DOI: 10.61782/fa.2025.0958

VIRTUAL AND EXPERIMENTAL ACOUSTICAL COMFORT TESTERS FOR EARPLUGS

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ABSTRACT[*]

Earplugs are widely used to prevent noise-induced hearing loss, but discomfort can reduce their effectiveness by affecting their consistent and proper use. Earplug comfort can be described by four dimensions: physical (biomechanical and thermal interactions with the earcanal), acoustical (noise/useful sound perception), functional (usability and efficiency), and psychological (well-being and satisfaction). (Dis)comfort results from the interplay within the user/earplug/work environment triad. The components of this triad and their interactions across multiple phases, ultimately shape the comfort judgment and are defined by various physical and psychological characteristics that must be assessed to fully understand comfort. This paper targets acoustical characteristics of both disposable and reusable earplugs when inserted in the earcanal, focusing on indicators such as sound attenuation and occlusion effect. It presents a synthesis of various acoustic comfort testers developed by the authors' research team to assess these characteristics. Virtual and physical truncated realistic artificial ears and whole head are explored. This research aims to provide manufacturers with comfort-driven design methods for earplugs.

Keywords: *earplugs, comfort, sound attenuation, occlusion effect*

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1. INTRODUCTION

Earplugs are commonly used to prevent noise-induced hearing loss, but their effectiveness can be compromised by discomfort, which affects consistent and proper usage. Comfort is a complex concept that encompasses multiple dimensions, including physical (biomechanical and thermal interactions), acoustical (related to noise perception), functional (usability and efficiency), and psychological (well-being and satisfaction) aspects [1].

The perceived (dis)comfort of earplugs results from the interplay between the user, the earplug, and the work environment—an interaction framework known as the "triad" [2]. Various intrinsic physical and psychological characteristics associated with each triad component, interact across several phases (fitting, interaction, internal human body effects, and perceived effects), ultimately shaping the comfort judgment [3]. Examples of physical factors include the earplug's design parameters (shape and material properties), the user's earcanal (EC) morphology, hand dominance and hearing loss condition, and the work environmental conditions. Examples of psychological characteristics involve the earplug's attractiveness or aesthetic design, the user's sex, age and prior experience with earplugs, as well as the nature of the work environment and required physical activity. During the interaction phase of the comfort model, the earplug interacts with the user's EC, leading to additional physical characteristics of the EC/earplug system, that can influence comfort [4]. Examples of such characteristics are the static mechanical pressure exerted by the earplug on the EC and the sound pressure field in the EC.

Understanding these physical and psychosocial influences is essential for enhancing earplug effectiveness in noise protection. Incorporating comfort considerations into earplug design and selection can help ensure better compliance and protection for individual workers in different occupational settings. However, measuring comfort-related characteristics presents challenges, as objective and quantifiable indicators must be established for laboratory and field assessments.

This paper specifically explores the acoustical comfort of earplugs, focusing on the determination of key physical characteristics of the "EC/earplug" system in the interaction phase.

Acoustical discomfort from earplugs is primarily characterized by two conceptual acoustic sub-dimensions associated with the perception of “External Noises” (i.e. intelligibility of useful sounds) and “Internal Noises” (i.e. occlusion effect) [5]. Physical objective characteristics of the system “EC/earplug” that can impact these two sub-dimensions are the sound attenuation and the occlusion effect (OE) of the earplug [6,7]. The sound attenuation refers to the ability to block the incident noise and can be quantified by the insertion loss (IL). The OE is often described as an amplified and distorted perception of physiological noises, such as one’s own voice, which may sound boomy or cavernous, particularly at low frequencies, when the EC entrance is obstructed. This effect results from both an increase in sound transmission through tissues (skin, cartilage, bone), primarily at frequencies below 1 kHz, and a decrease in air-conducted sound transmission due to the presence of the occlusion device. The OE can be objectively measured by calculating the difference between the sound pressure levels in the open ear and the ear occluded by the earplug when stimulated by tissue conduction, either through physiological noises or a bone conduction transducer.

