Comparison of different measurement systems for the assessment of the individual noise attenuation of earplugs

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Summary In recent years, a number of measuring systems have been presented to the German market that allow the individual determination of the sound attenuation of earplugs. In some cases, these systems are already being used in the companies by professional physicians or safety engineers or by manufacturers of hearing protectors. For the study presented here, five of these measurement systems have been tested in direct comparison. The results show that the individual attenuation measurement in principle supports an optimum selection of hearing protectors helping to avoid under- or over-protection. However, not all measurement systems always yield the same results.

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For various reasons it is of interest to determine the sound attenuation of individual earplugs.
Unlike earmuffs, the individual behavior during the insertion and the wearer's anatomy (ear canal shape) are of considerable importance. For custom molded earplugs the situation is even more complicated, because these products are custom manufactured. Regardless of user behavior, this creates another possible source of error. Moreover, such a fitting check is part of the EC type examination according to EC Directive 89/686/EEC [1] (PPE Manufacturers Directive).

Checking the maximum permissible exposure value

In the European Noise Directive 2003/10/EC [2] the concept of exposure limit is introduced. This limit must not be exceeded at the ear of any employee wearing hearing protectors. The Directive defines the daily noise exposure level $L'_{EX,8h}$ = 87 dB(A) and peak sound pressure level $L'_{p,Cpeak}$ = 140 dB(C). In the German implementation of the directive, the Noise and Vibration Occupational Safety and Health Ordinance (LärmVibrationsArbSchV [3] [Noise Vibration Labor Protection Regulation]), the term "limit" was avoided and instead the maximum permissible exposure value (maximal zulässiger Expositionswert, MZE) was defined. In addition, the limits have been adjusted to the upper exposure action values, so that the limits of $L'_{EX,8h}$ = 85 dB(A) and $L'_{p,Cpeak}$ = 137 dB(C) must be complied with nationwide.

For all employees it must be ensured that the MZE is observed. This requirement necessitates corrections in the selection process.

Before the introduction of maximum permissible exposure values, the selection of hearing protection was based on sound attenuation values, which were determined in the type examination by laboratory measurements. In the type examination test, sound attenuation values for the hearing protector are determined with 16 subjects under optimal using conditions by a subjective measurement method according to DIN ISO 4869-1 [4]. The goal is to characterize the performance of the product under proper and careful use.

There are two aspects to the question of compliance with the maximum permissible exposure values:

- In the practical situation at workplaces (real-world), typical users achieve generally lower attenuation values than the reference group in the type examination test (see following section).
- The attenuation values of the group of subjects only provide a statistical indication of mean and standard deviation of the 16 measured attenuation values. In the series of standards EN 352 [5], which is used in the type examination test of hearing protectors, the "Assumed Protection Value" (APV) is defined as the mean minus one standard deviation. This corresponds to a confidence level of 84%, i.e. 84% of users achieve at least the specified APV as sound attenuation. The APV is declared for all test frequencies from 63 to 8000 Hz. In most cases however, the so-called HML values or SNR value are used for the selection, and those values do not take into account the frequency content of the workplace noise in the individual frequency bands but only following the categories high-, medium- or low-frequency (HML) or via the difference of L_C - L_A of the workplace noise (SNR). These characteristic values rely on the APV and thus also have a confidence level of 84%. Depending on the standard deviation from the type examination test, which may be in the range of 6 to 8 dB for a specific hearing protector, the range of possible attenuation values for a single user is considerable. Here under- and over-protection must be considered.

Reduced real-world sound attenuation

Numerous studies by various institutions worldwide [6 through 8] have shown that the sound attenuation values, which are achieved in practice at workplaces, are significantly lower than the results of laboratory measurements with experienced subjects.

Apart from improper insertion or fitting, the cause of these discrepancies can also be aging effects, concomitant use of other personal protective equipment on the head or selecting the wrong hearing protector. Particularly, foam earplugs to be formed before use show significant differences to the laboratory sound attenuation so that correction values seem advisable.

These so-called practical deratings can be realized in different ways. In Germany fixed deratings are in place for the individual types of hearing protectors that are based on studies by IFA ([7; 9]): 9 dB for formable earplugs, for premolded earplugs, banded earplugs and acoustic earmuffs 5 dB, and 3 dB for custom molded earplugs with fitting check. In France, a similar system is in place that combines fixed deratings with the deduction of two standard deviations from the mean [10]. In the U.S., however, the method of the federal Occupational Safety and Health Administration (OSHA) is in use that sets a relative derating of 50% from the laboratory attenuation value (NRR) [11]. On the other hand, the U.S. National Institute for Occupational Safety and Health (NIOSH) recommends relative deratings depending on the type of hearing protector: 25% for earmuffs, 50% for foam earplugs, and 70% for all other earplugs [12]. In addition, there are other approaches in other countries, so that for the same product different real-world sound attenuation values may be assumed depending on the location.

Unfortunately, derating provides no indication of the individually achieved sound attenuation since the derating was determined via measurements with a population of subjects. It should be noted that the spread of the sound attenuation values achieved in practice is significantly greater than that achieved in the type examination test. Usually there is a small group of the hearing protector users, who approximately reach the values from the type examination test in their workplace.

Now, if the selection of hearing protectors for all employees is done with the derating values, such users may encounter problems by overprotection through excessive attenuation values, unsuitable for the workplace (feeling of being isolated, not able to hear warning signals). In principle, it should be noted that deratings in line with the LärmVibrationsArbSchV are intended to eliminate or minimize the risk of too low noise attenuation (under-protection).

For these reasons, different measurement methods have been developed, intended to facilitate a determination of the individual sound attenuation. These methods were first applied in the U.S. Meanwhile, however, manufacturers of hearing protectors represented in Europe as well as users and statutory accident insurances are also involved in these developments.

Fit check of custom molded earplugs

In addition to the above-described problem that affects all types of hearing protectors, yet another aspect must be considered for custom molded earplugs. These products are custom manufactured using an ear impression of the user and achieve the protective effect ascertained in the type examination test only when they seal the ear canal properly. Errors or inaccuracies in the impression of the ear or production (computer image processing or machining of the blank) may result in leakage that can significantly reduce the achievable noise attenuation. Because this problem cannot be solved by particularly careful insertion (such as, e.g. with foam plugs), an examination subsequent to manufacturing is necessary.

This can be achieved by an individual measurement, the so-called fit check. The fit check of custom molded earplugs has been mentioned in the DGUV regulation 112-194 [13] since 2008, and also in the Technical Regulations for LärmVibrationsArbSchV (TRLV Lärm [14]) since 2010.

Upon delivery, the manufacturer is responsible for performing a fit check (within six months) in order to prove that the product has been manufactured correctly and corresponds to the type tested models so that the attenuation values from the type examination test are applicable. This obligation arises from the requirements of the EC Directive for Personal Protective Equipment 89/686/EEC.

In addition, the employer is obliged to check regularly the condition of the provided hearing protectors pursuant to § 8 (4) of the Lärm-VibrationsArbSchV. According to TRLV Lärm a fit check must be performed for custom molded earplugs every two years. The employer may delegate the test, e.g. to the occupational physician, or have it performed by the manufacturer of the custom molded earplugs.

The relevant provisions (such as e.g. the prevention guideline “use of custom molded earplugs“ [15]) do not give instructions regarding the measurement method to be used. The procedures for the periodic inspection must ensure comparability with the test results of the fit check at time of delivery. This requires a calibration method to be used during the delivery measurement.

