

PERSONAL HEARING PROTECTION DEVICES IN REAL WORKING SITUATIONS

Development of a simplified attenuation test method for
personal hearing protection devices and determination of
attenuation values in real working situations

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HEARING PROTECTION DEVICES: THEIR ATTENUATION IN REAL WORKING-SITUATIONS AND SIMPLIFIED METHODS TO MEASURE THEIR EFFECTIVENESS

EXECUTIVE SUMMARY

In occupational health services, there is an increasing need to determine the attenuation of a hearing protector worn by an individual worker at his workplace. If this attenuation is known it is possible to decide whether the hearing protector in question, as worn by the individual worker, offers sufficient protection. One of the aims of the project described in this report is to meet the observed need of occupational health services by developing measuring methods by which the attenuation of hearing protectors as worn by individual workers can be determined.

The other aim of the project is to determine the attenuation of hearing protectors, as worn by workers in the coal- and steelindustry in real working situations.

The project has been carried out within the scope of the fifth EGKS-program for medical research, by order of Hoogovens B.V. by the TNO Institute of Preventive Health Care in the period of May 1991 to April 1993, and has been carried out in a number of stages:

- stage 1a experimental research, in which measuring methods are prepared to be used in the field research of stage 2;
- stage 1b collecting and analyzing noise spectra collected at workplaces at Hoogovens to determine a number of spectra, representative for the noise situations in the coal- and steelindustry;
- stage 2 field research with measurements of the frequency-dependent attenuation values of several types of hearing protectors and analysis of data. Determination of a simplified method to test the attenuation of hearing protectors;
- stage 3 field research to apply the simplified test method;
- stage 4 repetition of field research to determine the reproducibility of the simplified test method.

In the project, gradually two simplified test methods have been developed, based on the following considerations:

- a method should be usable for (nearly) all workers, irrespective of their noise induced hearing impairment or other hearing deteriorations;

- a method should be useful for all types of hearing protection devices. In advance, active hearing protectors have been excluded;
- a method should not be too expensive considering the purchase of equipment;
- a method should be simple to apply and should give in a quick and reliable way a useful result;
- a method should be applicable close to the workplace of industrial and other workers.

It turned out to be necessary to consider two test methods: one method for devices worn *in* the ear canal, insert type hearing protectors (foam and cotton wool ear plugs and individual pre-moulded hearing protection devices) and another method for devices worn *over* the ear canal (ear muffs, safety cap ear muffs, ear plugs connected by a headband). Both methods are comparable considering test signals, test equipments and test circumstances. In the method to test insert type hearing protection devices a special constructed 'deep' ear muff is used to ensure that the devices do not touch the ear muff during testing. Small loudspeakers, such as usually used for audiometry, are mounted in the muffs. The hearing threshold levels are measured twice: once with the hearing protection devices and once without them. The difference is the attenuation of the hearing protection device. Research in the laboratory showed that there were no statistically significant differences at any frequency in the attenuation, determined by this method compared with the standardised method (ISO 4869-2).

In the method to test hearing protectors which are worn over the ear canal, use was made of a 'reference' ear muff with known attenuation values. The test signals are presented by a loudspeaker in the testroom. The hearing threshold levels are measured twice: once with the hearing protector and once with the 'reference' ear muff. To determine the attenuation of the hearing protector, comparisons are made between these two hearing threshold levels, taking the average attenuation of the 'reference' ear muff into account. Both methods can be carried out in a small audiometric booth within a mobile audiometry-unit, which is suitable for conventional threshold audiometry in hearing conservation programs.

The test signal in both methods is a narrow band noise with centre frequency 500 Hz. In the method in which the deep ear muff is used, also a pure tone of 500 Hz can be used. The choice of 500 Hz as the only test frequency is a result of an analysis of the relations between the frequency-dependent attenuation of 236 hearing protectors, worn by 173 workers, and the sound pressure levels of 13 representative noise spectra. The measurements of the attenuation of the hearing protectors, worn by workers of the coal- and steelindustry, have been carried out in stage 2. The 13 representative noise spectra have been derived from 196 1/3-octave band spectra measured at workplaces in the coal- and steelindustry. The 13 noise spectra have been splitted up into three categories. As criteria for the

categories were taken the differences in C-weighted and A-weighted level ($L_C - L_A$): for low-frequency spectra more than 9 (3 out of 13 spectra), for high-frequency spectra less than 1 (4 spectra) and for the middle-frequency spectra between 1 and 9 (6 spectra). In choosing 500 Hz as test frequency, not only the results of the analysis of the relations between the attenuation of hearing protectors and the noise spectra have been taken into account, but also the reproducibility of the test results at the various frequencies. The reproducibility of the test results has been the main object in the stages 3 and 4 of the project. In that respect it was shown that the individual attenuation-values at 500 Hz of the hearing protectors worn over the ear canal have a standard deviation of 6 dB. This standard deviation is of about the same magnitude as the standard deviation of the difference of two hearing threshold level measurements at 500 Hz using conventional audiometric test techniques.

Therefore the following was concluded:

- the attenuation of hearing protectors as worn over the ear canal (ear muffs, safety cap ear muffs, ear plugs connected by a headband) by an individual worker does not show any substantial variations from measurement to measurement;
- the measurements using the reference ear muff are an optimum, since more reliable results can not be achieved considering the nature of the measurements.

The standard deviation of the individual attenuation-values at 500 Hz of hearing protectors worn in the ear canal turned out to be 8 dB. Analysis of the data shows:

- the attenuation of hearing protectors worn in the ear canal (foam and cotton wool ear plugs and individual pre-moulded hearing protection devices) as worn by an individual worker does show an appreciable variation from measurement to measurement. This variation is represented by a standard deviation of 6 dB;
- the measurements using the deep ear muff are an optimum, since more reliable results can not be obtained, considering the nature of the measurements.

When the attenuation at 500 Hz is determined, using the simplified test methods, standard deviations of 6 and 8 dB have to be taken into account for respectively the reference ear muff method and the deep ear muff method.

Due to bone conduction, the simplified test methods do not give correct attenuation values in a (small) category of workers. It concerns partly those workers in which the hearing threshold level at 500 Hz, determined while wearing the hearing protection, is over 55 dB. If a worker appears to have such a hearing threshold level, then conventional air- and bone conduction audiometry is necessary to

determine whether the determination of attenuation is appropriate. The report describes the measurement procedure.