The sound attenuation and OE can be measured directly on human subjects or using original laboratory tools, called "comfort testers". These testers are intended to help manufacturers improve the comfort of their earplugs by knowing the objective characteristics that influence comfort, but by freeing themselves from participants. This is similar to what is done to estimate the acoustic performance of the protector by measuring its acoustic attenuation in the laboratory on artificial heads (also called ATF for "Acoustic Test Fixture" in English), equipped with an ear simulator. These earplug comfort testers can operate in the real world using physical sensors — we then speak of an "experimental" tester — or in an idealization of the real world using virtual sensors — we then speak of a "virtual" tester. In the latter case, we refer to an analytical or numerical model capable of predicting the physical characteristics of interest. A virtual tester can be useful to (i) better understand the physical mechanisms involved in the triad, (ii) study the effect of various factors on the quantity of interest (acoustic or mechanical), (iii) help design real-world testers.

Commercially available ATFs fail to assess key physical characteristics related to acoustic comfort, as they do not account for essential features such as realistic EC geometry and various tissue conduction paths that influence the sound pressure field in the EC induced by external or internal sound sources [8,9]. As a result, they are unable to capture intra- and inter-individual variability in these characteristics. These reasons make them unsuitable for evaluating sound attenuation and OE from a comfort perspective [10]. Therefore, developing more realistic testers is crucial to accurately replicating the EC/earplug system under both acoustic and mechanical excitations.

This paper provides a comprehensive synthesis of various virtual and experimental testers developed by the authors’ research team to assess sound attenuation and OE, both of which could influence acoustical comfort. These testers can be classified into two categories, distinguished by the level of geometric simplification they consider: (i) truncated ears of various anatomical complexity that consider a region of tissues surrounding a simplified or realistically shaped EC, including or not the pinna and (ii) whole head.

The synthesis presents key principles, selected example results, and limitations of each comfort testing method, starting with experimental and virtual testers for sound attenuation and followed by an analysis of those for the OE.

2. EXPERIMENTAL AND VIRTUAL TESTERS FOR SOUND ATTENUATION

2.1 Realistic truncated ears (Fig.1(a), (b) and (c))

The first tester, shown in Fig.1(a), includes an experimental version and its virtual counterpart. It features a realistic EC and surrounding tissues [11] reconstructed from medical images of a participant. The synthetic materials were selected for their mechanical properties, close to those of biological tissues. The experimental tester, manufactured by a company specializing in anatomical phantoms, includes an embedded microphone positioned at the eardrum but lacks an eardrum simulator. The tester evaluation was based on comparing the predictions provided by the virtual tester with those obtained using the associated experimental tester, both in the open ear and in the ear occluded by a cylindrical steel earplug. The latter has the advantage of being non-deformable and having well-characterized mechanical properties. Although the numerical model generally reproduces the trends observed experimentally, particularly in terms of pressure levels in the open and occluded ear as well as attenuation (not shown here), some differences persist in certain frequency bands. A calibration of the material properties in the finite element model could improve this correspondence. Furthermore, the steel earplug poses challenges related to the contact conditions with the surrounding tissues. The use of a more conventional earplug, such as a molded silicone earplug, could facilitate the evaluation of the tester. Finally, the simulated IL follows a similar evolution to the attenuation curves measured on human subjects: an increase in attenuation up to the resonance frequency of the open canal, followed by a decrease.

The experimental tester was also evaluated against a reference participant who served as a model of the artificial ear and a commercial ATF. Attenuation measurements for 2 types of earplugs were conducted using the 3M E-A-Rfit system at 3 insertion depths. Results (not shown here) show that the artificial ear better replicate attenuation for roll-down foam earplugs than commercial ATF. However, for push-to-fit earplugs this remains challenging for both. Discrepancies between the virtual tester, the experimental tester, and participant measurements may be attributed to several issues with the experimental tester. These include: (i) material defects—such as degradation of the soft-tissue analogs in the EC due to overly thin walls and irregular surface conditions—that can induce acoustic leaks (ii) insufficient self-IL of the artificial ear, (iii) the fact that synthetic materials at room temperature mimic biological tissues at body temperature, leading to potential deviations (iv) the absence of a heating system which may affect the earplug's behavior and the lack of a eardrum simulator.

To circumvent some of the issues associated with the previous truncated artificial ear (manufacturing defects and self-IL), a simplified version, devoid of cartilage was considered (see Fig.1(c)). It was designed based on a different participant and manufactured at the ICAR laboratory using 3D printing and a soft tissue molding technique. This artificial ear is integrated into a cylindrical metal housing, simulating an artificial head, to limit parasitic transmissions through the side and rear walls of the artificial ear. Preliminary results (see Fig.2) show that the attenuation of the earplugs measured with the artificial ear is lower at low frequencies than that observed on the corresponding human participant, regardless of the insertion depth. At higher frequencies, the results are closer but may be higher or lower depending on the insertion depth. These discrepancies may arise from (i) an overestimation of tissue conduction due to the use of a single homogeneous, overly soft material to represent soft tissues, (ii) the absence of a heating system, (iii) the fact that artificial materials at room temperature mimic biological tissues at body temperature, and (iv) the lack of cartilage and an eardrum simulator.

