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Verifying the attenuation of earplugs in situ: comparison of transfer functions for HATS and human subjects

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ABSTRACT

Recent studies have clearly demonstrated that hearing protector's attenuation determined in laboratory conditions significantly exceeds the actual protection offered to the individual user. Hence, the performance of hearing protection devices should also be verified in-situ, for instance by the MIRE-method (Microphone In Real Ear). The attenuation is hereby calculated from the difference in sound levels outside the ear and inside the ear canal behind the hearing protector. To apply this technique without altering the protector's characteristics, a custom-made earplug with an inner bore that allows insertion of a miniature microphone can be used. However, this approach does not account for differences between the sound spectrum at the microphone and at the eardrum. Therefore, studies have been conducted with a head-and-torso-simulator and human subjects to determine the transfer function between these two points for protectors manufactured in acrylic and silicone. The use of different materials resulted in clearly distinguishable functions, but the characteristics of the spectrum in general correlated with the acoustical features of the earplug's design. All transfer functions showed a comparable global configuration, however variability among humans was substantial for the exact frequency and amplitude of the major pressure differences.

1 INTRODUCTION

Recent studies have clearly demonstrated that attenuation values of hearing protectors determined in laboratory conditions significantly exceed the actual protection offered to the individual user [1], [2], [3], [4]. Therefore, the performances of the hearing protection devices should also be verified in-situ. Different measurement techniques have been proposed [5]; the MIRE approach (Microphone In Real Ear) for instance offers a quick [6], [7] and objective way to evaluate the attenuation. Testing may be carried out with one or two microphones. In the single microphone technique, the receiver is placed in the ear canal during separate, consecutive measurements with and without a hearing protector. Using the two microphone technique, one is placed inside the ear canal underneath the hearing protector, the other measures simultaneously the sound level outside the ear. Both methods have proved to be successful with earmuffs [7], [8], but the application with earplugs often requires extra adaptations [9], [10], [11], [12]. By contrast, Voix and others [13], [14], [15], [16] describe a custom-made earplug with an inner bore that allows insertion of a miniature microphone registering sound pressure levels inside the residual ear canal portion. Since this test design becomes more widespread [13], [17], [18]

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a more thorough investigation of the underlying acoustical mechanisms is required, especially with regard to the spatial variation of sound pressure levels in the subject's outer ear canal and the earplug's inner bore. Of particular interest is the relation between the sound level measured by the MIRE-microphone at the inner bore and the level at the eardrum, since the latter is predicted from the former. Between these two points, an apparent difference is expected at certain frequencies since several authors report substantial pressure fluctuations even in an unoccluded ear canal [19], [20], [21].

This issue can be addressed by tests with a head-and-torso-simulator (HATS) consisting of a torso and artificial head equipped with pinna, ear canal and ear simulator mimicking the impedance of the eardrum at the end of the ear canal [22]. The main reason for working with these simulators is their ability to facilitate certain measurements more difficult to perform with human subjects. Hence, they allow testing in a very stable and controlled set-up. The HATS appears to give reproducible results, close to those obtained with other methods verifying the attenuation of hearing protectors [22], despite its impossibility to simulate all features of the human head and auditory system [23], [24], [25].

However, since the artificial character of the HATS can never be ruled out, measurements should also be carried out with human subjects to verify whether both test situations yield to similar results. In humans, the sound pressure at the eardrum may be registered by using an extra microphone inserted in the ear canal [10], [11].

The aim of this research project is to gain inside into the transfer function between the sound level measured at the inner bore of the hearing protector and the sound pressure of interest at the eardrum. In particular, it was investigated whether the pattern of the transfer function correlates with acoustical features of the earplugs' design and/or with the properties of the ear canal for both the HATS and humans.

2 MATERIALS AND METHODS

This section subsequently describes the relevant characteristics of the test subjects, the hearing protectors, the material, the general set-up and finally the measurement sequences for each hearing protector. Each subsection first deals with the settings for the HATS and secondly addresses the adaptations made for testing human subjects.