To determine whether a hearing protector attenuates sufficiently noise at a workplace, the frequency-weighting of noise according to the A-characteristic also plays an important role, since the harmful effect of noise is determined by the A-weighted equivalent sound level over a workday ($L_{Aeq,8h}$). In that respect, the ultimate aim of using hearing protection is to attenuate noise at the workplace sufficiently to prevent the worker from noise-induced hearing loss. In the practical situation, when the equivalent sound level is for instance 95 dB(A) at the workplace, the overall attenuation of the hearing protector should be at least 15 dB(A) to limit the resulting noise exposure to less than 80 dB(A). The report gives relations between the attenuation ($D(500)$) of a hearing protector at 500 Hz and the overall attenuation in dB(A) ($D(A)$). These relations depend upon the frequency composition of the relevant noise:

$D(A) = 4 + 0,75 D(500)$: low-frequency spectra;

$D(A) = 7 + 0,75 D(500)$: middle-frequency spectra;

$D(A) = 15 + 0,75 D(500)$: high-frequency spectra.

To prevent noise-induced hearing loss from exposure to noise at the workplace of 80 dB(A) or more, the attenuation at 500 Hz of a hearing protector has to be at least 0 dB and has to fulfill the following requirements:

$D(500) > 4/3 (L_{Aeq,8h} - 79)$: low-frequency spectra;

$D(500) > 4/3 (L_{Aeq,8h} - 82)$: middle-frequency spectra;

$D(500) > 4/3 (L_{Aeq,8h} - 90)$: high-frequency spectra.

In general, the attenuation values such as determined in the second stage of the project by the extensive method, turned out to be less than those given by the manufacturer of the hearing protection devices. As an example, the attenuation-characteristic used in the Netherlands (mean attenuation minus one time the standard deviation) at 500 Hz turned out to be less: for the two types of ear muffs 0 to 11 dB, for safety cap ear muffs 3 dB, for ear plugs connected by a headband 18 dB, for two types of individual pre-moulded hearing protectors 8 and 17 dB and for foam ear plugs 16 dB. This elicits the necessity of a method to determine the attenuation of hearing protectors worn by the individual worker.

1. INTRODUCTION

It is becoming increasingly obvious that in occupational health services there is a need for a way to determine the attenuation of hearing protection devices worn by individual workers in real-world situations. If this attenuation is known, it can be determined on the basis of noise measurements whether in an individual case the hearing protector in question is providing satisfactory protection against the actual noise at the workplace. One of the goals of the project described in this report was to try to fulfil this identified need by developing a measuring method which could be used to determine the attenuation provided by hearing protection devices worn by workers in practical situations. The second goal of the project described was to determine the attenuation of the hearing protection devices as worn by workers under actual working conditions.

The project was carried out during the period from May 1991 to April 1993 by TNO as part of the fifth EGKS (European Coal and Steel Community) program for medical research under contract to Hoogovens B.V. The measuring method which was developed is, in the first instance, intended for use in determining the attenuation of hearing protection devices specifically in the coal and steel industry. The measuring method finally arrived at, has general applicability, however. The attenuation values determined in the project are valid only for the situation dealt with in the project. In other situations, such as those involving different instructions of the workers on the wearing of hearing protection devices and different maintenance procedures of the hearing protectors, different attenuation values may be appropriate.

The various parts of the project are described in detail in four NIPG-TNO Reports 93.018, 93.019, 93.020, and 93.021. This report (TNO-PG 94.028, indicating a change in the name of the Institute) is an English translation of NIPG-TNO Report 93.022 and it presents the broad outlines of the study and describes the results obtained. The first draft translation of NIPG-TNO report 93.022 has been provided by Cabot Safety Corporation, Indianapolis, USA.

2. CONDITIONS FOR THE MEASURING METHOD TO BE DEVELOPED

To be usable within the framework of occupational health services, a method for determining the attenuation provided by personal hearing protection should meet a number of practical conditions. At the beginning of the project, our attention was focused on the following conditions:

- the method should be applicable to (almost) every worker who wears hearing protection. In this regard, special attention must be given to the requirement that the measuring method should also be applicable without systematic error to workers with (some) (noise-induced) hearing loss;
- the method should be applicable to (almost) every type of hearing protection device. In this respect active hearing protectors, that is, hearing protectors with variable sound attenuation, have been excluded from the project;
- it should be possible to apply the method without the need to purchase expensive equipment;
- the method should be easy to use and lead quickly and reliably to a useful result;
- it should be possible to implement the method close to the workplace of the workers.

With these five conditions as a basis, two measuring methods were developed gradually over the course of the project. At the very beginning of the project, it appeared necessary to take into account two methods, not just one: one for insert type of hearing protection devices, such as pre-moulded ear plugs, glass fiber plugs, custom moulded plugs and foam plugs; and another method for hearing protection devices which are worn over the ears or which block the entrance to the auditory canal such as ear muffs, helmet muffs (ear muffs mounted on a safety helmet), and ear plugs attached to a headband. It was tried to make the two measuring methods as compatible with each other as possible with respect to, for example, test signals, test apparatus and test conditions.

3. FROM THE LABORATORY TO THE REAL WORLD

A measuring method for determining the attenuation of hearing protection devices has been published by the International Organization for Standardization (ISO) as ISO 4869-2, entitled "Acoustics — Measurement of Sound Attenuation of Hearing Protectors — Subjective Method". This method for determining the attenuation of hearing protection devices consists in determining the hearing threshold levels of a prescribed minimum number of test persons, once without wearing and once wearing hearing protection. The difference between both measurement results is taken as the attenuation value. The test signals are presented to the test subjects through loudspeakers, and the test is conducted simultaneously in both ears. For the determination of the hearing threshold levels, the background sound level in the testroom should meet strict requirements. However, in practice, such as in factories and plants, such rooms are unlikely to be found. Then, the following two possibilities are available in dealing with these strict requirements pertaining to the background level in the testroom:

1. the test signals can be presented to the test subjects through loudspeakers, which are installed inside deep muffs. This method is suitable only for insert type of hearing protectors. The deep muff should fit over the entire hearing protector without touching it.