Since the fit checks must be carried out for all custom molded earplugs, there is a problem for older products that were delivered without being inspected by the manufacturer. There are no comparative values that can be used as a reference by the occupational physician.

In principle, the afore-mentioned measurement methods for individual sound attenuation can also be applied for the fit check. In addition, an air leakage test is possible (and has been in use for many years). This is not associated with a determination of sound attenuation; it only determines the tightness or leakage rate of the earmold inside the ear canal.

Objective of the study

As described above, various methods have been developed to determine the individual sound attenuation of hearing protectors, in particular earplugs. Often the methods differ significantly from those of the type examination test, so that, without additional testing it cannot be assumed that the attenuation values of the different measuring systems are consistent with those of the type examination test. It should also be noted that the values of the type examination are determined for a group of 16 subjects and not for a single individual.

Regarding this topic, some studies have been performed that were able to establish matches ranging from partially sufficient to good, between individual sound attenuation and type examination. In a study by Kotarbinska [16; 17] Howard Leight’s VeriPRO system was used. The individually determined sound attenuation values were below the laboratory SNR values and were more in line with the NRR values for which two standard deviations are subtracted from the mean. The INRS [18] compared different measurement systems directly to the type examination test. The correlation was acceptable except for VeriPRO. Berger et al. [19] developed correction factors for the 3M Company’s E-A-Rfit system by comparing the individual data with values from the type examination so that in most cases there is a good correlation between the individual sound attenuation and the type examination test. Murphy [20] published a study that also compared different testing methods. However, Murphy's study only considers the calculation method for the attenuation and residual levels at the ear, since all systems receive as input the same octave band attenuation values.

Finally, at the Institute for Occupational Safety and Health of the DGUV (IFA) a study is currently ongoing about the suitability of audiometers for hearing protector testing and the fit check of custom molded earplugs.

The main objective of the present joint study of the German Social Accident Insurance Institution for the foodstuffs industry and the catering trade (BGN), the Expert Committee for Hearing Protection in the Department of Personal Protective Equipment of the DGUV and the Institute of Occupational Safety and Health of the DGUV (IFA) was to compare different, commercially available measurement systems for determining the individual sound attenuation of earplugs. The focus was on reliability, repeatability and applicability for various types of earplugs. The experience gained could also be incorporated into a standardization project of the CEN/TC 159 "Hearing protection", which will define the performance requirements of such individual measurement systems.

The tested devices are described in the next section.

Measurement methods

Measurement principles: Audiometer, loudness balancing, MIRE

The reference value ("Gold Standard") for determining the sound attenuation of hearing protectors is the so-called REAT method ("Real Ear Attenuation at Threshold") in accordance with DIN ISO 4869-1, which is also used in the type examination test. Here the hearing threshold of the subject is measured twice in a diffuse sound field: once with and once without hearing protector. The measurement is performed with one-third octave band noise in the eight octave band center frequencies between 63 and 8000 Hz. The hearing threshold is usually determined via a bracketing method (e.g. by Békésy). The levels are repeatedly increased and reduced alternately and the hearing threshold is bracketed upward and downward. The REAT method provides information on a sample of 16 subjects (mean, standard deviation) and requires according to the specifications of the standard very low ambient noise levels and a diffuse sound field.

A method of similar principle can be implemented using an audiometer. Again, the hearing threshold of the subject is measured with and without hearing protector. Differences to the REAT method are the sound sources (mostly headphones, partly also open field audiometry) and the test signals (sine waves). The hearing threshold can be determined either with monotonically increasing levels or by a bracketing method.

Another subjective measurement method is based on the loudness balancing. Here, measurements are not taken at the hearing threshold, but at significantly higher levels in the range of 60 dB(A). The loudness of sine tones provided through headphones must be set identically for both ears. This is carried out for three situations: both ears open, one ear with hearing protector and both ears with hearing protectors. From this, the attenuation value of the earplugs used can be calculated for each ear separately.

The so-called MIRE method ("Microphone in real ear") is a measurement method that is not dependent on the cooperation of the subject and that determines the difference between the level at the ear underneath the hearing protector and outside the ear directly on the concha by the use of two microphones. It should be noted that this measurement value ("noise reduction") does not correspond directly to the sound attenuation of an earplug ("insertion loss"). For the insertion loss two measurements would be required at the same point of the ear canal, with and without earplug. This must be considered when specifying the determined attenuation values. The fundamental method of measurement in the ear canal is described in the standard DIN EN ISO 11904-1 [21]. Speakers or headphones can be used as a sound source.

Available measurement systems

Audiometers (and similar systems):

– MA 33 (Maico): PC-based audiometer with special software to display the measurements with earplugs; sound source: headphones, applicable to all earplugs.

– Oscilla (Inmedico): PC-based audiometer with special software to output a measurement report on the hearing protector test; sound source: headphones, applicable to all earplugs.

– CAPA (Cotral): PC-based measurement system (no audiometer), automated measurement, attenuation values of earplugs stored; sound source: headphones, applicable to all earplugs.

– ePRO-Meter (Egger): PC-based measurement system (no audiometer); sound source: headphones, applicable to all earplugs.

Loudness balancing:

-VeriPRO (Honeywell): single system with loudness balancing; sound source: headphones, applicable to all earplugs.

MIRE:

– E-A-Rfit (3M): PC-based system, broadband measurement over seven frequencies; sound source: loudspeaker, applicable only to specially prepared earplugs from the company 3M, for each product: correction values are saved in the system.

– CT EarGuard (Ceotronics): PC-based system, broadband measurement over seven frequencies; sound source: loudspeaker, applicable only for Ceotronics custom molded earplugs.

– Elacin SI-meter (Elcea): Complete instrument; sound source: loudspeaker, applicable for different custom molded earplugs (if filter adapter available).

– SV 102 (Svantek): Dual-channel dosimeter, sound attenuation determination by measurement underneath the hearing protector (with probe microphone) and on the shoulder, external sound source required, works only with earmuffs.

Test parameters: Octave values and PAR value

With almost all of the above mentioned measurement systems attenuation values for single frequencies or frequency bands (one-third octave bands) can be determined. If attenuation values are available at all octave bands from 125 Hz to 8 kHz, all the attenuation parameters or selection methods of the DIN EN ISO 4869-2 [22] may in principle be applied: Octave band method, HML method or HML check and SNR method.

The octave band method is relatively elaborate and based on experience is used today only for individual cases (such as individuals with severe hearing loss or spectrally distinctive workplace noise).

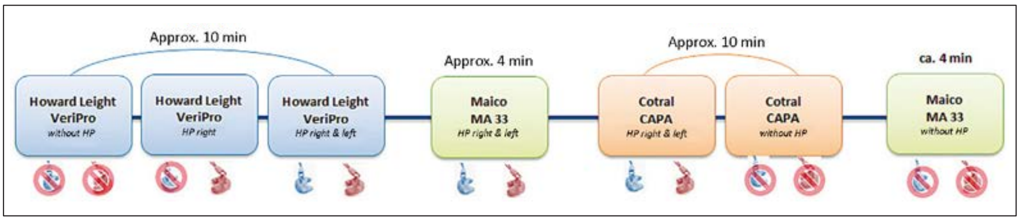

Figure 1 Sequence of the first study. In each case, the measurement time and the ear-plugs used (right or left ear) are provided.

