustics [11] (useful tools for acousticians), among others. It is important to mention that the processing time block for the sound processing was limited to 300 ms for WID detection purposes. Indeed, over 80% of the within-speaker gaps between words or phrases in the speech (pauses), are between 200 ms and 1000 ms [12].

3. Test strategy for verification and validation purposes

In order to test the real-time algorithms implemented in Python, a set of tools were developed to verify that the results were equivalent to those obtained by Bonnet et al. [3, 4]. A validation process was

developed in this project using data collected and processed via Matlab functions developed by Bonnet. These tools helped to identify potential implementation mistakes when comparing the Matlab and Python implementations with the original Matlab code and algorithms.

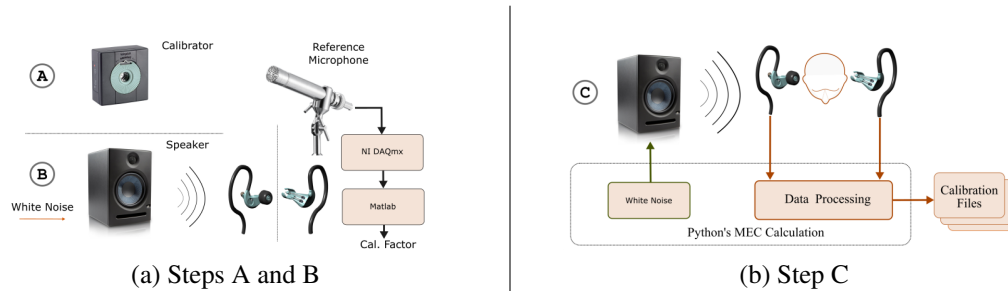


Figure 5: Illustrations of steps A, B and C of the calibration procedure

The calibration procedure comprises three distinct steps, as depicted in Fig. 5(a) and 5(b). The first two steps (A and B) pertain to microphone calibration. First, sound data from a reference microphone G.R.A.S. (GRAS Sound Vibration A/S, Skovlytoften, Denmark) model 40HF connected to a sound calibrator BK (Brüel Kjør Sound and Vibration Measurement A/S, Nærum, Denmark) Type 4231, shown in step A, is acquired.

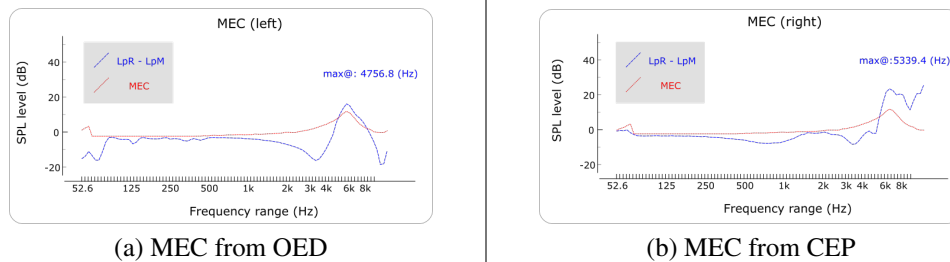


Figure 6: MEC frequency response obtained from the calibration procedure

The data acquisition for microphone calibration is performed using National Instruments (National Instruments Corp., Austin, TX, USA) DAQmx equipment and an appropriate Matlab code. In step B, the prototypes and reference microphone are placed together in the same location facing a PRESONUS (PreSonus Audio Electronics, Inc., Baton Rouge, LA, USA) Model ERIS E3.5 amplified speaker that is generating white noise. The signal measurements are then performed and calibration factors for the miniature microphones are then obtained using comparisons with the reference microphone measurements. The last calibration step (Fig. 5(b)) is the identification of the MEC function, which is unique to each subject's ears. This is done by inserting the prototypes in the subject's ears and performing measurements in the presence of the white noise generated by the loudspeaker. An algorithm was developed to estimate the MEC with either the OED or the CEP. Examples of MEC identification are shown in Fig. 6. Once all the correction factors were obtained and applied, the entire system (prototypes, platform and assembly) was validated in a laboratory environment. A subject was instrumented with the CEP in the right ear and was asked to generate WIDs in background noise in a semi-anechoic room and in a reverberent room. Time signals were recorded on the ARP3 platform and saved as wavefiles. These files were processed with both the Python implementation and Bonnet's Matlab implementation for comparisons. Output results included data such as Outer-ear SPL, In-ear SPL (WID included), In-ear SPL (ALL WID excluded), etc. The following test scenarios indicated in Fig. 7 were carried out in the semi-anechoic room and reverberent room. The tests in the semi-anechoic room were performed with only one loudspeaker whereas in the reverberent room four loudspeakers were employed to generate white noise.

Positions P1, P2 and P3 shown in Fig. 7 refer to the head position relative to the speaker(s) during the tests.

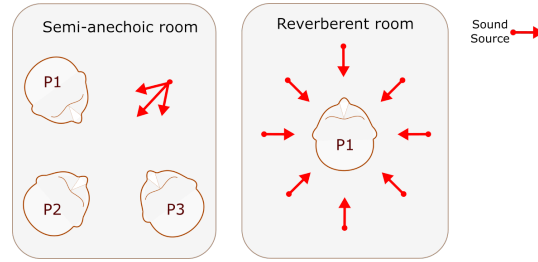


Figure 7: Illustration of the subject's positioning in the semi-anechoic room (left) and reverberant room (right) during the acoustical tests

As previously mentioned, the CEP device was worn in the right ear. In both rooms the SPL generated was around 87 dB(A) and the subject was asked to utter a short sentence and make noises, such as coughing, sneezing, tapping the earpiece, etc., very similar to the tests in the original work of Bonnet et al. [1–3].