The use of a deep muff offers the advantage that the background level in the testroom can be much higher than would be acceptable for measurements without muffs, because the deep muffs are able to reduce the background level to a certain extent at the ears of the test subject.

Applying the deep muff method, one measurement is made with the hearing protector inserted in the auditory canal and one measurement is made without the protector; each ear is tested separately. In the project, the deep muff developed for this purpose and supplied in the Netherlands by Veenhuis Medical Audio have been used. The headphones in the deep muffs were connected to a Madsen clinical audiometer, model OB802;

2. to measure the attenuation of ear muffs, etc., a "reference muff" with known attenuation characteristics was used. The measurement of the hearing threshold levels without hearing protection as prescribed in ISO 4869-2 is replaced by a measurement of the hearing threshold levels while the reference muff is being worn. In conjunction with the known attenuation of the reference muff, the difference between the hearing threshold levels measured with the reference muff and those measured while the hearing protector in question is being worn gives the attenuation of the hearing protector in question. As prescribed in ISO 4869-2, the test signals are presented simultaneously to both ears of the test subject through a loudspeaker.

In applying the reference muff method in the project, the Madsen OB802 audiometer mentioned above and its accompanying output amplifier has been used.

Since it is very important in practice to be able to measure the attenuation of hearing protection devices close to the workplace of the workers in question, it was checked whether use could be made of a mobile van. The available mobile van has been described in Passchier-Vermeer, 1988. A small sound-insolated booth has been installed in this mobile van. The sound insulation of this "minicabin" together with the sound insulation of the mobile van is sufficient to be able to carry out threshold audiometry in the cabin, even if the mobile van is located in noisier surroundings. The use of the mobile van thus presents no problems with respect to the background sound levels during the measurement of the attenuation of hearing protectors by either the deep muff or the reference muff method. The question was whether the sound field of the test signals, as they are being transmitted by the loudspeaker in the minicabin for the reference muff method, satisfied the requirements of ISO 4869-2. When this was checked, it was found that 5 out of the 63 measurement values showed a somewhat greater deviation than allowed by ISO 4869-2 (see Table 3 of NIPG-TNO Report 93.018). These deviations could be corrected to a sufficient extent by keeping the head of the test person more or less steady by means of a head support and by applying narrow bands of noise as test signals instead of pure tones. Fortunately, it could therefore be concluded that the minicabin was suitable in principle for measurements with test signals produced by the loudspeaker.

In the first, experimental phase of the project, the following was determined:

- the agreement between the attenuation of an insert-type hearing protection device as measured in accordance with ISO 4869-2 and the attenuation determined by means of the deep muff method. To meet fully the requirements imposed by ISO 4869-2, these measurements were conducted in the acoustic chamber of NIPG-TNO;
- the attenuation of the reference muff. This attenuation was also determined in accordance with ISO 4869-2 in the acoustic chamber of NIPG-TNO;
- the agreement between the hearing threshold levels of test subjects wearing the reference muff during the measurement in the acoustic chamber of NIPG-TNO, for which all requirements according to ISO 4869-2 were completely satisfied, and during the measurement in the mobile van.

The results of the experimental phase appeared to justify the use of the mobile van of NIPG-TNO to measure the attenuation of hearing protectors by both the deep muff method and the reference muff

method. For a detailed account, see NIPG-TNO Report 93.018. For the purposes of the present report, the following four outcomes appear to be of importance:

1. The measurements with the deep muff were conducted both with pure tones and with narrow-band noise as test signals. The measured hearing protectors were the foam plugs EAR. The agreement between the mean attenuation measured with pure tones applied to the deep muff and the mean attenuation measured according to ISO 4869-2 appeared slightly better than that between the mean attenuation determined with narrow-band noise and that according to ISO 4869-2 (see Tables 13 and 14 of NIPG-TNO Report 93.018). On this basis, measurement with pure tones is slightly preferable in the deep muff method to measurement with narrow-band noise. Nevertheless, preference is given to the latter alternative, because the sound field of pure tones in the reference muff method does not at all fulfil the specifications of ISO 4869-2, and therefore in the reference muff method narrow-band noise had to be used.
2. The reference muff used in the project was a "Viking" model (foam filled muff cushions) from Bilsom. The average attenuation of this muff as measured by NIPG-TNO was somewhat higher at almost all frequencies than that supplied by the manufacturer. The standard deviations in the attenuation values appeared in general somewhat smaller in the measurements by NIPG-TNO than in those of the manufacturer. The measurements by NIPG-TNO therefore show somewhat higher attenuation than the results supplied by the manufacturer.
3. Both in the mobile van and in the acoustic chamber, the hearing threshold levels were determined at nine frequencies, while the reference muff was being worn. At two frequencies, the results obtained at the two measurement sites appeared to be statistically significant different. At 500 Hz, the hearing threshold levels in the acoustic room were, on average, higher (greater hearing loss), and at 6000 Hz lower. In view of the fact that attenuation measurements do not involve absolute hearing threshold levels but rather only differences in hearing threshold levels, the observed differences are of minor important in practical terms.
4. Even though the deep muff method is suitable for measuring differences in hearing threshold levels, the deep muff is not suitable for determining absolute hearing threshold levels, since in threshold audiometry, hearing threshold levels should be determined with respect to the internationally standardized zero-level of an audiometer (ISO 389). There is not such an internationally standardized zero-level for the deep muff nor a standardized calibration method. An indication of the zero-level for the deep muff was obtained from the experimental phase of the project. It turned out that there was a difference between this zero-level and that of a conventional audiometer (see Tables 15 and 16 of NIPG-TNO Report 93.018) and that this difference appeared to be strongly dependent on frequency. For pure tones, for example, this

difference turned out to be 31.5 dB at 1000 Hz and 14.4 dB at 2000 Hz. For narrow bands of noise, different values are applicable. Therefore it should be concluded that the deep muff is not suitable for determining absolute values of hearing threshold levels.

4. THE FIRST STEP FROM THE COMPREHENSIVE TEST METHOD TO THE SIMPLIFIED TEST METHOD

According to ISO 4869-2, the attenuation of a hearing protector should be determined at a minimum of 9 frequencies in the range from 125 to 8000 Hz. To simplify the measuring method, it was considered whether sufficient information could be obtained from fewer frequencies.