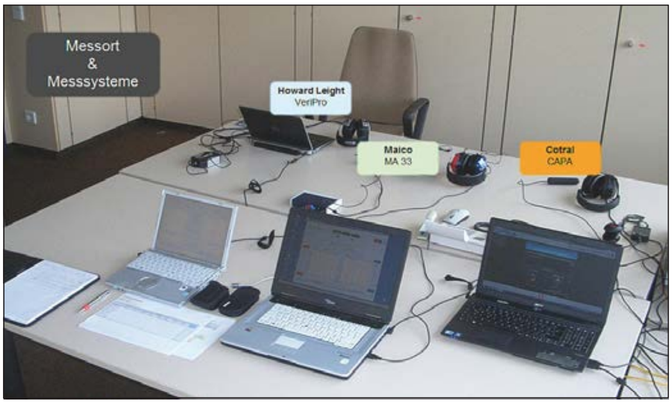

Figure 2 *Experimental setup of first study. Each measurement system is controlled by a separate computer.*

However, in most cases, it is up to the user of the measurement systems how many of the possible test frequencies he wants to measure. Sometimes a rapid test is also offered in which only a few frequencies (one to three) are used. Especially when measurements are performed only at 500 Hz, the significance of the result is limited, but may be sufficient for a quick check (e.g. to identify problem cases).

For easy interpreting of the results of the measurement systems by the user, the so-called PAR value (personal attenuation rating) has been defined. This value is calculated by most systems that measure the noise attenuation in several frequency bands. It is based on the SNR value of the DIN EN ISO 4869-2 and uses the same reference spectrum to calculate the level reduction by the hearing protector. This means that the C-weighted sound level must be known at the workplace. The SNR or PAR value is subtracted from this to obtain the A-weighted residual level at the ear underneath the hearing protector. The PAR is well suited to compare different hearing protectors with one another. However, since all frequencies contribute to this single number value, e.g. leakages in the low-frequency range are usually not in evidence. In addition, during a direct comparison of individually determined PAR on one hand, and SNR from the type examination test on the other hand, the fact that the SNR value has a confidence level of 84% must be considered, i.e. in the case of about 16% of the users a lower attenuation is to be expected without noticing a deviation from the type examination test.

Experimental Procedure

The measurements were performed in two chronologically separate studies with three measurement systems each. In this case, a system was used twice (Maico MA 33), so that a total of five systems were investigated. For both studies, five hearing protectors were selected, each representing the behavior of a product group or suitable for the measurement systems.

First study: MA 33, VeriPRO, CAPA

Since the measurement systems required different starting conditions, the sequence of the test series of measurements had to be defined in a meaningful way (see **Figure 1**). Each system had its own computer to ensure a trouble-free operation of the programs. The goal was for the hearing protector to remain in the ear unchanged (only one fit) during the entire test series. **Figure 2** shows the experimental setup for this test series. VeriPRO by Howard Leight was operated by the user of the hearing protector himself. The other devices were controlled automatically (CAPA) or controlled by the experimenter.

The test series started with the VeriPRO measurement method by Howard Leight. First, a loudness balancing without hearing protector was performed. For this, the test subject balanced the volume of the sound in one ear with a sound of fixed volume in the other ear. After successful balancing, the actual measurement was started. Here, the loudness balancing was carried out across the frequencies. Thereafter, the user had to insert the hearing protector into the right ear and the loudness balancing was repeated over the range of frequencies. Then the user was prompted to insert also the hearing protector into the left ear, and the measurement was carried out for a third time. The hearing protector remained in the user's right ear. After the measurement, the user obtained a personal evaluation of the attenuation for both ears.

Next, the test series was continued with the MA 33 audiometer by Maico. In the menu, the program "hearing protector test" was selected. The hearing thresholds are recorded with and without hearing protection devices. For the measurement, a level increment of 5 dB was set. First, the hearing threshold of the right ear was recorded with the earplug, then for the left ear with the earplug. The subject was subjected to a series of frequencies that he had to confirm at first perception using the response button. In order to obtain increased accuracy, the measurement was repeated on both sides. After finishing the measurement, the hearing protector remained in the ear.

Next, the measurement was made with the CAPA system by Cotral. In this system, the user followed the instructions of the test assistant. The measurement started with the determination of the threshold of hearing with hearing protectors inserted into both ears. The user heard a series of frequencies that were each repeated three to ten times. The user had to confirm these with the response button. The program delivered sounds alternately to the right and left ears. After the measurements with hearing protectors, the user is prompted by the test assistant to remove the earplug and to repeat the measurement. This is followed by the determination of the hearing thresholds without hearing protectors.

Some measurements with the CAPA system could not be used for the evaluation because the program required re-insertion of hearing protectors during the measurement, as a result of which

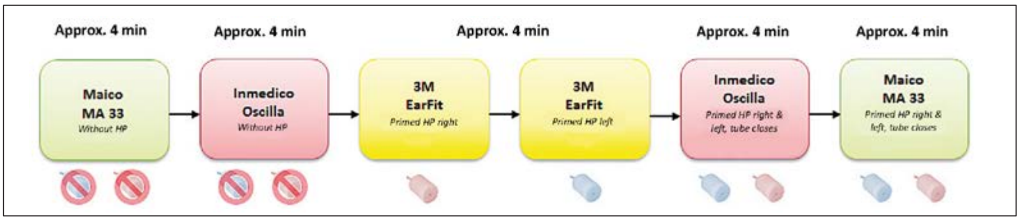

Figure 3 *Sequence of the second study. In each case, the measurement time and the earplugs used are shown (right or left ear).*

the objective - the hearing protectors remain inside the ear untouched throughout the entire series of measurements - would not be fulfilled.

Finally the hearing threshold without hearing protection with the MA 33 by Maico was measured.

After completion of the measurements, the attenuation values of the different measurement systems were determined. In the case of the VeriPRO and CAPA systems the attenuation values of the tested frequencies can be displayed. With the MA 33, both calculated curves are shown in one diagram, the respective attenuation values are tabulated underneath.

Second study: MA 33, Oscilla, E-A-Rfit

The second series of measurements was carried out with the two audiometers MA 33 by Maico and Oscilla by Inmedico and the system E-A-Rfit by 3M. For this purpose, the measuring sequence from **Figure 3** was selected. **Figure 4** shows the experimental setup for the second study.

To carry out the measurements, special probed earplugs (surrogate earplugs) manufacturer by 3M had to be used since for these earplugs only the 3M E-A-Rfit system can be used.

We started with the MA 33 audiometer from Maico. First, the hearing threshold of the subjects was determined without hearing protectors. The procedure corresponds to that described above. Then, the hearing threshold was determined without hearing protectors using the audiometer Oscilla by Inmedico. The user confirmed the played sounds upon initial perception using the response button. In both systems, the level was set to 5 dB increments.

After the measurement, the surrogate hearing protection was inserted into the right ear of the subjects. Then the attenuation value of the right ear was determined using the E-A-Rfit system. After successful measurement, the earplug was inserted into the left ear and the measurement of the E-A-Rfit system started again (see **Figure 5**). The evaluation can be displayed immediately after finishing the measurement.

The test subject left the hearing protector inserted in both ears. For further measurements with hearing protection, only the probe tubes of the surrogate earplugs were cut off and the ends sealed with a cornstarch-water mixture (see **Figures 6** and **7**). Thus, the plug could be worn under the headphones of the audiometers without leakages affecting the sound attenuation.

