Verifying the attenuation of earplugs in situ: variability of transfer functions among human subjects

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The use of in situ measurements of hearing protectors' (HPD's) attenuation following the MIRE-protocol (Microphone In Real Ear) is increasing. The attenuation is hereby calculated from the difference in sound levels outside the ear and inside the ear canal behind the HPD. Custom-made earplugs have been designed with an inner bore that allows inserting a miniature microphone. A thorough understanding of the difference, henceforth called 'transfer function', between the sound pressure of interest at the eardrum and the one measured at the inner bore of the HPD is indispensable for optimizing this technique and extending its field of application. Of particular interest is the variation of these transfer functions among humans.

This was checked experimentally on 19 subjects. Differences in sound pressure were measured at the HPD's inner bore, by the MIRE-microphone, and at the eardrum by inserting an extra tube microphone in the ear canal.

All transfer functions showed a comparable shape, however variability was substantial for the exact frequency and amplitude of the resonance peaks. The link between this variability and the morphology of the individual's HPD and ear canal was addressed using FDTD-simulations (Finite-Difference Time-Domain) of the outer ear canal occluded by an earplug with inner bore.

1   Introduction

Several studies clearly demonstrate that attenuation values of hearing protectors determined in laboratory conditions significantly exceed the actual protection offered to the individual user [1, 2]. In contrast, the European Noise Directive [3] on exposure limit values stipulates that the worker's effective exposure must take account of the attenuation provided by the individual hearing protector. Therefore, the performances of the hearing protection devices should also be verified in situ.

Different methods have been proposed [4], the MIRE (Microphone in Real Ear) approach for instance measures the attenuation in a quick and objective way [5]. This technique basically determines the difference between the incoming sound pressure level and the remaining level in the ear canal behind the hearing protector.

A critical issue when testing earplugs with the MIRE technique is the wire of the microphone measuring the sound pressure level in the ear canal behind the hearing protector. This wire might break the seal between the hearing protector and the ear canal's wall, causing leakage and yielding to an underestimation of the hearing protector's true attenuation.

To avoid this, a custom-made earplug has been developed with an inner bore that allows insertion of a miniature microphone, the measurement microphone, registering sound pressure levels inside the ear canal without altering the attenuation of the protector [6, 7]. In practice, this microphone is mounted in a probe that also contains a reference microphone measuring the sound pressure outside the ear canal (see Fig. 1).

An important aspect of this design is the possible difference, henceforth called transfer function, between the sound pressure of interest at the eardrum and the one measured at the inner bore of the hearing protector. Furthermore, the variation of these transfer functions between humans is of particular interest.

These issues can be addressed by simultaneously measuring the sound pressure at the eardrum and at the MIRE measurement microphone for a sample of volunteers. In addition, the influence of the morphology of an individual's hearing protector and ear canal on the transfer function will be assessed using FDTD simulations (Finite-Difference Time-Domain) of the outer ear canal occluded by an earplug with inner bore.
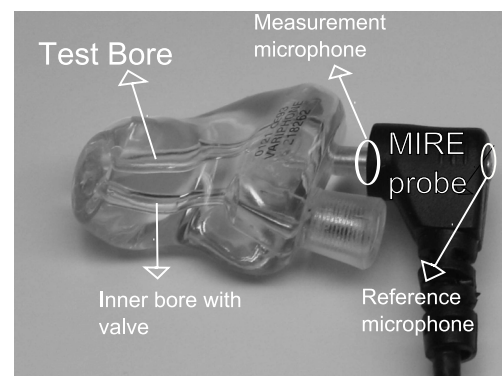

Figure 1: Earplug with two inner bores; one to adjust the attenuation with a valve and the test bore for insertion of the MIRE probe with measurement and reference microphone.

If the simulated and measured transfer functions are in good agreement for the sample under study, the transfer function for whichever user of these custom-made hearing protectors can be predicted using a particular set of morphological parameters.

2   General setup

This study has been approved by the Ethical Committee of the University Hospital of Ghent (Belgium).

2.1   Subjects

Nineteen subjects, 11 female and 8 male, between 18 and 48 years old are randomly selected from students and employees at Ghent University. Fifteen of them were inexperienced with respect to hearing protectors, none of them has a history of otological problems. All participated voluntarily and signed an informed consent.

Before the MIRE measurements takes place, otoscopy is carried out and the hearing of the volunteers is tested with pure-tone audiometry performed by a qualified audiologist in accordance with the modified Hughson-Westlake technique. Audiometry takes place in a sound-proof audiometric cabin at the Audiology Center of the Department of Oto-rhino-laryngology of Ghent University Hospital, using a regularly calibrated

Orbiter 922 audiometer. All subjects have normal pure-tone hearing thresholds better than 20 dB HL for octave frequencies between 125 Hz and 8000 Hz.

