# In-ear noise dosimetry: challenges and benefits

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**Summary**

Noise at work and noise induced hearing loss (NIHL) are worldwide major problems in many industries. Although efficient noise control measures should be promoted and be directly applied to the damaging noise sources, hearing protection devices (HPDs) remain currently the most commonly used defense against NIHL. Evaluating HPDs effectiveness in the workplace is particularly contingent upon two variables: the ambient noise level and the attenuation of the HPD. Unfortunately, in practical workplace conditions, a precise knowledge of these metrics is rather uncommon. Large imprecisions may lead to improper HPD selection and may result in workers being underprotected or even overprotected. To address this problem, recent researches have involved the development of in-ear dosimetric devices, specifically designed to monitor the noise exposure levels directly in the ear canal in real-time. This paper presents the scientific and technical challenges of such a research project that targets the development of two in-ear dosimetric devices: an earplug-type and an open-ear insert. The main research topics are presented and discussed. They are: i) determination of personalized relationships between in-ear and free-field levels; ii) effect of ear canal occlusion on hearing sensitivity; iii) effect of self-induced noise; iv) hardware implementation. Representative results are presented for each topic to illustrate how in-ear dosimetry can be efficiently implemented and offer clear benefits for hearing conservation programs.

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# 1. Introduction[1]

In many industries, a comprehensive hearing conservation program (HCP) is often needed, if not required, to prevent hearing loss due to noise in the workplace. The evaluation of noise exposure is a key component of such a program.Indeed, a reliable method to measure noise exposure levels in the workplace is essential to properly identify and evaluate corrective solutions, to support prevention efforts and to help in the selection and fitting of appropriate hearing protection devices (HPDs) to protect the hearing of overexposed workers. The latter aspect is of particular importance as HPDs are often the only option left to protect workers from excessive noise exposure. A good HPD selection is one that ensures that the HPD is effectively worn and that it offers sufficient attenuation while leaving speech and communication signals unaltered. Additionally, a good HPD selection should avoid overprotection as it may cause users to feel isolated from their environment and remove their protector, hence increasing the risk damage to their hearing [1]. It is therefore essential that each worker's individual noise exposure is precisely known when wearing a particular HPD. Unfortunately, it is rarely the case in practice as noise exposure is generally estimated by combining measurements of the unprotected noise levels, obtained from noise surveys or through standard noise dosimetry, and the attenuation of the HPD. However, noise levels in the workplace may vary significantly from one worker to another, from one location to another or simply as a function of time during a workshift[2]. Moreover, it is well known that HPD attenuation is subject to significant intra- and inter-subject variability[2], [3]. Hence, a consequence of current measurement approaches is that noise exposure levels may only be grossly estimated for a group of workers and may considerably misrepresent the noise exposure of a given individual.

One solution to overcome this issue is the new emerging in-ear noise dosimetry method. In this approach, noise levels, and thus noise exposure, are measured directly in the ear canal of individuals, using miniature microphones. Real-time measurements can be performed and noise dose calculations can be directly assessed. While appealing in theory, this approach poses several technological and scientific challenges. From this perspective, this paper presents the challenges related to in-ear noise dosimetry through a research project that targets the development of two in-ear dosimetric devices: an earplug-type and an open-ear insert. After a short review of the existing methods for noise exposure assessment, focus will be given to the in-ear noise dosimetry approach. The benefits and opportunities of this method will be described together with its challenges with regard to hearing-loss prevention. The development of two in-ear dosimetric devices will also be presented.

# 2. Existing methods

## 2.1. Standard noise measurements

The conventional way to monitor noise exposure of individuals (eg. $_{Lex,8h}$) is to use either sound-level meters (SLM) or personal noise dosimeters (PND). Sound-level meters are hand-held devices that are used to perform noise measurements at the worker's ear, in the various work conditions and tasks performed by the worker in a representative workshift. By estimating the exposure time associated to each noise level measurement, an assessment of the daily exposure can be established. To be effective, SLMs must be used by trained and qualified users. SLMs can be used to perform spot-checks or noise level estimations in specific work area, and generally offer advanced functions that facilitate the analysis of the noise–at-work environment. However, the use of SLMs can be quite tedious and cumbersome when workers are to move frequently in the workplace as it can become very difficult and time consuming to follow them in their different tasks. In these circumstances, personal noise dosimeters may become handy. A PND consists of a microphone connected to a small portable device through a cable. The microphone can be clipped to the worker, typically close to its ear, pointing towards the noise source, while the device can be clipped to the worker's belt. The device is usually set so it records noise levels continuously during the entire workshift. In reality, for ergonomic reasons, the microphone is often attached to the shoulder of the worker, pointing downwards of upwards. Its positioning may then become a source of significant errors, particularly for directional sound field and/or noises with dominant high frequency contents [4]. On the other hand, as a PND is generally worn for the entire workshift, it reduces a significant source of error by eliminating the need to estimate daily noise exposures from short one-time measurements. PNDs also do not require the continuous presence of a trained user to perform the measurements. It is then very difficult to trace potential noise artifacts that may interfere or alter the “true” noise exposure, although many recent and modern PNDs can come with more advanced tracking and recording features. In short, both SLMs and PNDs are very valuable tools to conduct noise surveys and estimate noise exposure. The benefits and shortcomings of both types of devices can be found in the literature[3], [5].