2.1 Test subjects

Eleven women and eight men between 18 and 48 year voluntarily participated in this study. None of the them had otological antecedents and most participants were inexperienced with respect to the use of hearing protectors .

2.2 Hearing protectors

The hearing protectors tested in this research project were manufactured especially for the HATS in acrylic and silicone (40 shore) with a range of attenuation values available for each material. Each hearing protector had two inner bores, one allowing insertion of a miniature microphone to perform the MIRE-measurement (the test bore), the other containing a filter or an adjustable valve determining the attenuation. This yielded to following groups of hearing protection devices; acrylic hearing protectors with adjustable valve and silicone hearing protectors with filters. The attenuation of the earplugs with valves could be varied between open and completely closed. Conversely, the attenuation offered by the filters was fixed at 65 lohm. The unit 'lohm' is used by The LEE Company [26] to reflect flow resistance of gases and is calculated by the following equation

$$\mathrm{Lohms} = \frac{\mathrm{K} \cdot \mathrm{f_T} \cdot \mathrm{P}}{\mathrm{Q}} \qquad (1)$$

with Q representing the gas flow, K the gas units constant, f_T a temperature correction factor and P the upstream absolute pressure.

All human subjects received one pair of acrylic custom-made earplugs with adjustable valve and for eight randomly selected participants an extra pair silicone custom-made hearing protectors with a 65 lohm filter was manufactured. Proper fitting was checked with an ACU-device (Attenuation Control Unit) that verifies whether a 10 mBar pressure sent via the test bore can remain stable for 2 s in the residual part of the ear canal behind the hearing protector.

2.3 Measurement system

The measurements were 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. Recording equipment consisted of two prepolarized free-field $1/2''$ microphones type 4189 (Brüel & Kjær) with preamplifier (type 2669C, Brüel & Kjær), one Knowles low noise FG-3652 microphone (the MIRE-microphone) connected to a 9 V preamplifier and the head-and-torso-simulator (HATS) type 4128 C of Brüel & Kjær with a dual microphone preamplifier (Brüel & Kjær, type 5935). All microphones were calibrated before each measurement sessions using the pistonphone 4228 from Brüel & Kjær. The test stimulus was low pass filtered pink noise with a cut-off frequency of 12.8 kHz generated on the PC using Brüel & Kjær's Pulse Labshop version 7.0. The signal was 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.

For the measurements with human subjects, an extra GN ReSound Aurical microphone was inserted in the ear canal to measure the sound pressure at the eardrum.

2.4 Set-up

Testing took place in an anechoic room to prevent disturbances from sound reflection and background noise, therefore the PC was placed outside and the room was only entered between two successive stimuli. The HATS and one of the free-field microphones were symmetrically placed in front of the loudspeaker at 1.61 m, see figure 1. The right test ear of the HATS was oriented toward the loudspeaker. The earplug of interest was placed in the HATS's ear canal and the MIRE-microphone was inserted at the earplug's appropriate bore at a fixed depth so that the microphone did not touch the pinna of the HATS (figure 2). The aim of the measurements was the determination of transfer functions between the microphone at the ear simulator of the HATS and the MIRE-microphone. However, these results should not be influenced by the typical characteristics of the microphones, nor by the features of the test environment and the test signal. Therefore, the responses of the microphones were compared with the simultaneously registered responses of the free-field microphone. Mounting the free-field microphone at approximately the same place as the HATS was impossible since reflections at the HATS's body disturbed the reference signal, yielding to the set-up described earlier. An extra measurement was carried out with the second free-field microphone replacing the HATS to calculate the transfer function between the two measurement points.

Test set-up with human subjects followed utmost the description above, except that both the ears were tested and hence the right and left ear were subsequently oriented toward the loudspeaker.