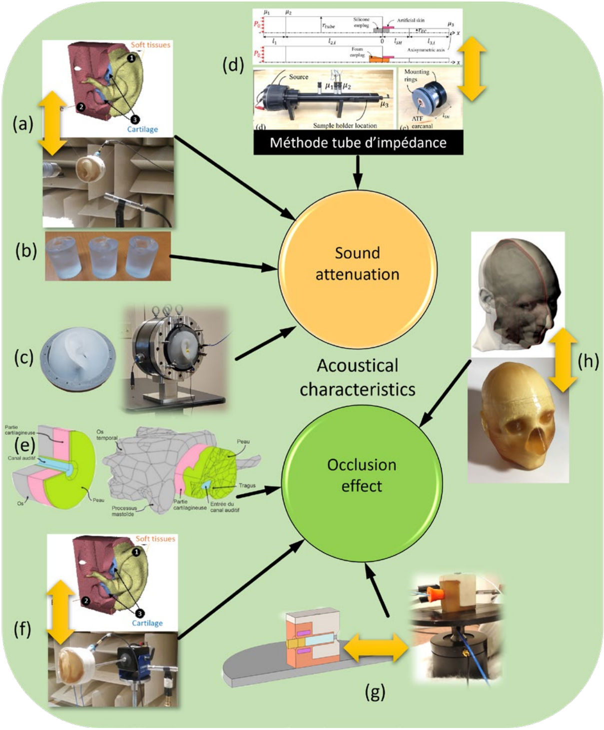

Figure 1. Experimental and virtual testers to assess acoustical physical characteristics of the coupled system EC/earplug

The testers of Fig.1(a) and (c) replicate the artificial ear of a specific individual. In contrast, the experimental tester in Fig.1(b) was designed to incorporate multiple artificial ears with realistic EC geometries but a simplified anatomical structure, adapted to the measurement of sound attenuation and representative of a sample of workers. An anthropometric analysis of a sample of ECs made it possible to identify three groups characterized by distinct morphologies [12]. For each group, the EC closest to the barycenter was selected as a representative model. Three artificial ears were thus manufactured using 3D printing, using a soft elastic resin of Shore 00 = 90 at room temperature. Heated to 37 ° C, these ears were evaluated for several earplugs using the 3M E-A-Rfit system, comparing them to measurements taken on participants during field training sessions. For each earplug, eight measurements were made, with insertions varying between standard depth and deeper insertion. The results (not displayed here) show that the ranking of sound attenuation obtained with these artificial ears is generally consistent with that observed in participants. However, while these testers satisfactorily represent the attenuation variability measured for pre-molded earplugs, they have limitations for roll-down foam earplugs and pre-molded foam with stems, where significant amplitude differences occur. These differences could be attributed to the excessive rigidity of the artificial tissue, the absence of cartilage and artificial eardrum, and potential parasitic transmissions through the lateral and rear sides of the truncated ears.

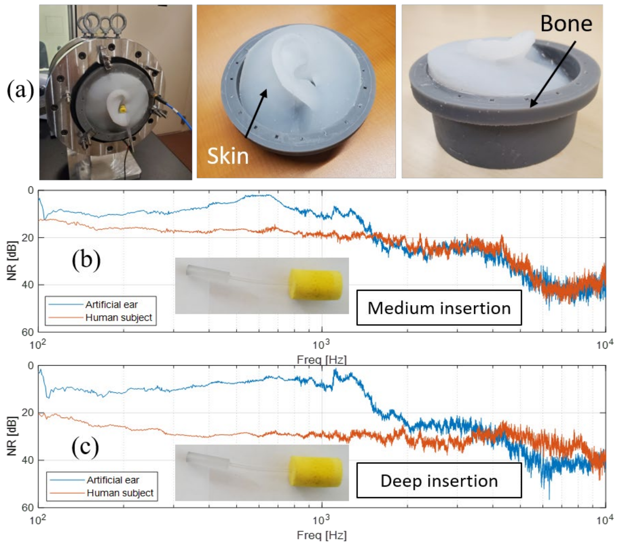

Figure 2. (a) Zoom on tester, noise reduction of a surrogate roll-down foam earplug measured with artificial ear and participant for (b) medium and (c) deep insertion.