In general, the attenuation of hearing protection devices is frequency-dependent, and the composition of the noise at workplaces is also often a frequency-dependent phenomenon. This is shown by octave and third-octave band sound spectra recorded at workplaces. To evaluate whether a hearing protector provides sufficient attenuation of the noise prevailing at the workplace, the weighting of noise according to the A-characteristic also plays a role. The harmfulness of a situation is defined by the equivalent sound level in dB(A), and ultimately the purpose of a hearing protector is to attenuate sound to such a degree that the resulting sound which manages to get through the hearing protector is not harmful to the auditory organ. For instance, at a workplace with an equivalent sound level of 95 dB(A), the attenuation of hearing protectors should be at least 15 dB(A), in order to reduce the resulting sound level to a value below the safe limit of 80 dB(A).

If the frequency-dependent attenuation of a hearing protector is known, it is possible to calculate the attenuation $D(A)$ of the hearing protector in dB(A) for each sound spectrum; the attenuation value in dB(A) depends on the shape of the sound spectrum in question. Therefore, the first step in simplifying the method was to examine the sound spectra which occur at workplaces. In the project, which was focused in particular on the coal and steel industry, use was made of the sound spectra recorded at a large number of workplaces during the past years at Hoogovens (see NIPG-TNO Report 93.019). The 79 sound spectra which were available at the beginning of the project were each normalized to a value of 80 dB in the octave band with center frequency of 1000 Hz without changing the shape of the spectrum in any way. Then, the 79 normalized spectra were grouped into eleven clusters, so that, within one cluster, the sound spectra had more or less the same shape. In this way, the number of spectra could be reduced to eleven. These spectra were indicated as "standard" spectra. Figures 1 and 2 show these eleven standard spectra: in Figure 1 unweighed and in Figure 2 the A-weighting has been applied. In the course of the project, the eleven standard spectra were compared with more recent data from 117 sound spectra. From this, it was found that situations with low-frequency sounds were underrepresented in the standard spectra. To obtain a more representative picture of the noise situation in the coal and steel industry, it was necessary to supplement the standard spectra with two

low-frequency sound spectra (spectra 13 and 16 of Appendix 4 to Report 93.019). These spectra are not shown in Figures 1 and 2 for the sake of clarity.

Figure 1. Octave band sound pressure levels (unweighed) of the eleven standard spectra.

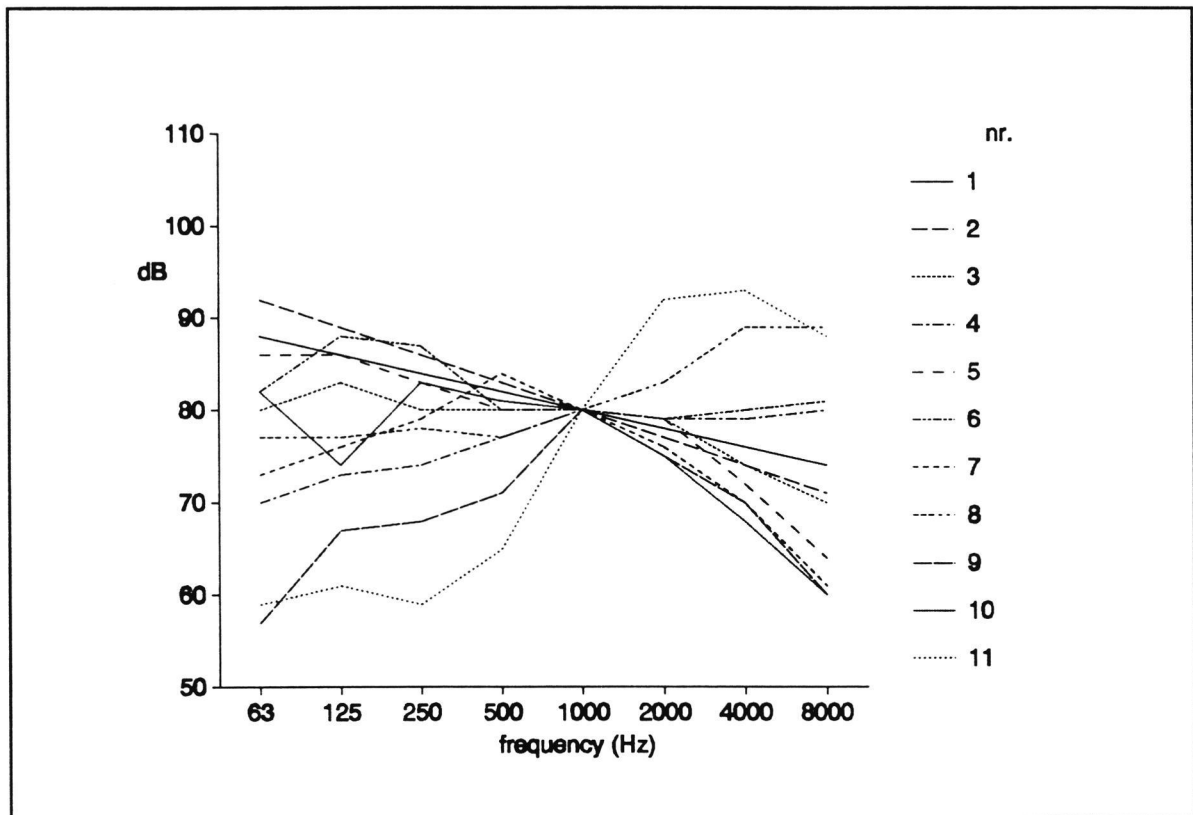
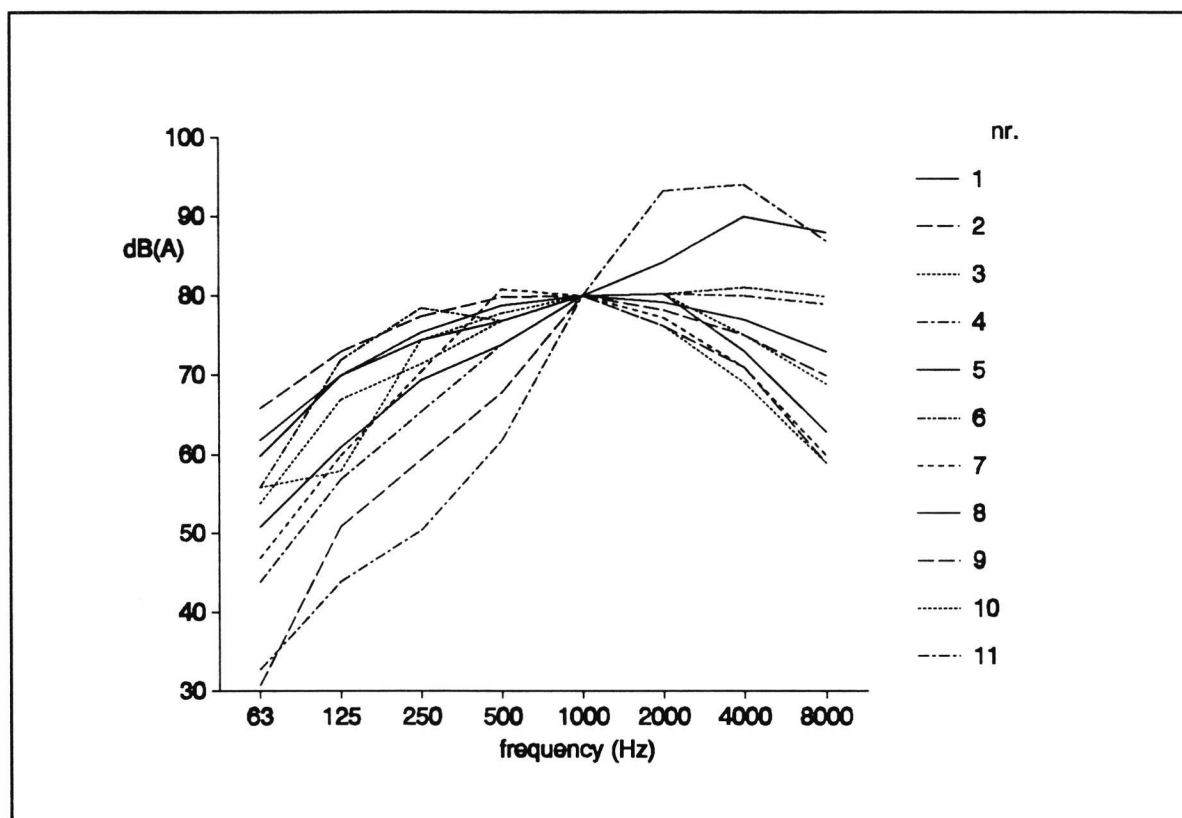


