Determination of sound attenuation of ear-plugs using audiometers

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Summary

Audiometers or audiometer-like systems can be used to determine individual attenuation values of earplugs, e.g. in conjunction with standard hearing loss screening in hearing conservation programmes. In order to evaluate if the measured attenuation corresponds to the laboratory data according to EN 24869-1 (ISO 4869-1) the two methods were directly compared.

Data analysis on a group level of subjects showed significant differences for the lower frequencies between the two methods. Possible reasons are presented. The influence of physiological noise masking for the audiometric measurement could explain the results.

Moreover the sources of uncertainty for the two methods are discussed that need to be taken into account for the comparison of individual data.

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1. Introduction

Hearing protectors (HPDs) are used to reduce the sound pressure level at the ear of the wearer to a safe level. To select a suitable product the sound attenuation of a protector has to be known. The standard procedure, laid down in a number of testing standards around the world, is the so-called REAT method (real-ear attenuation at threshold). E.g. EN 24869-1 (ISO 4869-1) [1] defines a procedure with 16 test subjects whose hearing thresholds are determined twice, with and without the hearing protector under test. Measurements are done for eight one-third octave band noises at the octave band centre frequencies between 63 Hz and 8 kHz. The difference of the two thresholds is the sound attenuation. These values are averaged per frequency to give mean and standard deviation. From these numbers suitable values for selection of HPDs are calculated according to EN ISO 4869-2 [2], like the APV or HML and SNR values.
This standard requires a certain confidence level for the derived quantities. The European standards on HPDs (EN 352 series [3]) define a confidence level of 84 %, i.e. that for all calculated quantities the mean minus standard deviation over the 16 test subjects is used. From this follows that 16 % of the wearers will obtain lower attenuation values than the declared ones since the procedure is based on a statistical approach.
Moreover, EN 24869-1 and the EN 352 series aim at the determination of the optimum sound attenuation accomplished by experienced and thorough test subjects. It is known from a number of studies (e.g. [4][5]) that the real-world attenuation found in the field use of HPDs is in most cases significantly lower.
Taking into account these two facts, it seems promising to measure the sound attenuation of HPDs individually. On the one hand results could be used to check compliance with the relevant occupational safety and health regulation (EU directive 2003/10/EC [6]). On the other hand the HPD wearer could get a feedback on his/her habit of fitting the protectors with the possibility of optimisation and increased motivation. Also wrongly sized HPDs etc. could be identified. For the special case of custom-moulded earplugs the individual measurement allows to detect leakages due to errors in production of the plug. In Germany, such checks are required [7] (also air leakage tests are possible). As a further advantage of individual attenuation determination the frequency dependence of the attenuation could be checked to optimise communication abilities in noise.

2. Methods for the individual determination of sound attenuation

In the last years, a number of different systems have been brought to the market that allow the individual determination of sound attenuation, based on different measurement techniques like audiometry, loudness balancing or objective determination (MIRE, microphone in real ear).
The study presented here concentrates on audiometric or audiometry-based systems. Work in this field goes back some decades, mainly in the US (e.g. [8][9]). The principle of measurement is analogous to the REAT method: The hearing threshold is determined for the two situations with and without HPD for a certain number of frequencies. The threshold difference is again the attenuation. There are two approaches: a standard audiometer (preferably with circumaural earmuffs) or a custom-built headphone with suitable signal generating equipment.
In order to be able to compare the individual results with REAT values the relationship between these two measurement methods has to be established. It cannot be assumed straightaway that the attenuation values are identical since the acoustic situation for the measurements are different in several aspects (diffuse-field vs. headphone, one-third octave bands vs. sinus tones, threshold determination via Bekesy method vs. single ascending or descending measurement).

3. How to compare audiometric results to REAT values?

A direct comparison of REAT with audiometric measurements should answer the question if the two methods give comparable results or if some correction factors or data conversion are necessary. There are different approaches how to gain information: One can compare the individual data sets for REAT and audiometric systems one by one, e.g. using scatterplots [8][9]. Ideally the data points should lie on the bisecting line with slope 1 (one-to-one relationship). It is now possible to define permissible deviations from the identity relation by drawing parallel lines to the bisecting line with a distance of e.g. 5 or 10 dB. Alternatively one can calculate the linear regression of the data to get the numerical relationship between the two methods. The second approach is to compare only group averages, no individual results.
Both ways have advantages and disadvantages. An individual comparison is complicated by the inherent measurement uncertainty of both subjective methods. And the comparison on the group level does not allow to judge if the individual results are reliable in itself although that's the way they will be used. Especially for the fitting check of custom-moulded earplugs monaural results are necessary to judge each plug on its own.