In that way the hearing threshold with hearing protectors could be determined with the Oscilla and Maico systems.

Results

In the first study, three hearing protectors were tested with the first three methods described: a custom molded earplug (Phonak Serenity Classic), a premolded earplug (3M E-A-R Ultrafit) and a formable foam earplug (3M E-A-RSoft Yellow Neon). **Figures 8** through **10** show the results of these measurements. Here, the mean value of the PAR values over all subjects is displayed. Depending on the measurement system, different frequencies were measured, e.g. for VeriPRO 250 Hz to 4 kHz, for CAPA 125 Hz to 8 kHz.

The respective frequency range was taken into account when calculating the PAR value. In addition to the average over all subjects, the standard deviations and the SNR value from the type examination test are shown.

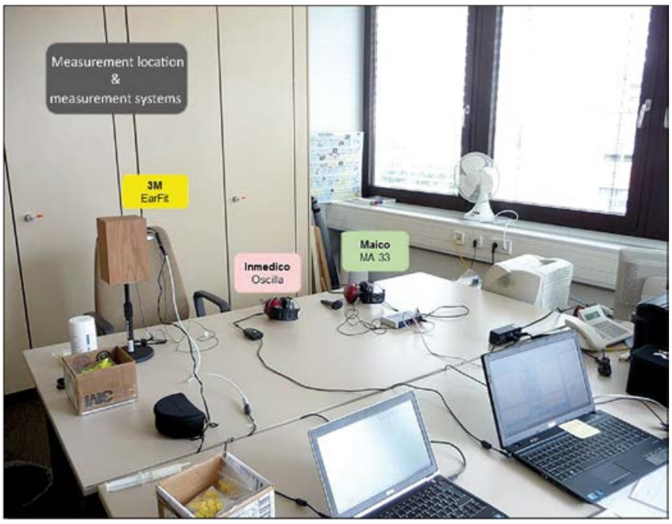

Figure 4 *Experimental setup of the second study. Each measurment system is controlled by a separate computer.*

Figure 5*-E-A-Rfit system with earplug with probe tube (3M E-A-RSoft FX) with connection to the measurement microphone.*

Figure 6 *Earplug of Figure 5 (fitting unchanged) after the probe tube was shortened and the opening was sealed.*

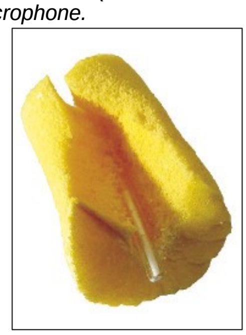

Figure 7 *Dissected plugs (3M EAR Classic). The dissected probe tub was closed using a cornstarch-water mixture.*

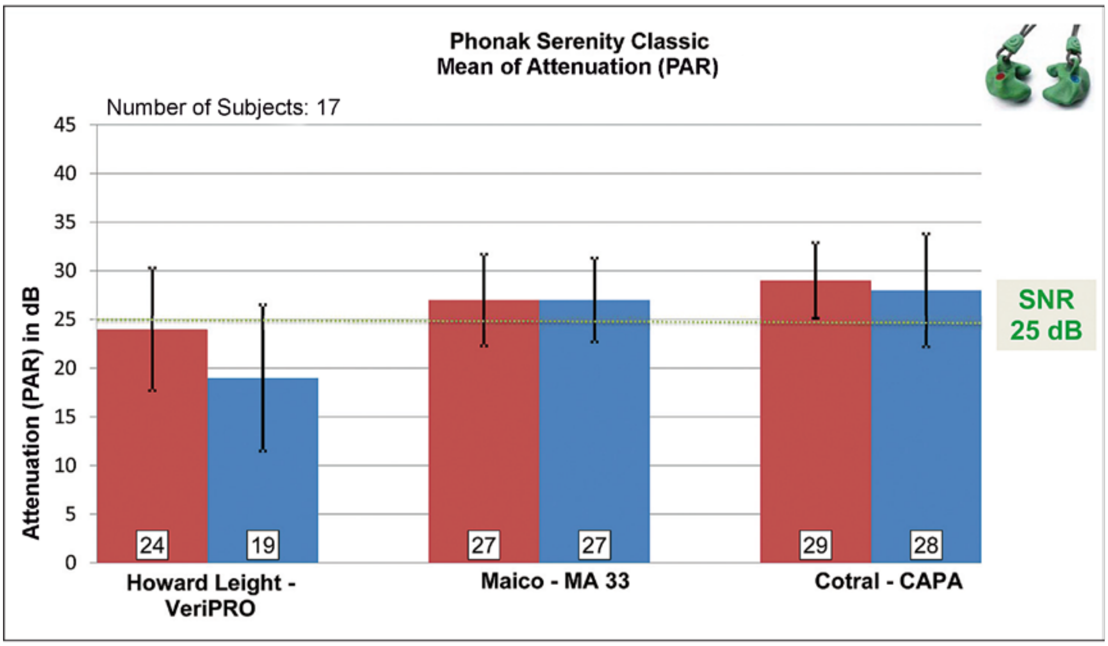

Figure 8 *Comparison of PAR values for the custom molded earplug Phonak Serenity Classic (mean values and standard deviations for 17 subjects), obtained with the measurement systems VeriPRO, MA 33 and CAPA.*

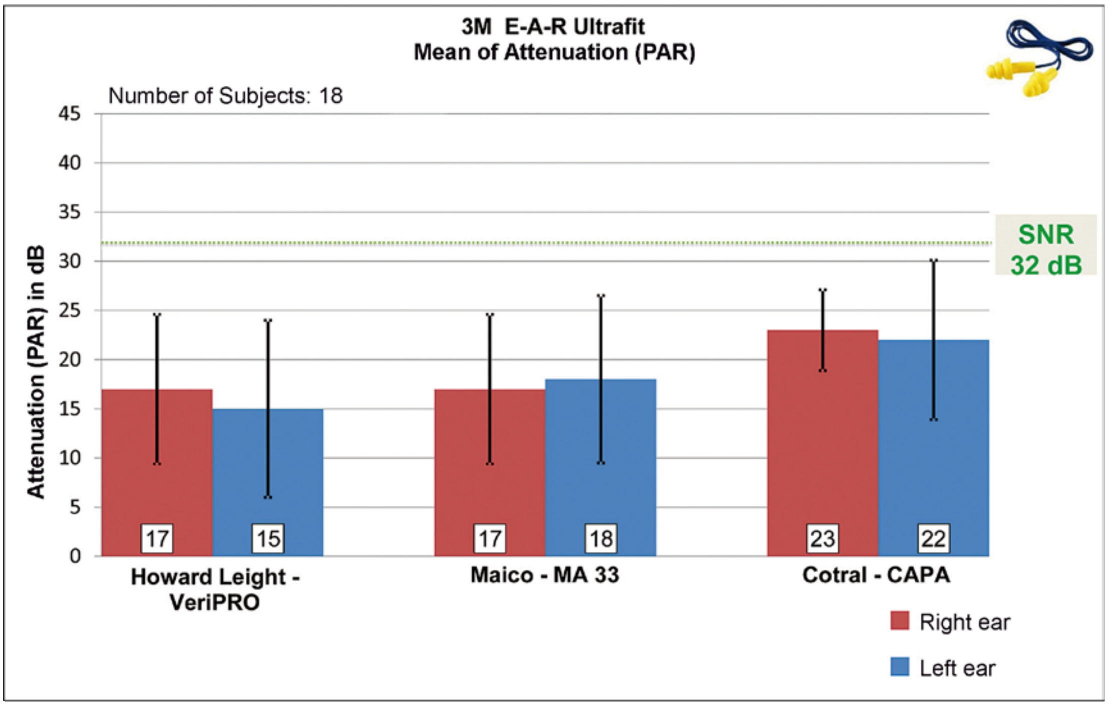

Figure 9 *Comparison of PAR values for the premolded earplug 3M E-A-R Ultrafit (mean values and standard deviations for 18 subjects), obtained with the measurement systems VeriPRO, MA 33 and CAPA.*