Figure 2. Octave band sound pressure levels of the eleven standard spectra.



Note: the numbers of the spectra in the figures 1 and 2 do correspond, but different marks have been used in both figures for the same spectrum.

In addition to the establishment of the noise situations in the coal and steel industry, it was also necessary for the problem at hand to know the frequency-dependent attenuation of the hearing protection devices such as worn by the individual workers at Hoogovens Groep B.V. These frequency-dependent attenuations were determined for 173 workers, wearing various types of hearing protection devices, in the first field study of the project (see NIPG-TNO Report 93.020). The average attenuation values, the standard deviations of the attenuation values, and the assumed attenuation (average attenuation minus one time the standard deviation) were determined for nine types and brands of hearing protection devices (see Section 4 of NIPG-TNO Report 93.020). The results are listed in Table 1 and in Figures 3-11. The attenuation characteristics given by the manufacturers are also given in the figures.

Table 1 Average attenuation values (m.a.), standard deviations (s.d.) and assumed attenuation (a.a.)*. All values in dB. The numbers of hearing protection devices tested (n) have also been presented.

type	brand	number		frequency in Hz								
				125	250	500	1000	2000	3000	4000	6000	8000
MUFFS	Peltor H3	n	m.a.	14.2	23.3	28.7	31.2	36.3	37.2	38.4	37.1	32.5
			s.d.	2.8	4.1	3.1	3.5	5.2	3.2	6.4	9.6	9.2
			a.a.	11.4	19.2	25.6	27.7	31.1	34.0	32.0	27.5	23.3
			n	13	13	13	13	13	11	12	13	13
	MSA Mark IV	n	m.a.	14.6	21.1	24.6	31.2	30.4	36.6	36.6	36.0	29.2
			s.d.	5.5	8.0	8.6	11.1	10.5	11.9	11.3	12.9	11.0
			a.a.	9.1	13.1	16.0	20.1	19.9	24.7	25.3	23.1	18.2
			n	13	13	13	13	13	12	13	11	13
MUFFS ON HELMET	Bilsom Comfort	n	m.a.	11.7	19.4	20.3	26.0	28.0	32.4	36.6	38.2	32.0
			s.d.	4.0	2.3	4.8	4.1	6.4	6.6	6.8	7.7	10.1
			a.a.	7.7	17.1	15.5	21.9	21.6	25.8	29.8	30.5	21.9
			n	20	20	20	20	20	20	19	19	20
PLUGS ON HEADBAND	Caboflex	n	m.a.	10.1	15.6	10.1	11.3	18.3	26.0	27.7	32.1	25.2
			s.d.	7.7	6.5	8.5	7.5	7.1	6.3	8.4	10.3	9.9
			a.a.	2.4	9.1	1.6	3.8	11.2	19.7	19.3	21.8	15.3
			n	28	28	28	28	28	27	27	26	28
CUSTOM MOULDED PLUGS	Eicea H03 grey filter	24	m.a.	7.7	11.5	13.5	21.9	30.2	33.5	33.1	34.0	32.5
			s.d.	6.5	6.8	8.8	10.3	7.3	5.9	9.0	11.7	10.6
			a.a.	1.2	4.7	4.7	11.6	22.9	27.6	24.1	22.3	21.9
	Varifoon	30	m.a.	19.5	22.5	27.7	30.5	37.2	41.3	38.8	40.3	39.3
			s.d.	7.7	8.1	10.4	9.6	6.9	7.9	8.0	8.7	9.6
			a.a.	11.8	14.4	17.3	20.9	30.3	33.4	30.8	31.6	29.7
FOAM PLUGS	EAR	58	m.a.	19.5	22.5	24.5	25.6	35.5	40.4	42.3	43.0	43.8
			s.d.	8.1	9.2	11.1	9.4	7.4	8.6	9.3	9.2	9.1
			a.a.	11.4	13.3	13.4	16.2	28.1	31.8	33.0	33.8	34.7
PRE- MOULDED PLUGS	Willson EP100	12	m.a.	7.9	8.3	9.2	9.6	15.4	19.2	19.6	18.3	17.1
			s.d.	8.4	10.7	11.8	6.7	6.7	9.4	13.4	14.0	13.4
			a.a.	-0.5	-2.4	-2.6	2.9	8.7	9.8	6.2	4.3	3.7
GLASS FIBER	Bilsom POP	20	m.a.	7.3	8.5	13.0	15.8	27.0	31.5	31.0	33.3	32.0
			s.d.	6.4	9.0	8.7	8.3	6.4	6.5	9.9	9.3	8.0
			a.a.	0.9	-0.5	4.3	7.5	20.6	25.0	21.1	24.0	24.0