2.2 Simplified truncated ear and the use of an impedance tube (Fig.1(d))

Although commercial ATFs are useful for assessing the sound attenuation of earplugs, they have drawbacks. They are costly and require expensive and bulky experimental setups, such as reverberation or anechoic chambers; they typically use a single-size EC, which does not account for variations in EC morphology between individuals and can result in significant differences in personal attenuation. Finally, commercial ATF measurements provide limited understanding of how the intrinsic acoustic properties of earplugs influence attenuation.

To address these challenges, a method for estimating earplug sound attenuation has been developed along with an associated experimental tester [13]. The technique allows to determine the acoustic properties of an earplug (transmission and reflection) inserted in a simplified truncated ear, consisting of a cylindrical artificial EC with a skin layer, all placed in an impedance tube. These acoustic properties are obtained from acoustic measurements upstream and downstream of the truncated ear, as well as using two separate acoustic loads. The measured earplug acoustic properties are then used as inputs to a one-dimensional analytical model to calculate the IL of the earplug. The latter is decomposed into two terms: the transmission loss (TL), which depends only on the physical objective characteristics of the "EC/earplug" system namely, mechanical properties of the inserted earplug and surrounding soft tissues as well as insertion depth, and a correction term, which depends on the reflection coefficients of the earplug medial face, the entrance to the EC and the medial termination of the EC.

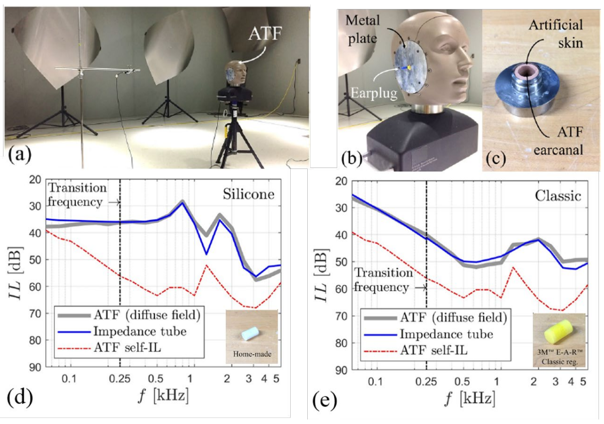

Figure 3. (a) ATF placed in the reverberant room, (b) zoomed-in view of the ATF, (c) ATF EC, Third octave band IL measured on ATF and estimated using the proposed impedance tube method for a silicone earplug (d) and roll-down foam earplug (e). The self-IL of the ATF is also displayed.

In parallel, two virtual testers (not shown here), based on numerical FE models of the experimental tester and an ATF, were developed to test the approach. The first simulated measurements to estimate the earplug's acoustic properties, which were then used in the one-dimensional analytical model to calculate the IL. The second simulated the IL on the ATF, allowing numerical evaluation of how the excitation field (normal incidence plane wave versus diffuse field) affects sound attenuation. The one-dimensional analytical model used to calculate the IL from the acoustic properties of the earplug was verified using the results provided by the previous virtual tester, which acted as a reference. The results obtained with the two testers agree and indicate that the attenuation of an earplug obtained in the tube is representative of that measured in a more realistic acoustic field. Furthermore, experimental comparisons, on various types of earplugs, between the results obtained with the proposed measurement technique and those from a commercial ATF (see Fig.3) further validates the method. The main limitation of the method concerns its working frequency range determined by the tube diameter (about 6.5 kHz for a diameter of 29mm).

This impedance tube method offers several advantages over ATFs: (i) the technique uses a commercially available impedance tube, thus eliminating the need for an ATF (including the ear simulator) and an acoustic chamber, (ii) the method allows easy integration of different EC geometries using different sample holders, (iii) the method decomposes the earplug's IL into two a TL and a factor influenced by the acoustical characteristics of both open and occluded ear canals, providing deeper insight into sound attenuation and enabling more effective control, and (iv) the method enables the direct incorporation of eardrum impedance variability during post-processing by allowing the calculation of earplug attenuation for any tympanic acoustic impedance once its transmission and reflection properties have been determined.