Furthermore, the status of the middle ear is verified by carrying out tympanometry with a ZODIAC 901 tympanometer of Madsen Electronics. All ears show normal patterns, suggesting that the reflection of sound at the eardrum is not perceptibly influenced by abnormalities of the eardrum or middle ear.

2.2 Hearing protectors

Custom-made earplugs in hypo-allergic acrylic are made for each participant, based on an impression of the ear canal taken by a well-trained audiologist. The fitting of each protector is tested using an Attenuation Control Unit (ACU). Via the test bore, this device builds up a pressure of 10 mBar in the residual part of the ear canal behind the hearing protector. If this pressure holds stable for 2 seconds, the fitting of the hearing protector is considered satisfactory. If not, a new impression of the ear canal has to be made for a new hearing protector. This procedure is repeated until each participant has a pair of perfectly fitting hearing protectors.

Each hearing protector (Fig. 1) has two inner bores, one test bore and one second bore with a valve determining the attenuation. When the earplug is worn in normal circumstances, the test bore is closed. By contrast, when measuring the attenuation, the MIRE probe with measurement and reference microphone is inserted. The measurement microphone registers the sound pressure behind the hearing protector in the ear canal while the reference microphone captures simultaneously the incoming sound level. The difference between both levels indicates the noise reduction offered by the earplug. Previous measurements have shown that the attenuation of the hearing protector is not altered by the insertion of the probe [8].

The attenuation of the hearing protectors can be altered by changing the position of the valve. Since previous research has demonstrated that the actual attenuation does not seem to influence the transfer function [8], measurements are carried out with a completely closed and a completely open valve.

3 Measurement setup

Measurements of the transfer functions are performed by simultaneously registering the sound pressure at the MIRE measurement microphone and at the test subject's eardrum.

3.1 Material

All measurements are carried out in an anechoic room to prevent disturbances from sound reflection and background noise. Measurements are performed with a laptop PC connected to a four input channel data acquisition front-end of Brüel & Kjær (type 3560-C) linking all sound equipment. The signals from the microphones are registered by the Brüel & Kjær's Pulse Labshop software version 7.0. Linear averaging is carried out over

3000 samples and overloads are rejected. In the frequency range between 0 Hz and 10 kHz the responses are spectrally analyzed using FFT (6400 points).

The test stimulus is low pass filtered pink noise with a cut-off frequency of 12.8 kHz generated on the PC using Pulse Labshop software. The signal is then transmitted via the front-end and a Pioneer A-607 R direct energy MOS amplifier through a Renkus-Heinz (model CM 81) loudspeaker. The quality of the sound generation system is not critical since the sound signal will be calibrated out in all measurements. The signal is set sufficiently loud to ensure that the lower working sound limit of each microphone is exceeded. On the other hand, it is also verified that the test signals are not harmful to the participants' hearing.

As stated previously, the MIRE measurements are performed with a probe containing two Knowles low noise FG-3652 microphones. Since the focus of this project lies in the transfer function between the measurement microphone and the sound pressure at the eardrum, the response of the reference microphone is of less importance.

Further, a GN ReSound Aurical microphone is used to measure the sound pressure at the eardrum. This device consists of a flexible tube to be inserted in the ear canal, connected to an ear piece with microphone. According to the Aurical's manual, the tube is inserted 31 mm in the ear canal for male subjects and 28 mm for female participants.

Finally, a prepolarized free-field $1/2''$ microphone type 4189 (Brüel & Kjær) with preamplifier (type 2669C, Brüel & Kjær) is used to calibrate unwanted influences out of the measured transfer functions.

3.2 Calibration and signal processing

It is extremely important that the measured transfer functions reveal the true difference between the sound pressure at the MIRE measurement microphone and at the eardrum. Therefore the results should not be distorted by the microphones' characteristics nor by the test signal used in this study. A detailed description of the different calibration steps can be found in [8] of which an overview is given here.

First, the influence of the different microphones has to be mapped. This is done by measuring the frequency response function between on the one hand the MIRE measurement microphone and the free-field microphone (HC_{mf}) and on the other between the Aurical microphone and the free-field microphone (HC_{af}), using the following equation

$$H_{xy} = \sqrt{\frac{G_{xy}(k)}{G_{xx}(k)} \cdot \frac{G_{yy}(k)}{G_{xy}^*(k)}} \qquad (1)$$

where x and y are M,A,F respectively, H_{xy} is the frequency response, $G_{xx}(k)$ and $G_{yy}(k)$ are the autospectra, $G_{xy}(k)$ is the cross-spectrum and $G_{xy}^*(k)$ is its complex conjugate.