Comparisons of measurements are possible both between the three methods as well as with the value of the type examination test. Figures 8 and 10 show significantly lower attenuation values for VeriPRO. For the custom molded earplug and the preformed earplug MA 33 and CAPA are in good agreement; CAPA shows higher values for the foam earplug. This is also confirmed by a statistical analysis using the t-test. The results of two measurement systems were checked as paired samples (values of the same subjects) with a two-tailed t-test. At a confidence level of 5% it was verified whether the means of the populations of the two samples are identical (null hypothesis) or not. With significant deviations (* or ** in **Table 1**), the null hypothesis is rejected, i.e. the results of the two measurement systems differ from each other. As shown in Table 1, VeriPRO shows greater deviations from MA 33 and CAPA than these two audiometric systems among each other.

The SNR value from the type examination test is approximately matched for the custom molded earplug if one calculates the mean minus the standard deviation for the PAR values, which represents a similar approach as for the SNR value. The foam earplug shows significant deviations depending on the measurement system. For the premolded earplug the individual measurement systems are very similar (see Figure 9 and Table 1), but differ significantly (at least 10 dB) from the SNR value.

An analysis of the standard deviations of the three measurement methods results in a slightly different picture for each of the three hearing protectors. For the custom molded earplug and the foam earplug the values for VeriPRO are each the greatest. For all three products, CAPA provides the lowest values for the custom molded earplug and the premolded plug, but only in the right ear.

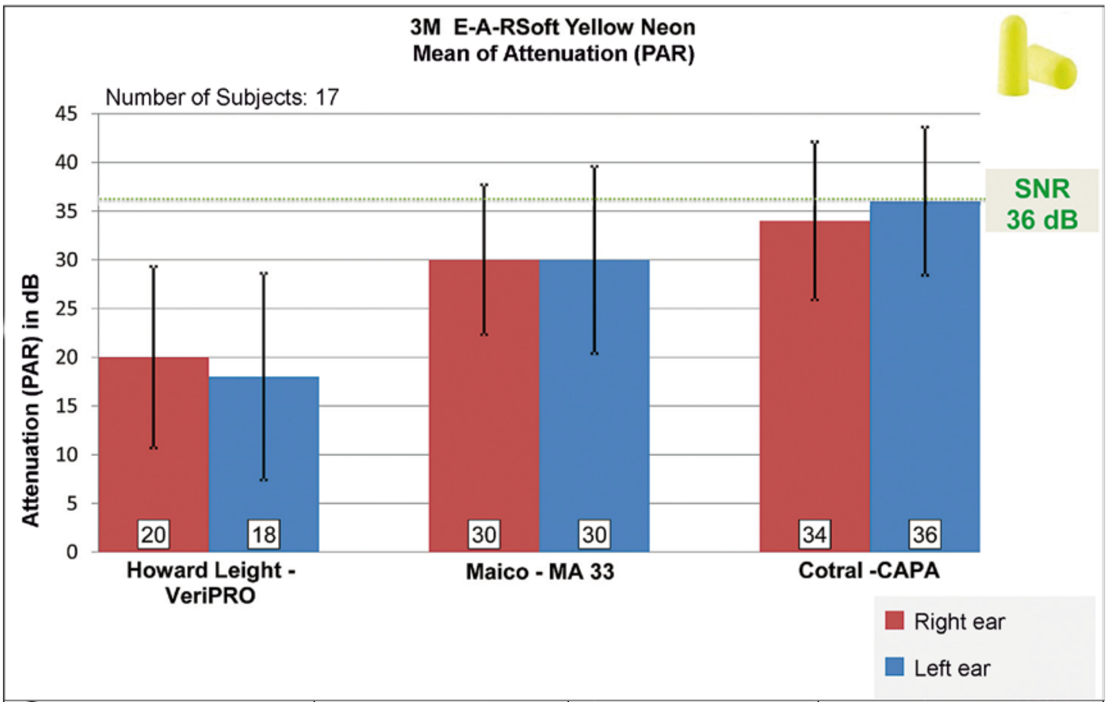

Figure 10 *Comparison of PAR values for the foam earplug 3M E-A-RSoft Yellow Neon (mean values and standard deviations for 17 subjects), obtained with the measurement systems VeriPRO, MA 33 and CAPA.*

Methods \ Hearing protector		Phonak Serenity Classic	3M E-A-R Ultrafit	3M E-A-RSoft Yellow Neon
VeriPRO - MA 33	right	*	–	**
	left	**	–	**
MA 33 – CAPA	right	–	–	*
	left	–	–	*
VeriPRO – CAPA	right	*	–	**
	left	**	–	**

Table 1 *Compilation of the results of the t-test for the data from the figures 8 to 10 (two-tailed t-test with paired samples, *: significant at the 5% - level, **: significant at the 1% level).*

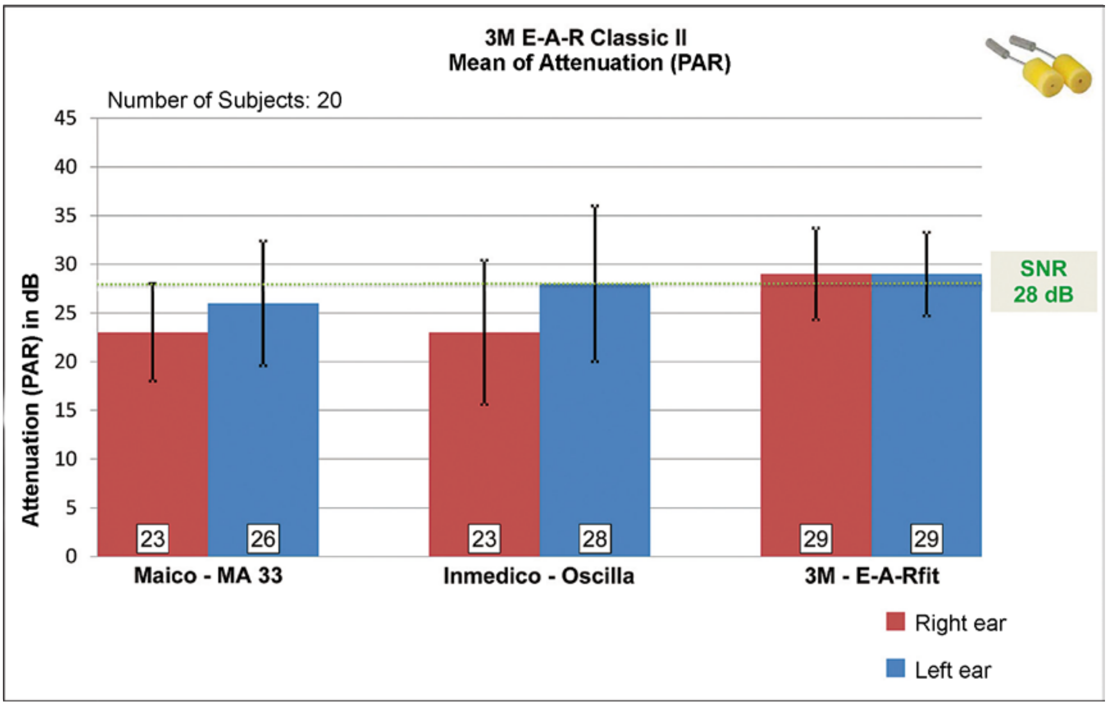

Figure 11 *Comparison of PAR values for the 3M E-A-R Classic II foam earplug (mean values and standard deviations for 17 subjects), obtained with the MA 33, Oscilla and E-A-Rfit measurement systems.*