3. EXPERIMENTAL AND VIRTUAL TESTERS FOR THE OCCLUSION EFFECT

3.1 Truncated ears (Fig.1 (e-g))

Virtual truncated ear testers, shown in Fig.1(e) and consisting of both lumped and FE models, were used to gain deeper insight into the fundamental physical phenomena underlying OE. These two modeling approaches are complementary. FE models supply input parameters for lumped models, while the latter offer a practical framework for interpreting FE simulations. For the FE testers, the set of mechanical boundary conditions and applied excitations was adjusted to reproduce a plausible vibration pattern of the EC wall [14] or to obtain simulation results consistent with experimental data from the literature on OE measured on groups of human subjects [15,16]. The virtual testers showed that OE occurs because blocking the EC creates a closed air cavity between the occlusion device and the eardrum, making it harder for the EC walls to compress it, which increases the acoustic pressure generated in the occluded EC. These models also allowed to revisit and clarify the interpretation commonly adopted in the literature of the OE—notably the influence of the high-pass filter of the open EC and the way in which this effect is modified by its occlusion—an interpretation which, although widespread, suffers from several ambiguities [17]. The first 3D numerical models of truncated cadaveric ears made it possible to highlight the influence of the vibration distribution of the EC wall on the OE [14]. The spatial distribution of the normal vibration of the open EC was characterized, at low frequencies, by the position of its barycenter along the curvilinear axis of the EC [18]. The axisymmetric 2D FE models then made it possible to study the mechanisms of contribution of earplugs to the OE [15,16]. Two mechanisms were highlighted: (i) a Poisson effect induced by the normal component of the parietal vibration of the EC and (ii) a longitudinal movement caused by the tangential component of this vibration.

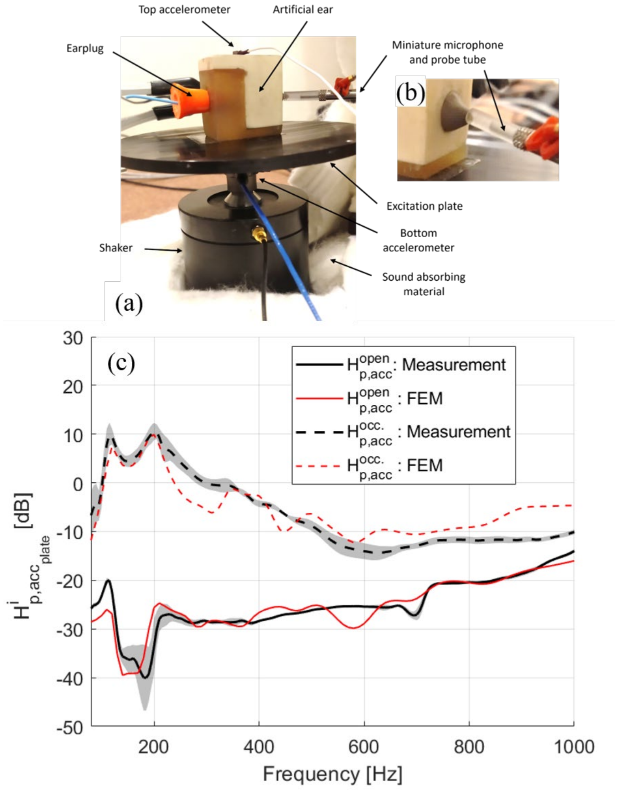

Figure 4. (a) View of tester of Fig.1(g), (b) rear view of the tester, (c) comparison between virtual and experimental tester - transfer functions between eardrum sound pressure and acceleration of excitation plate for open and occluded ears

The virtual tester presented in Fig.1(f) has been partially validated against its experimental counterpart [8,16] in the case of the steel earplug also used in section 2.1. The simulation of the objective OE approximately reproduces the slope of the measured data. However, significant deviations remain in some frequency bands. These discrepancies are attributed to differences in material properties, boundary conditions, coupling conditions or applied loads, between the experimental setup and the