2.5 Measurement sequences and processing

The following steps were carried out for each hearing protector. The protector was carefully inserted, correct placement was visually inspected and the MIRE-microphone was slided in the

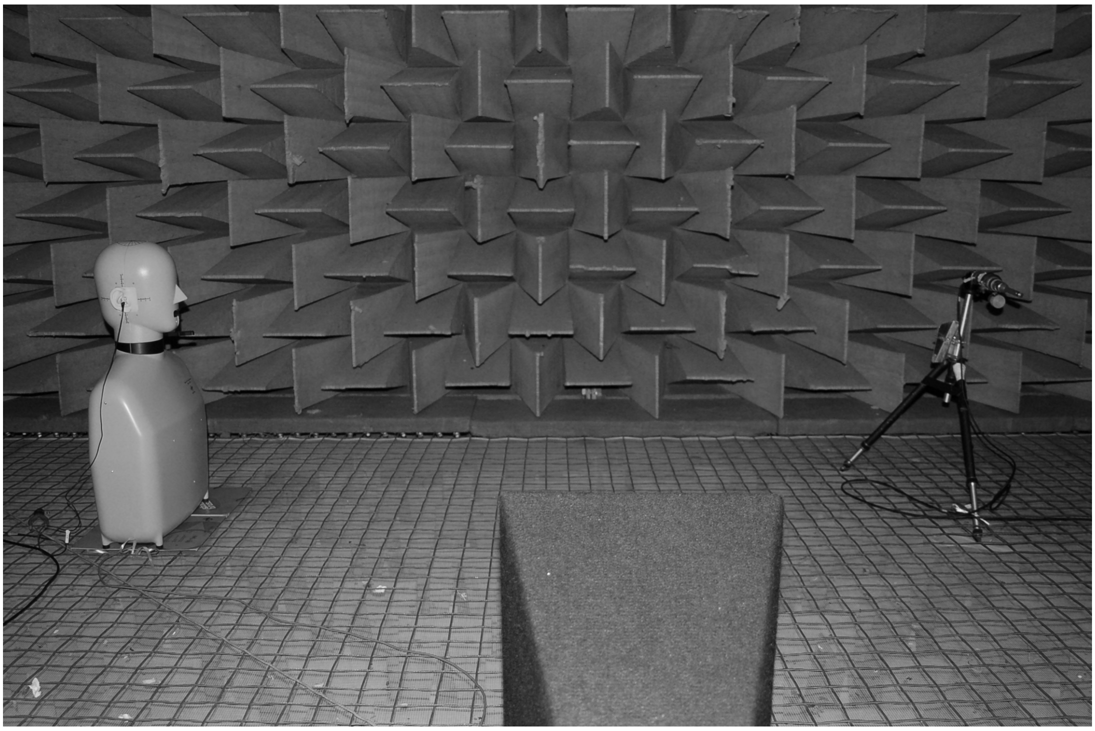

Figure 1: Test set-up with loudspeaker, HATS and free-field microphone.

inner bore. Subsequently, the position of the HATS was checked, the investigator left the room and the door was carefully shut. Each measurement was completely repeated in order to verify the reproducibility and to detect possible errors.

The signals from the microphones were registered by the Pulse Labshop software mentioned earlier. Linear averaging was carried out over 3000 samples and overloads were rejected. In the frequency range between 0 Hz and 10 kHz the responses were spectrally analyzed using FFT (6400 points). To eliminate possible artifacts described previously, the frequency response function was on the one hand calculated between the MIRE-microphone and the free-field microphone (HMF) and on the other hand between the HATS microphone and the free-field microphone (HHF) based on following equation

$$H = \sqrt{\frac{G_{xy}(k)}{G_{xx}(k)} \cdot \frac{G_{yy}(k)}{G^*_{xy}(k)}} \quad (2)$$

H being the frequency response, $G_{xx}(k)$ and $G_{yy}(k)$ the autospectra, $G_{xy}(k)$ the cross-spectrum and $G^*_{xy}(k)$ its complex conjugate. Afterward, the transfer function between the MIRE-microphone and the HATS microphone (HMH) was derived by dividing HMF by HHF.