4. Uncertainty of audiometric thresholds and attenuation measurements

Before comparing audiometric attenuation and REAT data it is worthwhile to discuss the uncertainty of the two methods itself.

4.1. Uncertainty of a single hearing threshold

The standard EN ISO 8253-1 [10] describes pure-tone air and bone conduction audiometry. The informative annex A deals with measurement uncertainty by assembling an uncertainty budget. Contributions thereto take into account the repeatability of the threshold under constant conditions, the behaviour of the audiometers itself, the type of transducer and its position on the ear, ambient conditions like background noise, the quality of the masking noise, the experience of the experimenter, unsufficient cooperation by the test subject and the effect of especially difficult measurement situations.
In an example for an uncritical situation a combined standard uncertainty of 4.9 dB is calculated.

4.2. Uncertainty of a threshold difference

When the attenuation of an HPD is determined with an audiometer two thresholds are measured directly one after the other under constant external conditions. Thus some of the uncertainty contributions from EN ISO 8253-1 should be negligible for the uncertainty of the threshold difference. These are contributions due to the audiometer and the transducer, the masking noise (not applied), the experimenter and the uncooperative subject.
But the following aspects have to be taken into account: The audiometer/transducer has to be linear in sound pressure level over the whole range (the value of attenuation, i.e. up to 40 dB or more). The headphone/earmuff will be fitted twice for the two thresholds. The background noise (if present)

will only influence the open threshold. And last, a high attenuation value (perhaps in combination with a hearing loss) can lead to difficulties in threshold detection.

Since no systematic data are available yet only an estimation can be proposed here. The uncertainty should be smaller than for the single threshold case and dominated by the repeatability of the threshold.

4.3. Uncertainty due to discrete level steps

One aspect that can be assessed quantitatively is the influence of the limited accuracy with which the sound pressure level can be varied (for screening audiometers typically 5 dB) [11]. This step size will be denominated s in the following.

A single threshold x in such a situation can therefore only be determined with an accuracy of s while the true threshold can be each value in the half-open interval between x and $x - s$ with the same probability $1/s$ (rectangular probability distribution).

The difference $y = k \cdot s$ of two of such quantised thresholds $x_1 = m \cdot s$ and $x_2 = n \cdot s$ has a triangular probability distribution with the maximum (and expectation value) at $k \cdot s$ (probability $1/s$). The probability decreases linearly down to zero at $k \cdot s \pm s$.

This triangular distribution results in a standard deviation (square root of the variance) of $s/\sqrt{6}$. For a step size of 5 dB this yields 2.04 dB and should give a significant contribution to the overall uncertainty. By reducing the step size to e.g. 1 dB also the standard deviation of the triangular distribution is decreased by a factor of 5, giving only 0.41 dB. It is clear that in this case the uncertainty due to limited repeatability of threshold determination (cf. EN ISO 8253-1 which states 2.5 dB) will dominate.

4.4. Uncertainty of REAT method

Of course also the REAT method has a significant measurement uncertainty that is due to its subjective nature. The relevant standards give estimations of the expected uncertainties (cf. EN 24869-1 and also ANSI S12.6 [12]). For earplugs, the within-lab uncertainty is around 2 to 3 dB while between-labs the value amounts to 6 to 8 dB. But these numbers only refer to the group average data, not an individual measurement. For the comparison with the audiometric method the uncertainty for a single subject would be necessary.

5. Experimental study: design

Binaural REAT measurements according to EN 24869-1 were compared to monaural measurements with a standard PC-based audiometer (Maico MA 33) with circumaural headphones (earmuff with built-in supraaural audiometric headphones). Experiments were performed in IFA's semi-anechoic room with experienced test subjects. All measurements were done with pulsed test tones and in the following order: occluded threshold REAT – occluded threshold audiometer (left and right ear separately) – open threshold audiometer (again left and right ear separately) – open threshold REAT. Subjects were informed to check if the fitting of the earplugs was influenced by donning the headphones.

REAT data was measured for all eight octave-band centre frequencies from 63 Hz to 8 kHz with one-third octave band noise, while the audiometer started at 125 Hz, resulting in seven frequency bands measured with pure tones.

Threshold determination was accomplished by different techniques. First of all, the audiometer allowed to vary the step size between 5, 2 and 1 dB. After an initial phase of the study, always the 1 dB steps were used with ascending levels together with the requirement on the subjects to confirm every single pulsed tone. This procedure aimed at determining the lowest sound pressure level for which the subject could hear all pulsed tones (not only a fraction) with a high accuracy and particularly high repeatability.

In total 16 different earplugs were investigated with 23 subjects resulting in more than 120 measurements. For seven products the sample size is larger than five, thus data analysis concentrates on them.