For these measurements, the free-field microphone is placed in front of the loudspeaker, mounted very closely together with respectively the MIRE measurement microphone and the Aurical microphone. This yields to

a calibration function for each microphone; HC_{mf} for the MIRE measurement microphone and HC_{af} for the Aurical microphone.

Further, certain singularities of the input signal may also not influence the outcome of the actual measurements. Hence, for each measurement, the frequency response function is again on the one hand calculated between the MIRE measurement microphone and the free-field microphone (H_{mf}) and on the other hand between the Aurical microphone and the free-field microphone (H_{af}), both based on equation 1.

Afterward, the transfer function between the MIRE microphone and the Aurical microphone (H_{ma}) may be derived by applying the following equation

$$H_{ma} = \frac{\dfrac{H_{mf}}{HC_{mf}}}{\dfrac{H_{af}}{HC_{af}}}. \tag{2}$$

3.3 Measurement sequences

At the beginning of each test day, all microphones are calibrated using the pistonphone 4228 from Brüel & Kjær. The test subject, the test ear oriented toward the loudspeaker, and the free-field reference microphone are placed symmetrically in front of the loudspeaker, the free-field microphone at the same height as the test ear. Further, otoscopy is carried out and it is verified that the test subject is able to insert his hearing protectors correctly by checking the fitting with the ACU. Subsequently the earplug is removed from the ear canal. Next, the tube of the Aurical is inserted at the appropriate depth by the investigator and the sound pressure at the eardrum for an unoccluded ear canal is measured. Finally, the earplug is replaced in the ear canal by the test subject, once with open, once with closed valve, the investigator places the MIRE probe at the test bore and leaves the room. Before each measurement, the response of the Aurical is investigated to make sure that the flexible tube is not squeezed by the earplug. After all measurements are carried out for one ear, the tube of the Aurical is disinfected.

It is worthwhile realizing that the tube of the Aurical breaks the seal between earplug and ear canal. This could be problematic if these measurements were intented to measure the hearing protector's attenuation, but this is not the case. In fact, this study is carried out to assess the difference between the sound pressure at the MIRE microphone and at the eardrum. Previous research has shown that the attenuation of the earplug does not seem to influence the transfer functions [8], hence altering the hearing protector's attenuation by placing a flexible tube in the ear canal is not considered an objection.

4 Numerical simulations

The sound pressure distribution in an ear canal occluded by an earplug with two inner bores is numerically simulated using the Finite-Difference Time-Domain or FDTD technique.

4.1 General characteristics

The key factor of the numerical FDTD simulation is in general that both pressure p and particle velocity $\mathbf{u}$ are discretised in Cartesian grids. These grids are staggered by shifting the grid for discretising $\mathbf{u}_\alpha$ over half of a grid step, $\frac{d\alpha}{2}$, in direction α with respect to the grid chosen for discretising p. In time, staggering is obtained by calculating p at $t = ldt$ and $\mathbf{u}$ at $t = (l + \frac{1}{2})dt$.

Boundary impedance of the form

$$Z = j\omega Z_1 + Z_0 + \frac{Z_{-1}}{j\omega} \tag{3}$$

can easily be implemented in the FDTD method [9]. Such boundary conditions will be used to model the earplug's and ear canal's material impedance.

In the numerical model of the occluded ear canal, two points of interest are defined where the sound pressure is registered, namely in front of the eardrum and at the end of the test bore where in reality the MIRE measurement microphone is placed.

In the modeling of the hearing protector, extra attention has to be devoted to the sound field in the two inner bores. Since these channels are very narrow, the effect of viscosity and heat conduction becomes potentially important. Because the bores have the same diameter for all earplugs, viscosity and heat conduction are included in each model.

Furthermore, all the participants are thought to have a normal outer and middle ear, based on their tympanometric and audiometric results. Hence, for the propagation of sound in the outer ear canal, the normal impedance of bone is included as boundary condition. This approximates the real-life situation where the hearing protector fills the cartilageous part of the outer ear canal and hence relevant sound propagation effects occur mainly in the ossicular part. For the influence of middle and inner ear the terminating impedance at the eardrum is based on the one-dimensional circuit model of the middle and inner ear by Kringlebotn [10].

4.2 Individual characteristics

Some characteristics of the hearing protector and the outer ear clearly depend on the individual under study, in contrast with the features described in the previous section. It will be verified whether this mostly geometrical variation can explain and predict the interindividual variation of the transfer functions.

First, the most striking features of the hearing protector that are thought to influence sound propagation, are accurately measured for each earplug. Therefore, the length of the test bore and second bore is measured with a digital caliper accurate up to 0.01 mm.