Noise exposure levels $L_{ex,8h}$ obtained with SLM and PND measurements are crucial in that they allow to estimate the potential noise hazards for an individual or a group of individuals and help to select appropriate measures to reduce the effect of such hazards. A very important limitation of SLMs and PNDs is when a worker has to wear a hearing protector. 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[3]. Yet, while the $L_{ex,8h}$ is only an estimation of the actual daily noise exposure, HPD attenuation values in real workplace conditions suffer from even larger variations and uncertainties[1]–[3]. The “real-world” attenuation not only regularly differs from laboratory-derived data, but may also fluctuate considerably over a workers’s workshift [2]. Given all the uncertainties in the estimation of the “unprotected” exposure levels as well as the HPD attenuation values, it becomes very difficult to obtain precise and reliable assessments of the effective exposure levels of individuals.

### 2.2. Measurement of individual noise exposure

To circumvent the problems mentioned in the previous section, more recent works have been focusing in measuring directly the effective (protected) noise exposure rather than relying on the unprotected noise levels combined with estimates of the attenuation provided by HPDs. As an example, an in-ear dosimetry system, the QuietDose, was commercialized by Sperian Protection following their 2008 acquisition of doseBustersTM USA. This consists of a generic eartip adapter with an integrated miniature microphone that inserts into compatible eartips and connected to a dosimeter. When the HPD is being worn, the dosimeter measures the protected level and when removed, the microphone continues to measure the level of exposure (unprotected). Such device appears to take into account the performance of the protector as well as proper fit, but does not provide any insight as to why a particular worker is over his dose as it gives little information regarding the exposure level when the HPD is worn. Furthermore, the convenience of this system is hampered by the necessity of downloading the exposure data at the end of the day. Another example is the SV102+ dual channel noise dosimeter developed by Svantek Sp. z.o.o. This noise dosimeter is designed so that simultaneous measurements of noise both outside and inside earmuff-type hearing protectors can be made using a MIRE microphone. The system includes octave and 1/3-octave analysis capabilities as well as audio events recording but is limited to earmuff-type HPDs or measurements in the unoccluded ear. The use of MIRE microphones to monitor noise in the ear canal, combined with advanced signal processing algorithms has gained popularity in the recent years. A recent product developed by Eers Inc shows the potential of such approach for in-ear monitoring. In their product, an earplug is instrumented with a dual microphone system to measure the exterior noise as well as the noise in the ear canal. The measurements are used in real-time and combined with communication capabilities. This prevents the worker from removing its protector to communicate in noisy environments, thus, expectantly, reducing hearing loss damages.

## 3. Some recent developments on in-ear noise dosimetry

As presented in the previous section, in-ear dosimetry systems have been recently developed and used with some success in the workplace. However, although advanced capabilities can be found in such systems, a few challenges remain to be tackled. The next sections present some of the challenges that are studied in an ongoing research project.