* In the Netherlands the mean attenuation minus one time the standard deviation is called the assumed attenuation and is the attenuation value used in the Netherlands.

Figure 3. Average attenuation and standard deviation for the Peltor H3 ear muff, as measured by NIPG-TNO and as given by the manufacturer.

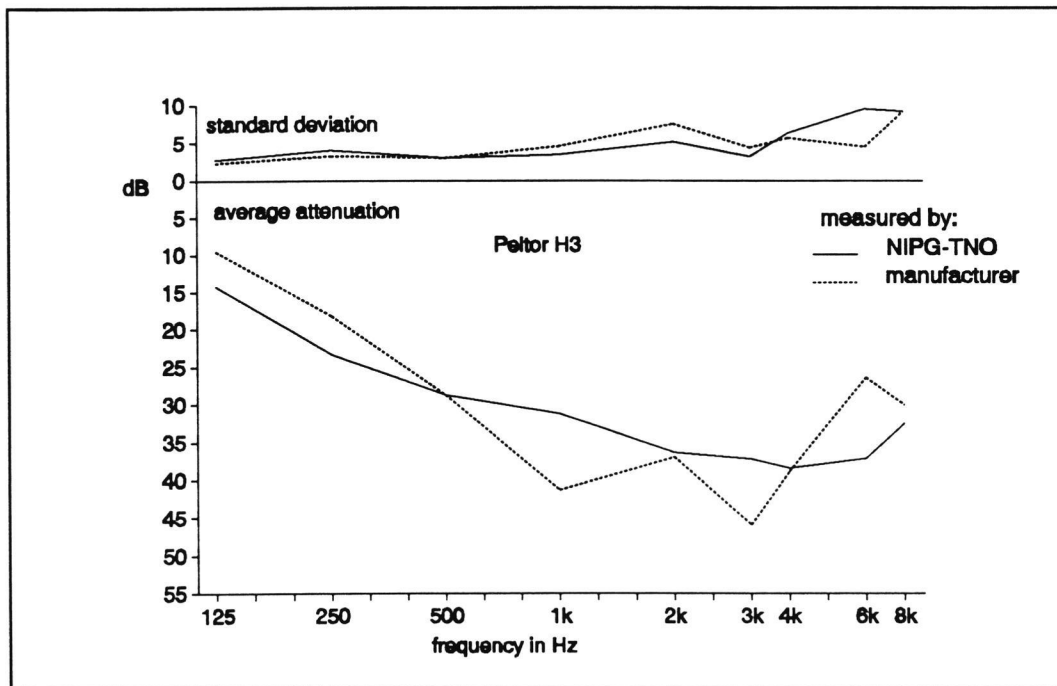


Figure 4. Average attenuation and standard deviation for the MSA Mark IV ear muff, as measured by NIPG-TNO and as given by the manufacturer.

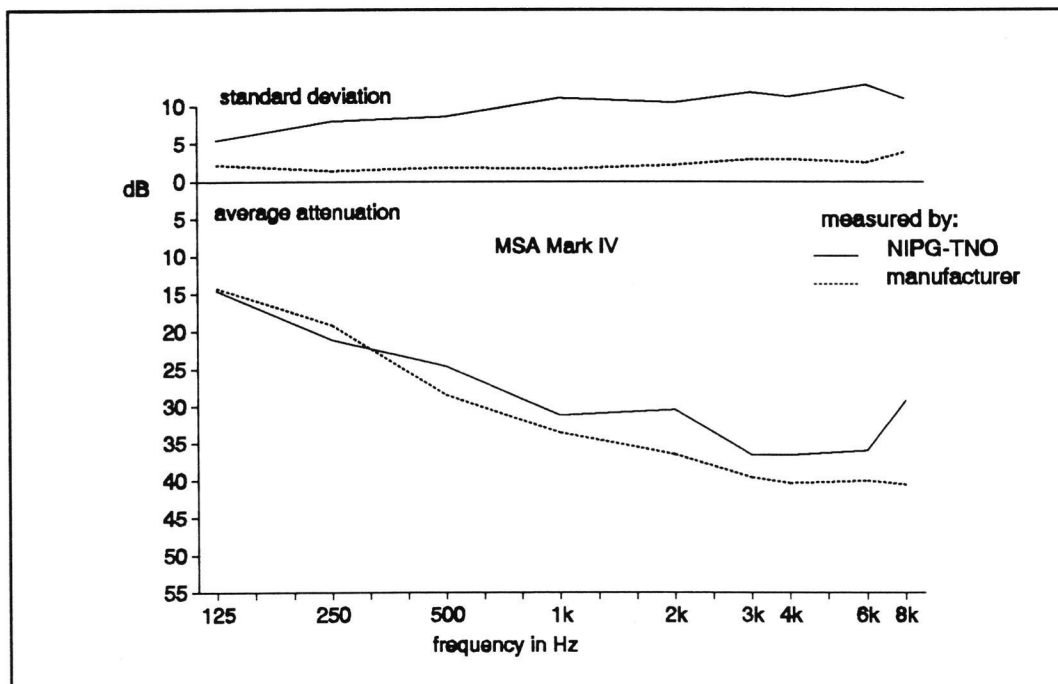


Figure 5. Average attenuation and standard deviation for the Bilsom Comfort muff mounted on a safety helmet, as measured by NIPG-TNO and as given by the manufacturer.