With human subjects, the same procedures and calculations were carried out with the Aurical microphone at the eardrum replacing the HATS microphone, only preparation took some extra steps. First, the height of the free-field microphone was adjusted to the height of the test ear. Meanwhile, the participants were allowed to practice positioning the earplugs and correct placement was verified using the ACU-device. Subsequently, the earplug was removed to allow insertion of the GN ReSound Aurical microphone at a fixed depth in the ear canal (28 mm for female and 31 mm for male subjects), as prescribed by the microphone's manufacturer. Finally, the earplug was reinserted by the test subjects and the MIRE-microphone was slided in the appropriate bore by the investigator as described previously.

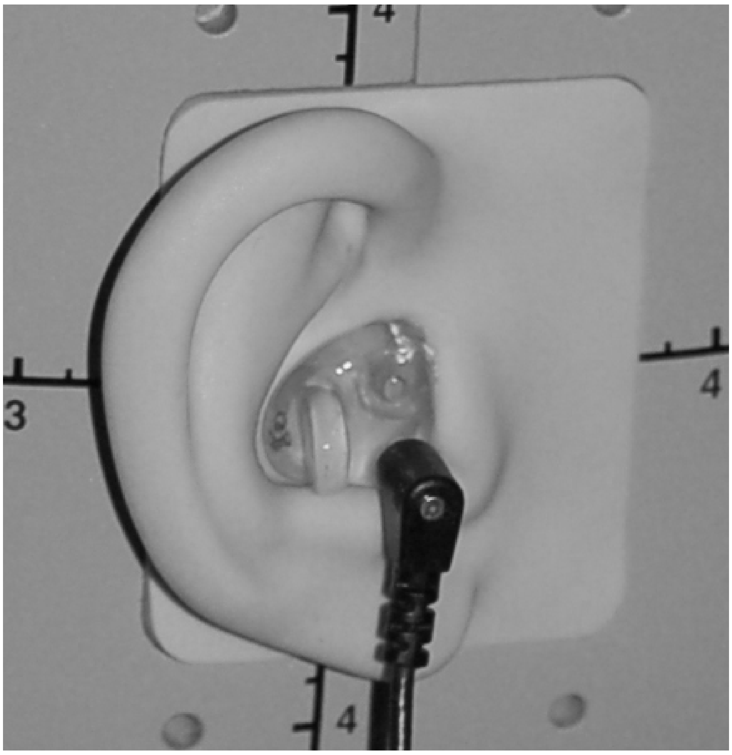

Figure 2: Test set-up with hearing protector and MIRE-microphone in ear canal HATS.

3 RESULTS

3.1 Transfer function between MIRE-microphone and HATS microphone

Examples of transfer functions (HMH) between the MIRE-microphone and the HATS microphone are depicted in figure 3.

The transfer functions between the MIRE-microphone and the microphone of the HATS are found to be flat in the lower and middle frequency region (up to 2500 Hz). Their amplitude increases above 2500 Hz with a clearly distinguishable peak around 3600 Hz for the acrylic earplugs and for silicone a plateau extending over a range of 3000 Hz. The length of the test bore suggests that this structure might be responsible for the observed resonances.