The results are summarized for the second study in **Figures 11 and 12**. Here two formable foam earplugs were tested, one with medium (3M E-A-R Classic II) and one with high sound attenuation (3M E-A-RSoft FX). For the earplug with medium attenuation the attenuation values from the type examination were approached for the E-A-Rfit system. The two audiometers showed somewhat lower values with a side difference between left and right, so that the t-test for the right ear results in higher significances for the deviation (see **Table 2**).

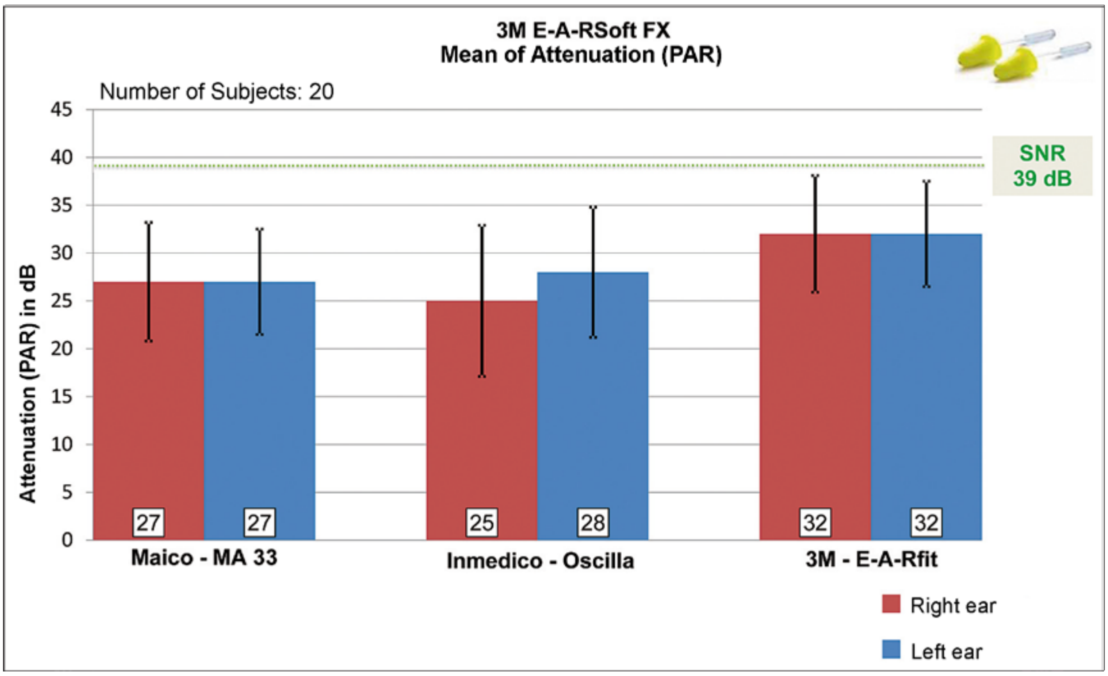

Figure 12 *Comparison of PAR values for the foam earplug 3M E-A-RSoft FX (mean values and standard deviations for 17 subjects), obtained with the measurement systems MA 33, Oscilla and E-A-Rfit.*

Methods \ Hearing protector		3M E-A-R Classic II	3M E-A-RSoft FX
MA 33 – Oscilla	right	–	–
	left	–	–
Oscilla – E-A-Rfit	right	*	**
	left	–	*
MA 33 – E-A-Rfit	right	**	**
	left	*	**

Table 2 *Compilation of the results of the t-test for the data from Figures 11 and 12 (two-tailed t-test with paired samples, *: significant at the 5% level, **: significant at the 1% level).*

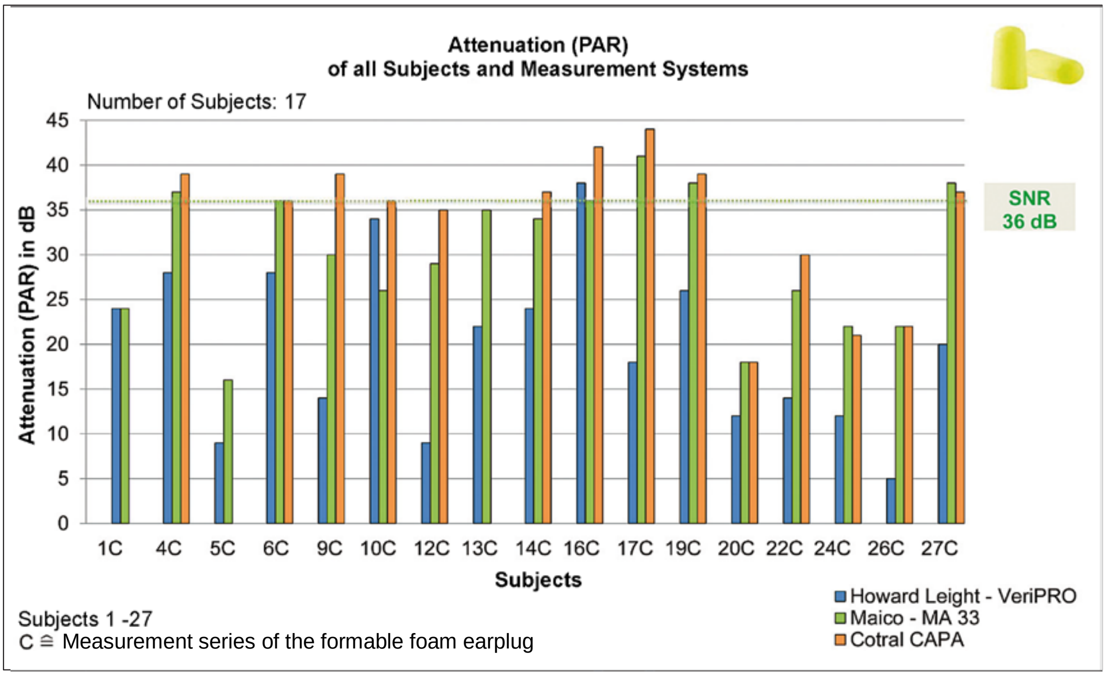

Figure 13: *PAR-values for the individual subjects and the three measurement methods VeriPRO, MA 33 and CAPA (mean values and standard deviations in Figure 10).*

For the high attenuation earplug, the ratios between the measurement methods are similar to the other product. The audiometers provide somewhat lower values than the E-A-Rfit system. However, in this case the E-A-Rfit system is also well below the SNR value of the type examination test (7 dB on average). Although the subjects were encouraged to insert the hearing protectors as well as possible, the test group in the present study seems to achieve consistently lower attenuation values than the subjects in the type examination test.