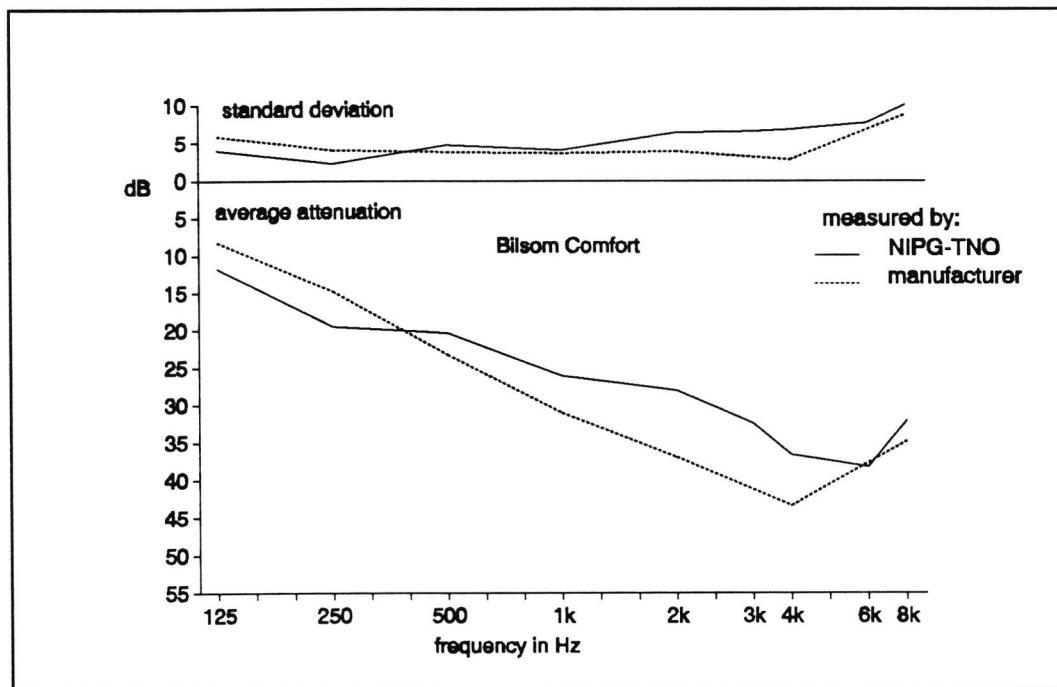


Figure 6. Average attenuation and standard deviation for the Caboflex ear plugs with headband, as measured by NIPG-TNO and as given by the manufacturer.

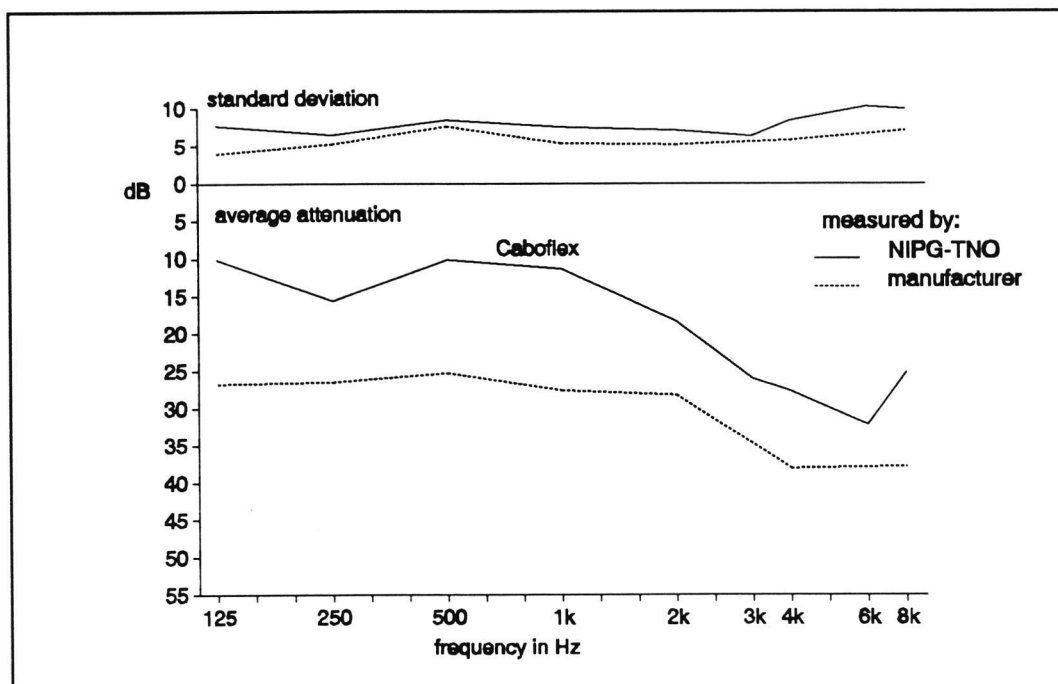


Figure 7. Average attenuation and standard deviation for the Elcea H03 custom moulded earplug, as measured by NIPG-TNO and as given by the manufacturer.