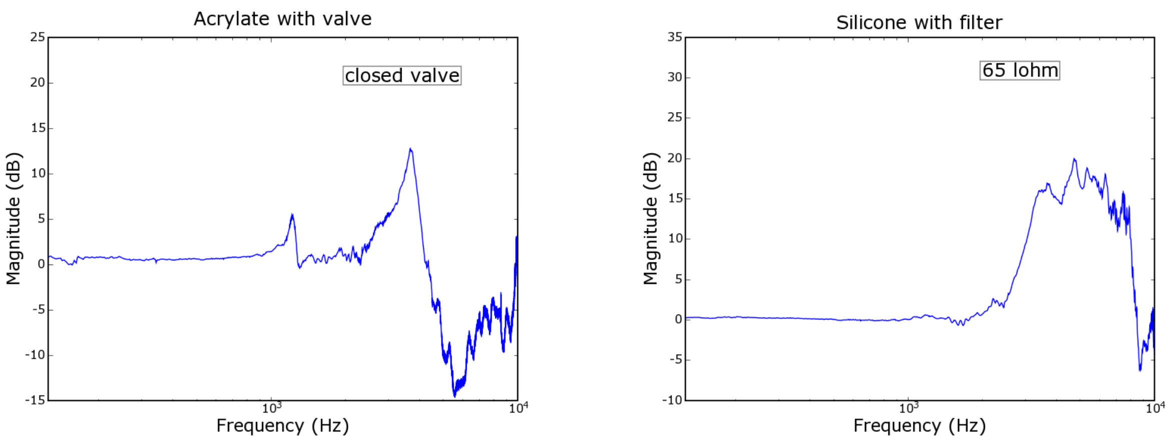

Figure 3: Transfer functions between the MIRE-microphone and the HATS's microphone.

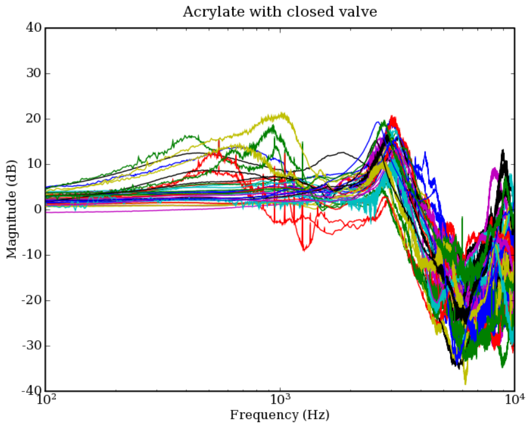

Figure 4: Transfer functions between the MIRE-microphone and the microphone at the subjects' eardrum.

In the higher frequency range, the transfer functions become less consistent with multiple small deviations, negative for acrylic and positive for silicone. However, for both types the most distinct variations were found between 5000 Hz and 6000 Hz. Since the HATS mimics the human auditory system, the structures responsible for these resonances might be found applying the characteristic dimensions of the human outer ear. From data reported by Tonndorf [27], the length of the residual volume between the hearing protector and the eardrum may be estimated at 16 mm, yielding to a resonance frequency of 5400 Hz. This finding makes the connection between the observed major variations and the residual volume of the ear canal likely.

The reproducibility of the test results was verified by comparing the results from repeated measurements. The responses of the MIRE-microphone appeared to be stable if the microphone was carefully placed. For earplugs made of acrylic, the reproducibility is within a 1 dB range in the frequency range from 300 Hz to 10 kHz, for silicone the same reproducibility is obtained for frequencies between 100 Hz and 2500 Hz. Outside this range, no variations greater than 2 dB were found.

3.2 Transfer function between MIRE-microphone and Aurical microphone

In general, good agreement was found between the global configuration of the humans' transfer functions and those of the HATS for both acrylic, with open and closed adjustable valve (see figure 4), and silicone. Furthermore, the within-subject reproducibility equaled the reproducibility of the measurements with HATS.

However, substantial intersubject variability was observed between the amplitude of major pressure differences and the exact frequencies at which they occurred. Combining the fact that the previous HATS analysis reveal a close relation between the transfer functions' spectrum and the characteristics of both hearing protector and ear canal with the knowledge that the morphology of the human outer ear varies among subjects leads to the hypothesis that variation in transfer functions between humans is caused by natural variations in the features of their custom-made hearing protectors and ear canals. Further research including accurate determination of the hearing protection devices' dimensions should reveal whether this line of thinking is valid.

4 CONCLUSION

The measurements with HATS and human subjects reveal a clear distinction between the sound pressure at the eardrum and at the MIRE-microphone attached to the inner bore of a custom-made earplug. Furthermore, it was shown that transfer functions can be obtained in a reproducible way and that the most striking features can be traced to the physical characteristics of the test design.

Despite the consistent global morphology of the human subjects' transfer functions, substantial intersubject variability was seen with respect to the exact frequency and amplitude of major pressure variations. Further research should clarify the relation between this individual transfer function on the one hand and the specific characteristics of the hearing protectors and ear canal on the other.

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