4. Results

Examples of WID detection are presented in Fig. 8(a), Fig. 8(b), Fig. 8(c) and Fig. 8(d). These figures show the WID detection decision ("1" indicates that WID has been detected) as a function of time for four subject positions as presented in Fig. 7. It shows that the results coming from the tests and processed with the Python implementation mentioned above matched exactly the data processed with Bonnet's Matlab implementation.

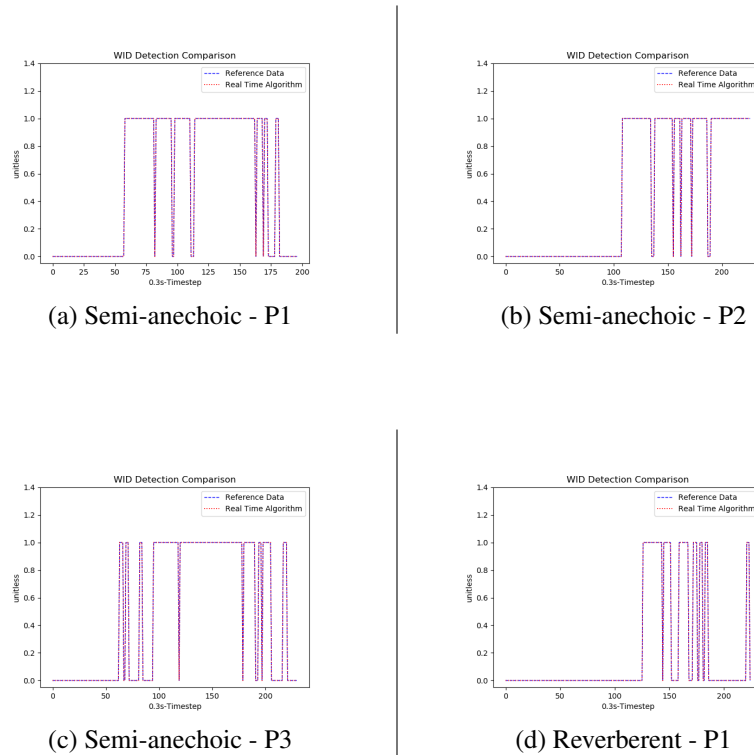


Figure 8: WID detection comparison for different test scenarios, showing a perfect match between both the Matlab code and the implemented Python algorithms

5. Discussion

Over the course of the development process of this project several prototypes were designed, implemented and tested until a "working" version was finally achieved. As can be seen in Fig. 2, the very first device produced the concept of the "Open Ear Device", however it was far from being a real and practical solution. Even though perfect acoustical transparency for the OED was not fully achieved, mainly due to the limitations of the current technological tools and materials, the final design itself proved to be mechanically very stable and robust after several tests on human subjects. Prototype improvements took into account important characteristics such as fit, comfort, measurement requirements and accuracy. Changes and improvements were made until an acceptable solution was reached. The development of the OED provided the knowledge necessary for the design of the closed earpiece. The CEP device was also required for the MEC identification process. Measurements with the initial design unfortunately showed the difficulty of obtaining a stable and reliable MEC, and modifications had to be made to the design. A solution to this problem was devised by creating a controllable leak mechanism (vent) that could be sealed after performing MEC calibration. With respect to the programming language, the choice of Python was based on its capacity to process real-time algorithms providing reliability and speed for the implementation of the needed signal-processing functions. These characteristics reduced the amount of effort that would have been needed to develop new code and consequently, shortened the length of the time required to reach the final goal of this work. Additionally, Python is widely used and has very strong community support with already developed audio, math and acoustic libraries. The Python environment also provides resources to develop a graphical user interface (GUI), which was implemented in the calibration procedure using the PyQtGraph package [13]. As in the calibration process, there was also a need for an application for acquiring and processing incoming time data from the earpieces. This was achieved by designing a GUI that provides the user options to set certain parameters for instance, the device type (open or occluded), A or C frequency weightings, exchange rate, threshold level for dose calculation, etc. Additionally, a wavefile recording option was made available. The test strategy was planned so as to verify that the same results could be obtained as those achieved in the original work of Bonnet et al. [3,4]. Although only laboratory data have been collected with this system so far, it has demonstrated that it is a very powerful tool for noise dosimetry purposes.

6. Conclusions

The present work aimed to develop a complete - hardware and software - solution capable of performing real-time measurements and calculating acoustic corrections needed for in-ear noise dose measurements in occupational settings. Regarding hardware, two measurement devices were designed and are now the property of the Institut de Recherche Robert-Sauvé en Santé et en Sécurité du Travail (IRSST, Quebec Health and Safety Research Institute). They can be utilized for many research and specialty applications, keeping in mind their current limitations for heavy duty industrial use. Regarding the software, all the measurement algorithms were implemented in Python and can run on inexpensive portable hardware, using Python open language. This innovative system opens the way for interesting applications for the field measurement of occupational noise exposure using dosimetric in-ear devices instead of dedicated and expensive DSP devices. The results presented in this paper are promising and the next step would be to further test the obtained system in the workplace.

7. Acknowledgements

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