In a second experiment the physiological noise under the headphones with and without earplug (one product) was measured with five test subjects. A tube microphone (ER 7 by Etymotic Research) was used that could be inserted through a hole up to the end of the custom-moulded earplug. For the measurements in the open ear canal the tube was inserted as far into the ear canal as the length of the earplug.

6. Results and discussion

6.1. Comparison REAT – audiometer

For every measurement (one earplug, one test subject) one data set of REAT values and two data sets of audiometric values exist. The graphical individual comparison shows in many cases quite large discrepancies between REAT and audiometer data. Figures 1 and 2 illustrate as examples one plot with a very good agreement and one with large deviations.

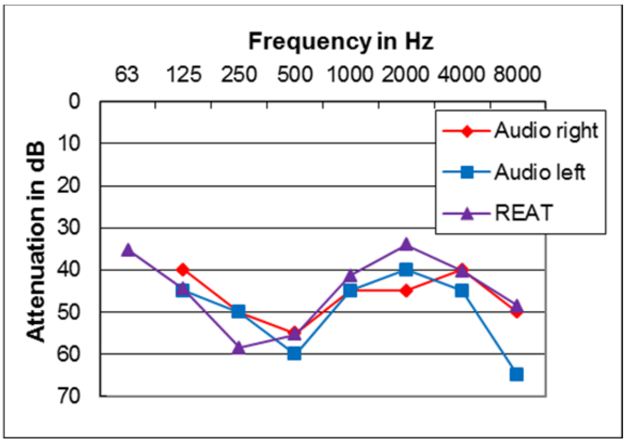

Figure 1. Comparison of REAT and audiometer attenuation for a high attenuating foam plug with a generally good agreement between the two methods.

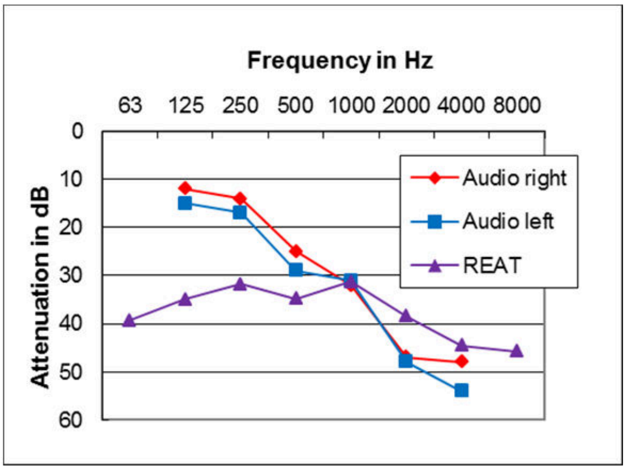

Figure 2. Comparison of REAT and audiometer attenuation for a custom-moulded earplug with large deviations between the two methods.

A characteristic signature that is visible in a high percentage of the measurements are lower attenuation values for the audiometer in the low frequency range (see also figure 2). This effect becomes obvious when the data are averaged over the subject group, as shown in figure 3. Left and right ear of the audiometer data coincide very well, but are clearly separated from the REAT curve (also taking into account the standard deviations).

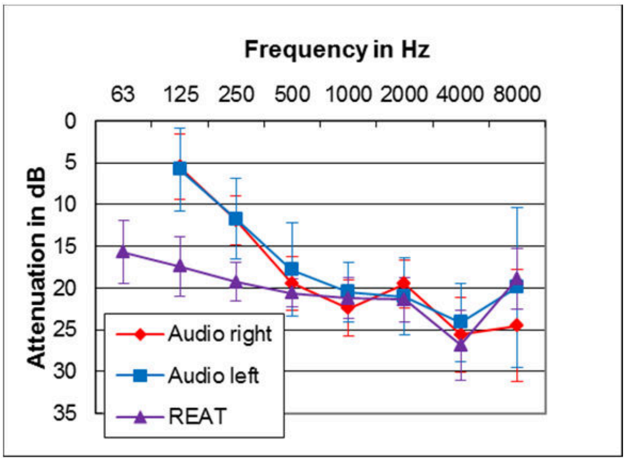

Figure 3. Group mean and standard deviation (18 measurements) for a custom-moulded earplug.

This impression was confirmed by t-tests between the audiometric and the REAT data for the frequencies 125 Hz, 250 Hz and 4 kHz (two-sided t-tests with paired samples). The seven HPDs each with left and right ear result in 42 comparisons. On a confidence level of 0.05 all of the 14 data sets for 125 Hz showed significant differences. For 250 Hz six data sets showed significant deviations while for 4 kHz only one result was significant. In general, for the higher frequencies (starting at 1 kHz) the agreement between the two methods is quite good.