simulation. For other types of earplugs, the validation of the virtual tester was not successful. Furthermore, the evaluations of the experimental tester against groups of participants did not give satisfactory results. Finally, the experimental tester was not directly confronted with the human subject from which it was designed.
To address the challenges associated with the tester shown in Fig.1(f), a new tester based on it and illustrated in Fig.1(g) was designed to simplify the validation process [9]. A virtual tester was developed first, followed by the manufacturing of its experimental counterpart (without artificial eardrum and heating system). The ear canal was reshaped into a straight cylinder with a circular cross-section, and the external boundaries of the truncated ear were modified into a parallelepiped form. The proportions of soft tissue, bone, and cartilage volumes were preserved relative to the realistic 3D artificial ear. Careful material selection and precise manufacturing ensured the faithful reproduction of key features essential for studying the OE. It also integrates excitation and boundary conditions that are more easily mimicked in the virtual tester. Its parallelepiped shape also facilitates experimental manipulations.
After rigorous calibration, the virtual tester was successfully validated against the experimental tester, in particular by comparing the transfer functions between eardrum sound pressure and acceleration of excitation plate for open ear and ear occluded by a silicone earplug (see Fig.4 (c)). The experimental tester was also successfully evaluated against measurements made on a group of participants. This device was shown to reproduce the main effects observed in OE measurements of several earplug types on participants, including (i) significant OE at low frequencies, decreasing with increasing frequency, (ii) reduced OE for deeper earplug insertion, and (iii) differences in OE between earplug types, particularly marked for deep versus shallow insertions. A numerical study also highlighted that the absence of cartilage significantly amplifies OE at low frequencies. Furthermore, the position of the cartilage influences OE, particularly when the artificial ear upper part is fixed. This tester was notably used to validate an innovative metamaterial earplug with reduced OE [19,20] which was then tested regarding perception and comfort judgment on human subjects [7].
The main limitations of this tester are the presence of parasitic structural resonances, which are not representative of what happens in a real head and the dominance of the air-conducted path over the bone conducted one when the EC is open in some frequency bands, potentially leading to an underestimation of OE compared to measurements on participants using a bone transducer.

3.2 Whole head (Fig.1 (h))

Two virtual testers based on the FE method and one experimental tester were developed from magnetic resonance images and computed tomography scans of a participant's entire head. The medical images were segmented using image processing software to reconstruct various anatomical structures of the head, namely soft tissues, auricular cartilage, bone, brain and cerebrospinal fluid, excluding middle and inner ears.
The first virtual tester, representing the participant (Virtual Participant), integrates tissue properties based on scientific literature and accounts for the acoustic effect of the middle and inner ear via an acoustic impedance boundary condition at the eardrum. The second, called Virtual AP-ATF is the counterpart to an experimental tester called augmented physical ATF (AP-ATF) made of artificial materials of known mechanical properties that mimic biological tissues. Unlike the Virtual Participant, neither the Virtual AP-ATF nor the experimental AP-ATF account for the acoustic effect of the middle and inner ear. Based on these testers, rigorous calibration and validation of the FE models used to simulate the physics are possible, as the simulations can be compared to measurements performed on the corresponding participant and on the associated AP-ATF [16].
The Virtual Participant tester was validated against experimental data from the literature on participant groups, as well as measurements on the participant used for its development (see Fig.5). It satisfactorily reproduces known effects, such as the reduction of OE with increasing earplug insertion depth and the influence of the earplug type on OE, particularly for deep insertions.
The Virtual AP-ATF tester was validated by comparing the simulated results with experimental data from the AP-ATF (see Fig.6). Although both testers were not calibrated, comparisons showed generally satisfactory results, with deviations of less than 5 dB. However, the results obtained with the AP-ATF show discrepancies compared to the measurements made on the participant. These differences could be due to the inadequacy of the synthetic materials used to reproduce biological tissues.
During the development of the virtual testers, several significant advances in modeling have been made [21,22] (i) the use of a perfectly matched layer improves the agreement of simulated results with experimental data, compared to a classical radiation impedance condition, (ii) the boundary conditions at the base of the head mainly influence the OE at very low frequencies (< 0.25 kHz), and (iii) modeling the external fluid and tympanic membrane's influence on the EC acoustic field using an impedance condition requires adaptation to account for the global

motion of both the EC entrance and the tympanic membrane. Otherwise, errors in the eardrum sound pressure can occur, especially when the EC is occluded.