The end of the earplug toward the eardrum has also a particular shape for each individual. This tip of the hearing protector is not flat, but forms a very small pit in which the two inner bores end. The cross-section of this pit is in general more or less elliptic, but the length of the major and minor axis varies among individuals, as does the pit's depth. Moreover, the distance between the two bore's terminus differs between subjects, just like their distance to the pit's edge. Finally, the width
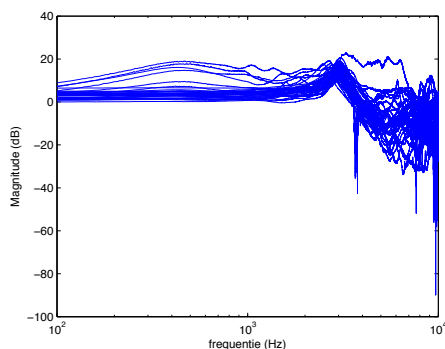
Figure 2: Magnitude of all measured transfer functions between the MIRE measurement microphone and the Aurical microphone at the eardrum for earplugs with open valve.

of the acrylic rim around the pit appears to be typical for each hearing protector.

To determine all relevant dimensions of the earplug's tip, measurements are carried out with the Coordinate-Measurement Machine (CMM) VM-250 Nexiv, manufactured by Nikon and accurate up to 0.1 μm.

The residual part of the ear canal between hearing protector and eardrum is for all participants modeled as a straight tube with uniform cross-section. The length of this tube is the difference between the length of the hearing protector and the length of the unoccluded ear canal. The former is measured with the caliper, the latter is estimated from the first maximum of the frequency response of the unoccluded ear [11]. The diameter of the ear canal is based on the earplug's diameter.

5 Results

From Fig. 2, it can be seen that the vast majority of all transfer functions appears to follow the same global trend with a distinct maximum in the frequency range between 2000 Hz and 3000 Hz and (multiple) minima for frequencies higher than 5000 Hz. However, substantial intersubject variability is observed between the amplitude of major pressure differences and the exact frequencies at which they occur [12].

Fig. 3 shows an example of the similarity between simulation and measurements for one particular ear. For the measurements that follow the global configuration, the simulated transfer functions neatly follow the shape of the corresponding measurements. Moreover, for each particular ear, the equivalent simulation adequately predicts the frequency and amplitude of the first maximum. The likeness for the frequency of the first minimum is also satisfying, but differences in predicted and measured amplitude are not seldom substantial. In the higher frequency regions, the resemblance seems to decrease for most ears.

For all 76 measurements (measurements with open en closed valves for 38 ears of 19 participants), 14 transfer functions differ substantially from the rest. By contrast, their corresponding simulations seem unable to predict these aberrations and do show the common shape.
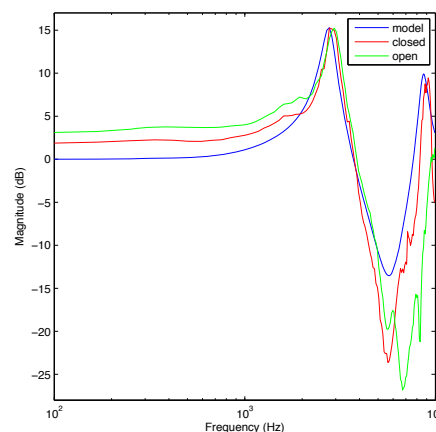

Figure 3: Example of similarity between simulation and measurements for one particular ear: magnitude of the measured transfer functions with open ('open') and closed ('closed') valve and magnitude of the simulated transfer function ('model').

6 Discussion

In general, the resemblance between simulations and measurements is satisfying for most ears. Hence the numerical FDTD simulations with geometrical parameters specific for each ear and earplug appear able to predict the true difference between the sound pressure measured by the MIRE measurement microphone and the sound pressure of interest at the eardrum. Naturally, there is still room for improvement, especially with respect to the increasing dissimilarity in the higher frequencies. A possible lead might be the shape and the length of the residual part of the ear canal behind the hearing protector.

Another issue is the influence of geometrical parameters included in the present model. To enhance the practical workability of this approach, it is important that only the essential geometrical measurements have to be made. Hence, the contribution of the different parameters to the accuracy of the model will be investigated.

A final topic are the deviant results apparent for some measurement situation. The main question is whether these results reflect a true transfer function between MIRE measurement microphone and eardrum, or, by contrast, whether they can be attributed to experimental error. If the former hypothesis can not be falsified, the model has to be redesigned to make sure that divergent transfer functions can also be predicted.

Despite these specific topics needing further research, it seems justified to believe that for whichever user of this particular kind of hearing protectors, the transfer function between sound pressure at the MIRE measurement microphone and at the eardrum can be predicted via numerical FDTD simulations with an individualized set of geometrical parameters. In this way, the MIRE measurement corrected with these simulated transfer functions can provide for each individual an accurate estimation of the effective exposure level when wearing these earplugs.

7 Acknowledgment

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