Looking at the standard deviations of the three measurement systems, relatively similar values are obtained for MA 33 and E-A-Rfit while Oscilla results in values that are 1 to 2 dB higher.

To illustrate the variability between the measurement systems and the individual subjects all individual results of PAR for the foam earplug of Figure 10 are shown in **Figure 13**. It can be clearly seen that the attenuation values obtained scatter in a relatively wide range of 30 dB. In single subjects the results of the three measurement systems are similar to each other (e.g. 16C). For many subjects, the two audiometric methods (MA 33 and CAPA) provide similar values, while the results of VeriPRO are significantly lower, as also the average shows in Figure 10.

For a more detailed analysis of the measured values the data for the custom molded earplug from Figure 8 are shown spectrally across the measured octave frequencies in **Figure 14**. With VeriPRO only the frequency range of 250 Hz to 4 kHz can be measured, the other two audiometric methods cover the range from 125 Hz to 8 kHz. In addition to the dotted individual attenuation values, the average across the subjects and the mean value of the type examination test are shown as a comparison.

Again, it can be clearly seen that VeriPRO usually provides lower values than the other two systems. When comparing the different audiometric methods CAPA shows a smaller scattering. The measurement with CAPA is performed automatically, the hearing threshold is repeatedly remeasured. Measurements with MA 33 were carried out manually by the experimenter with a level increment of 5 dB.

For a comparison of the individually determined attenuation values with the type examination test results across the test frequencies, the representation of **Figure 15** is suitable. The dashed gray line is the average of the type examination test. The light green area includes mean ± 1 x standard deviation, while the pink area indicates mean ± 2 x standard deviation. The upper edge of the green area is therefore the APV value, which is used for selecting hearing protectors according to the sound attenuation (octave-band method). 68% of all data lie within the green area (for normal distribution of the measured values). In the pink area there are correspondingly about 95%. If a measured result therefore is outside the pink-colored area, it is compatible with the type examination test by a low probability, only.

The example in Figure 15 displays results for the preformed earplug from the first study along with a photo of the earplug inserted in the ear. Based on the visual impression a good fit and therefore a high attenuation can be expected. Here, however, the results of all three measurement systems (colored curves) indicate a considerably lower attenuation than could be assumed from the type examination.

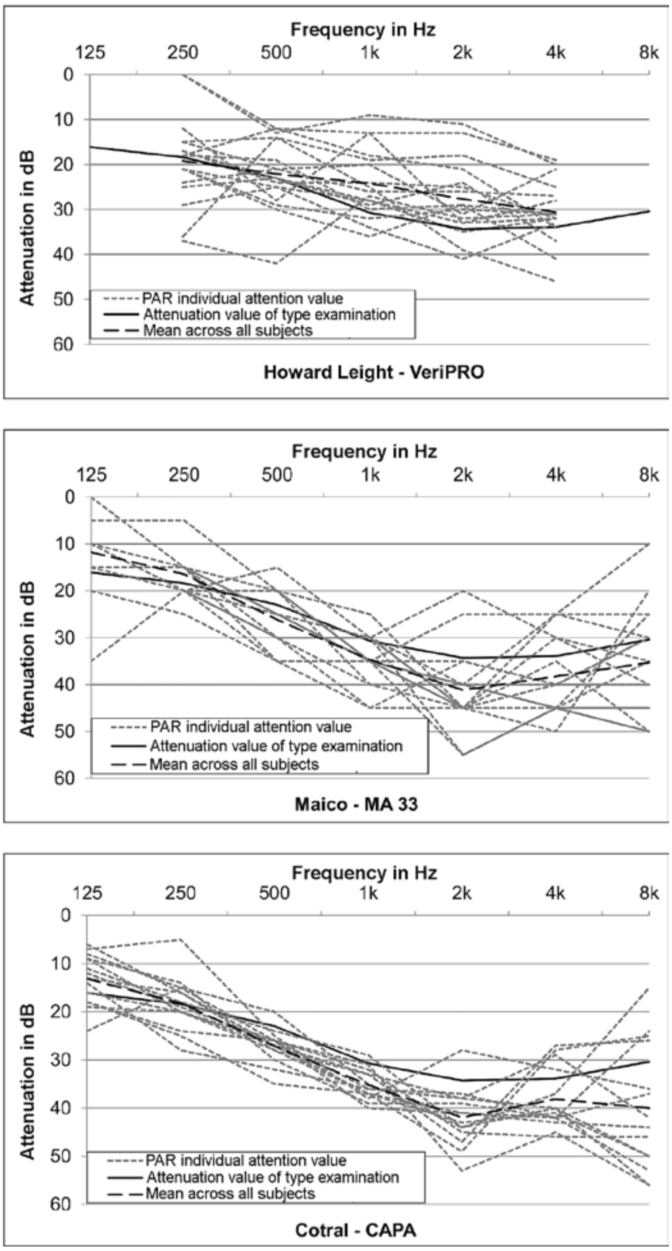

Figure 14 *Individual attenuation values across the seven measurement frequencies for the custom molded earplug from Figure 8. For each of the three measurement methods, the mean value of the individual curves (black dashed line) and the average of the type examination (black) are displayed.*

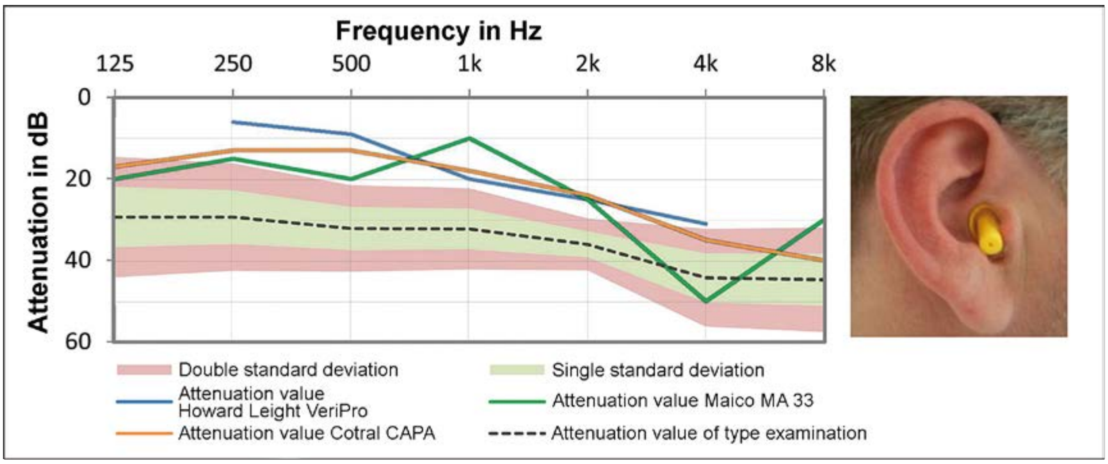

Figure 15 *Comparison of the individually determined attenuation values for a subject (right ear) with the values of the type examination in the frequency range of 125 Hz to 8 kHz for the 3M E-A-R Ultrafit. The colored areas include mean ± 1 x standard deviation (light green) or mean ± 2 x standard deviation (pink). The individually determined curves are at lower attenuation values than the type examination test.*