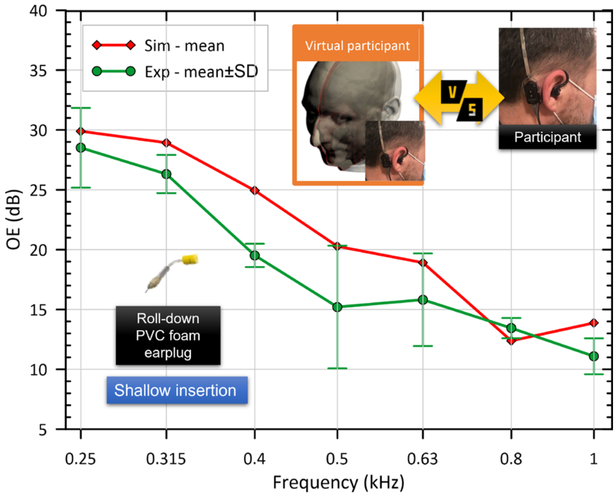

Figure 5. OE simulated using the Virtual participant and measured on the participant

The Virtual Participant tester was used to examine the effect of uncertainties related to several factors on the OE at low frequencies [21]:

• Position of stimulation on the head: the OE is not very sensitive to the global position of the stimulation (ipsilateral mastoid, contralateral mastoid, forehead). However, subtle variations in the stimulation position on the ipsilateral mastoid can contribute to the variability of the OE.

• Position of the measurement point in the EC: OE is little influenced by the exact position of the measurement point in the EC, especially for common earplug insertion depths. Differences between assessments performed at the medial surface of the earplug and at the eardrum are minimal, especially for medium or deep insertions. From an experimental point of view, these results suggest that OE, which is often measured at the medial surface of the earplug for safety and comfort reasons, is a good approximation of measurements performed at the eardrum.

• Mechanical properties of tissues: The stiffness of soft tissues and cartilage is a major factor influencing OE. This effect depends on the frequency band studied, with OE being more affected by the mechanical properties of soft tissues than by those of cartilage. At low frequencies, OE is sensitive to the skull bone Young's modulus, while the soft tissues Poisson's ratio also plays a key role.

Whole-head virtual testers provide more realistic FE simulations of EC vibration and sound pressure field than truncated ear models by accounting for full-head tissue conduction and eliminating boundary condition issues. Unlike other artificial ears used to assess the OE of earplugs [9], the whole-head tester allows for OE evaluation across different stimulation positions and can also be used for other hearing protection devices like earmuffs. However, the initial experimental prototype requires further refinement to better match participants' measurements.

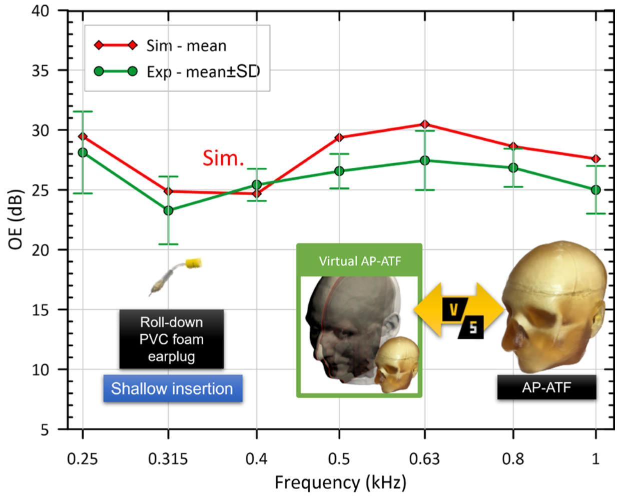

Figure 6. OE simulated using the Virtual AP-ATF and measured on the AP-ATF

4. CONCLUSIONS

This paper presented a synthesis of various virtual and experimental acoustic comfort testers developed by the authors' research team, designed to assess the sound attenuation and the OE of earplugs. While some testers are more advanced than others, they have collectively yielded promising results. Future work will focus on (i) optimizing synthetic materials to better replicate the EC/earplug interactions and tissue conduction, (ii) systematically integrating instrumentation (microphones, heating system and eardrum simulator), (iii) improve the knowledge about tissues and earplugs material properties, (iv) calibrating and validating sound attenuation and OE virtual testers, accounting for uncertainties, (v) incorporating inter-individual variability into both experimental setups and models and (vi) use whole-head virtual testers including middle and inner components to predict the differential intracochlear pressure and the subjective OE.

5. ACKNOWLEDGMENTS

We gratefully acknowledge IRSST (2015-0014), Mitacs (IT10643) and NSERC (RGPIN-2016-04926, RGPIN-2016–06795, I2IPJ 586099-2023), for funding this work.

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