### 3.1. Equivalent diffuse/free field acoustical corrections

Noise exposure limits rely on noise measurements collected in the absence of the worker or close to him using a SLM or a PND. With in-ear dosimetry, measurements are made inside the ear canal at some distance of the tympanic membrane. Such in-ear measurements may differ considerably from their "free-field" counterparts as they are affected by various acoustical resonance and amplification effects. Therefore, acoustical corrections must be applied to in-ear measurements if one is interested in comparing those with diffuse/free-field measurements following noise regulations. These acoustical corrections are mostly due to the Transfer Function of the Open Ear (TFOE), as well as the Microphone to Eardrum Correction (MEC). The TFOE represents the amplification of the sound pressure caused by the resonance in the open ear canal, which varies with the geometry of the human head, torso, pinna, and shape of ear canal as well as eardrum impedance. The MEC is mostly dependenton the length of the probe tube used in the in-ear dosimetry device and on the length of the residual part of ear canal between the earplug and the eardrum. Such correction factors, both dependent on the user's morphology, also depend on the direction of the sound field. They are essential for comparison with noise regulations since most noise criteria are expressed as free-field or diffuse-field values. Estimates of such corrections have been derived from measurements on a head and torso simulator [6] or from groups of subjects[7], [8], but future instrumentation would benefit from individualized factors that can take the high variability of the mentioned ear characteristics into account. In this project, a method based on earcanal microphone measurements was developed to identify better estimates of the above-described correction factors. Individualized factors have been derived and validated against results obtained on a set of human subjects using a probe-microphone inserted close to the tympanic membrane. Additionally, tests in various types of noise demonstrated the importance of these corrections with regard to the associated overall exposure levels. Preliminary results will be presented in the accompanying presentation.

### 3.2. Wearer's own internal noise

The noise induced in the ear canal by the HPD user himself was clearly identified by several authors as an important noise source in medium-level noise environments[2], [6]. This can be caused either by low-frequency noise generated by movements from the wearer or by his own voice that directly contributes to the recorded noise levels inside the ear canal. Whether these internal noises contribute or not to hearing loss is debatable and still a subject of research, but the effect is deemed important enough by the authors to warrant the development of an automatic detection method to discriminate such time events. An algorithm that simultaneously uses the external and internal microphones was developed and proved to be efficient in detecting internal noise events in various noise and signal-to-noise conditions.

### 3.3. Effects of ear canal occlusion on hearing sensitivity

The question of whether varying the acoustic load applied to the ear canal when wearing a HPD might impact hearing sensitivity is essential if one needs to establish realistic noise damage risk criteria. Some researchers have raised questions about the potential influence of ear occlusion on noise susceptibility. According to Theis et al.[9], "human subject data is extremely important in developing and validating calibration factors for any type of noise dosimeter but particularly so for in-ear dosimetry". This statement comes along with data (see also [10]) supporting the idea that in-ear dosimetry overestimates the noise dose and that correction factors should be used to account for a shift in the sensitivity of the hearing system due to the occlusion of the ear canal. To verify this finding, the authors conducted a study involving loudness-balance tests performed on a group of human subjects[11]. Using an earplug to occlude the ear canal, in-ear SPLs were compared between the occluded ear and the unoccluded ear at equal loudness. Results of this study support the idea that there should be no difference in loudness perception between the occluded, cushioned or open ear.

### 3.4. Hardware implementation

Two digital devices were developed within this project: an open-type earpiece for use on an unprotected or earmuff-protected ear and an earplug-type earpiece as illustrated in Figure 1.

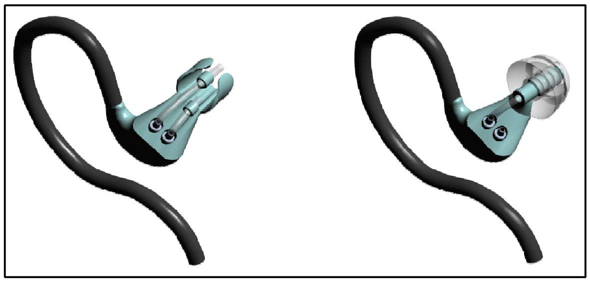

Figure 1. Open type (left) and earplug type (right) earpieces for in-ear dosimetry measurements

The two earpieces each consists of miniature FG Series electret microphones (Knowles, Itasca, IL) connected to probe tubes measuring sound pressure signals occurring at approximately 8 mm past the ear canal entrance when fully inserted. A calibration procedure was developed to establish the effect of the probe tubes. The two earpieces can be connected to a recording and signal processing device that can clip to the belt. The device, still in development, should comprise the DSP, microcontroller and memory card, along with necessary analog-to-digital converters. The whole system must be efficient and powerful enough so that complex calculations (fft, fractional-band analysis, etc.) can be performed in real-time and meaningful data can be stored over workshifts.

## 4. Conclusions

This paper presented the development of two earpieces designed specifically for in-ear dosimetry measurements. The two earpieces allow noise dosimetry measurements to be made in protected or unprotected ears. Some challenges and advantages related to in-ear dosimetry were presented. In the long run, it is expected that such measurement device will provide the user with real-time feedback on personal noise exposure, complying with standardized practices and providing advanced features such as the effect of the contribution of the user's inner noise on the measured noise dose. It should enable collecting large individual datasets, thus improving our knowledge of noise-induced hearing loss in the workplace especially if audiometric data are collected in parallel[12].

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