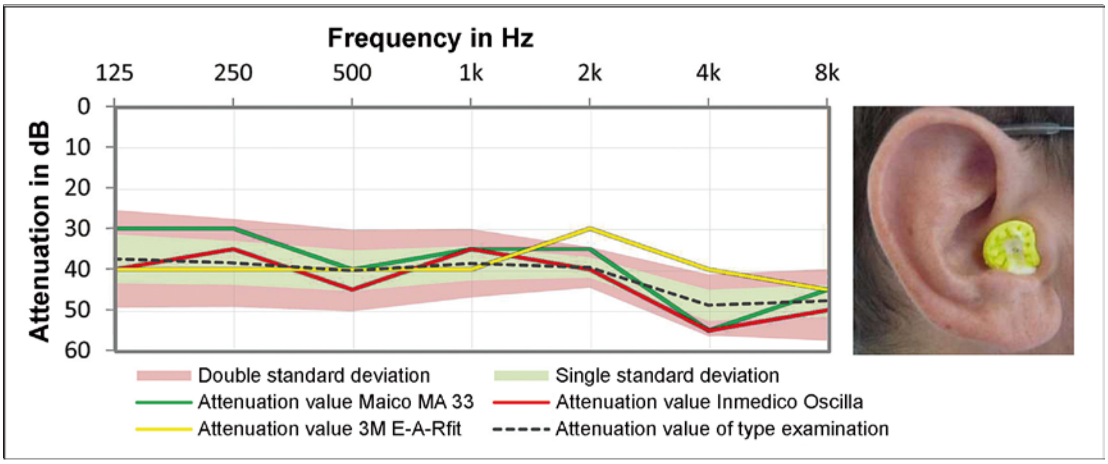

Figure 16 *Comparison of the individually determined attenuation values for a subject (right ear) with the values of the type examination test in the frequency range of 125 Hz to 8 kHz for the 3M E-A-RSoft FX. The colored areas include mean ± 1 x standard deviation (light green) and mean ± 2 x standard deviation (pink). The individually determined curves agree well with the values of the type examination test.*

The example in **Figure 16** shows the results for the high attenuation foam earplug from the second study. Here are almost all data points of the three measurement systems within the value range mean ± 2 x standard deviation from the type examination test. Matching to this the picture shows a deep in the ear canal seated earplug.

Discussion

The results of the two studies are very extensive and can be analyzed from different perspectives:

1. How good is the reproducibility of a system?

In the present studies, no systematic repeat measurements were performed. But the comparison of different measurement systems for a group of subjects (with an unchanged fit of the hearing protectors) points to differences between the systems. VeriPRO results in higher variations in the attenuation values than the audiometric procedures. CAPA, which determines the hearing threshold with an automated process, yet yields slightly smaller variations than the screening audiometer MA 33, which was manually controlled with an increment of 5 dB.

By comparison, the scatter with the EA-Rfit system is even smaller. This was also the only objective measurement system in the study. For this system, the reproducibility was determined in laboratory tests [19].

2. How comparable are the different systems for the determination of individual attenuation values among each other?

In the study design, it was attempted, as much as possible not to change the boundary conditions between the different measurements on an individual subject, i.e. the measurements were carried out immediately after each other and the fitting of the earplugs was not changed. However, is must be considered that in four of the five systems studied the data are determined based on the subjective auditory perception of the test subject. This may explain some of the differences for a single subject, as shown e.g. in Figure 8.

Considering the accuracy of audiometric methods, most differences between the procedures are acceptable for a subject. Training and familiarization with the measurement method should increase the significance of the data. The system VeriPRO shows the largest deviations from the results of the other methods, mostly towards lower attenuation values. This tendency was observed already by other authors [17; 18]. As such, the loudness balancing used by VeriPRO is easy to understand and by the supra-threshold levels robust in the implementation and thus suitable for operational use in the companies. The loudness balancing is, however, obviously more difficult to reproduce than the hearing threshold measurement. This is why the probability of measurement errors is relatively high.

3. How close are the results of an individual attenuation value determination to the value of the type examination test?

One possible application of systems for individual attenuation value determination is the comparison with the results of the type examination test, e.g. for the fit check of custom molded earplugs. For this, it must be known exactly how the individual measurement systems can reproduce the type examination values. According to the present study, this question can be answered only approximately. For this, in parallel with the individual attenuation measurement also a determination by the method of the type examination test would have to be done. The IFA is currently performing such a test. Here an audiometer is compared with the standard procedure for the type examination test in a diffuse sound field.

The significant deviations shown in Figures 9 and 12 of all measured systems from the type examination test might have been caused by different group of subjects.

4. How meaningful is a single number attenuation value such as the PAR?

Like the SNR value, the PAR describes the attenuation of a hearing protector for pink noise. The sound attenuation values are considered for all frequency bands, however, the low frequencies contribute only slightly to the total attenuation value due to the A-weighting. Therefore, particularly leaks that are clearly visible in the spectral plot, are difficult to detect in the single number rating. Depending on the application (e.g. fit check of custom molded earplugs), it is therefore recommended, especially to look at the low frequencies. Additionally it has to be taken into account that for the calculation of the residual level at the ear, the C-weighted sound pressure level at the workplace must be known, which is usually not the case.

Outlook: How can systems for individual sound attenuation determination be utilized in practice?

For use of systems for individual sound attenuation determination at the workplace, it is necessary that the achieved results can be easily and quickly obtained and easily interpreted. Especially when occupational physicians perform the measurements in the context of occupational medical prophylaxis, guidance should be available to assess the results that does not require expert knowledge about sound attenuation of hearing protectors.

The measurement systems provide one or more of the following values:

– Attenuation value at one frequency (rapid test, e.g. at 500 Hz)
– Attenuation values in several octave band frequencies (in the range between 125 Hz and 8 kHz)
– Single number attenuation value (usually PAR based on the SNR value).

In principle, any of these three values may be used for evaluation. However, it is necessary to define an appropriate target or benchmark, which results from the type examination values or the requirements at the workplace. Then limits must be established for this value, which must be met by the respective hearing protector.

In case of comparison with values based on the type examination test, the statistical confidence level has to be considered. The values, which are normally used for the selection of hearing protectors are based on a confidence level of 84% (average - 1 x standard deviation). This means that 16% of subjects have reached lower attenuation values during the type examination test. Referring to a confidence level of 98% (mean value - 2 x standard deviation), only real outliers are identified that are not in accordance with the examination test.

Another important point is the question of whether a measurement at only one frequency is useful to adequately estimate the exact sound attenuation of the hearing protector. In particular, it must be clarified, which frequency is suitable for the rapid test and what safety level can be achieved with this measurement (in particular regarding the use of hearing protectors at high sound levels).

These and other topics for the practical implementation of the individual sound attenuation measurement will be dealt with in a future publication in this journal.

Conclusion

The individual determination of the achieved levels of protection allows the selection of optimal hearing protectors, provides protection against unrecognized under-protection and reduces the problem of overprotection. In the past, despite the use of hearing protection, under-protection has led repeatedly to a progressive hearing threshold shift due to noise at the work place up to the development of a hearing loss.

The opportunities offered by the individual determination of the sound attenuation, have been recognized and led to different measurement systems being developed in a short time. Now the task is not only to systematize these systems, but to achieve sufficient quality control in the application.

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