6.2. Binaural vs. monaural audiometric measurements

The data presented in figures 1 to 3 are binaural for REAT and monaural for the audiometric method. As mentioned above, there are applications that require to measure each ear individually. In order to check if the agreement between the data can be made better the two monaural audiometer results were transferred into one binaural data set. For this aim for each threshold (open and occluded) the minimum value of left and right ear was determined and the difference of these two values gave the binaural attenuation.
Although the visual inspection of the artificially derived data seemed to promise a generally better agreement with the REAT data the t-tests mentioned in the section above for the three

frequencies proved the opposite. None of the significant differences vanished while for 250 Hz even two more cases appeared. Thus it seems that this approach of binaural vs. monaural thresholds cannot explain the differences in the results.

6.3. Physiological noise

Another theory to explain the systematic deviations between the two measurement methods is the effect of physiological noise in the ear canal. The open threshold for REAT is measured with a completely open ear canal while for the audiometric measurements the ear (including pinna) is occluded by the headphone. The measurement of the threshold with earplug is very similar for both methods because the ear canal is closed and partially filled anyway.
The circumaural earmuff with the built-in supraaural audiometer headphone used in the Maico MA 33 has only a small occluded volume when worn. In contrast to that the system presented in [8] or the FitCheck system by Michael and Ass. [13] have occluded volumes of up to 200 cm³.
Figure 4 shows the results for one of the five subjects measured with a tube microphone for the four situations with/without headphone and with/without earplug. The results confirmed the expectation: The sound pressure level in the open ear canal is significantly higher when the headphone is worn. The measurement under the earplug showed no differences with and without headphone. This would lead to a reduced attenuation value for the audiometric data.

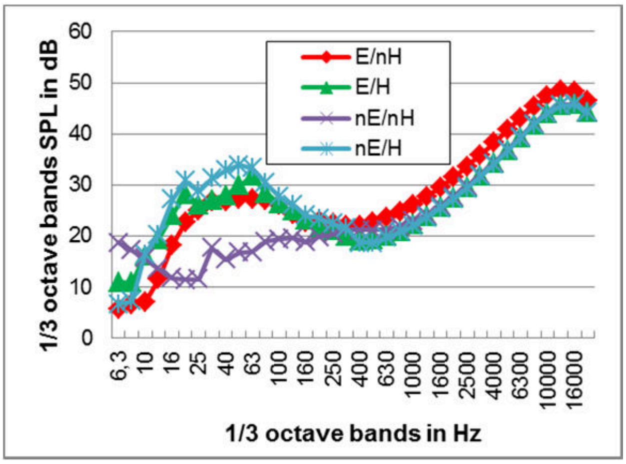

Figure 4. Tube microphone measurements on one ear either with or without a custom-moulded earplug E and the audiometric headphones (H). Increasing levels for higher frequencies are due to inherent noise of the tube microphone setup.

On the other hand it is known that the occlusion effect also affects the attenuation values determined by the REAT method. In this case the open threshold is undisturbed while the occluded one is increased due to physiological noise. Berger and Kerivan have quantified this effect [14].
These two arguments could explain the observed discrepancies: For the lower frequencies audiometric attenuation values are too low because of a biased open threshold while the REAT values are too high due to a shifted occluded threshold.

7. Discussion and outlook

The explanations given above on the effect of physiological noise due to a small occluded volume under the headphone need be verified by analogous measurements with headphones with large occluded volume. That includes determination of the physiological noise under the headphones with and without earplug. In addition to that it should be investigated how the sound level produced by the headphones in the occluded volume under the cup is influenced by the insertion of an earplug (cf. [8]). Depending on the occluded volume of the headphone the portion of the total volume that is missing due to the plug and thus the effect on the resulting sound pressure level should be higher for smaller occluded volumes like the headphone used in the present study.
The influence of the different test sounds (one-third octave band vs. pure tones) should be negligible according to [9].
If these factors have been checked the comparison between REAT and audiometer need to be repeated. As discussed above it needs to be defined if the correlation between the two methods should be determined by a linear regression or if the confirmation of the identity between the methods (in the range of a suitable uncertainty) should be the goal. The comparison of group mean values (as in figure 3) does not contain much information on the individual behaviour, but could help to identify systematic effects because the individual scatter of the data has been cancelled by averaging.

8. Conclusions

The need for a valid measurement method for the individual sound attenuation of earplugs exists. This method should be applicable to a variety of earplug models. Ideally the measurements could be

included as fitting checks into the hearing conservation programme using audiometers.
The data available so far don’t allow yet recommending standard audiometers without reservation for this aim. Further research needs to be done.
After that the inherent measurement uncertainty for the individual data whose contributions have been sketched shortly in this paper can be assessed.

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