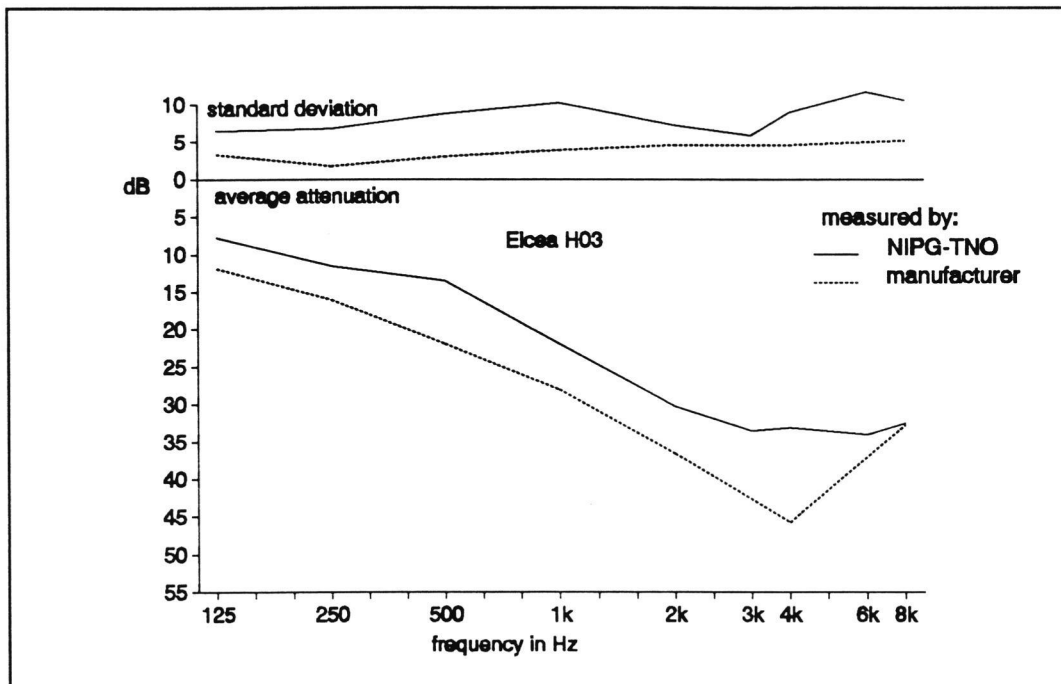


Figure 8. Average attenuation and standard deviation for the Varifofo custom moulded earplug, as measured by NIPG-TNO and as given by the manufacturer.

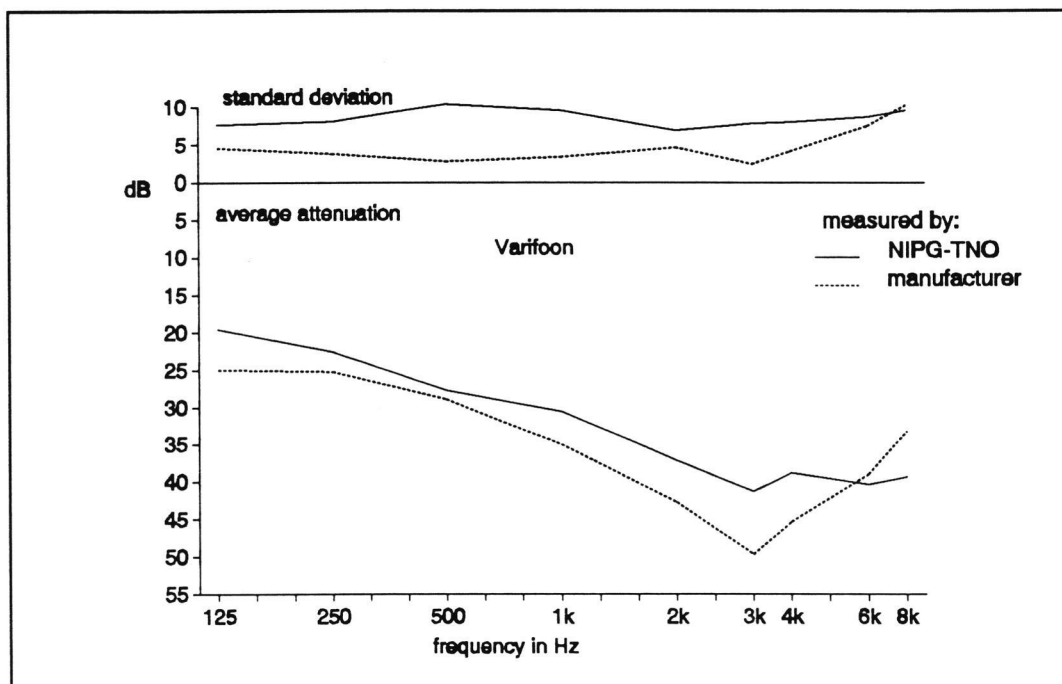


Figure 9 Average attenuation and standard deviation for EAR foam earplugs, as measured by NIPG-TNO and as given by the manufacturer.

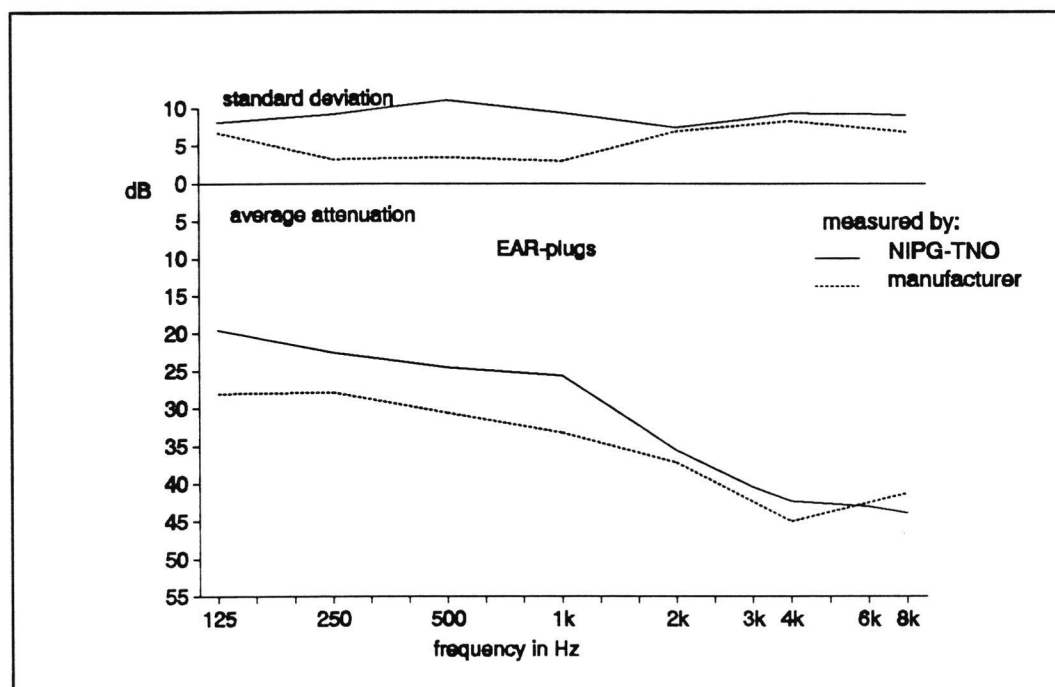


Figure 10. Average attenuation and standard deviation for Willson EP100 pre-moulded flange-type earplugs, as measured by NIPG-TNO and as given by the manufacturer.

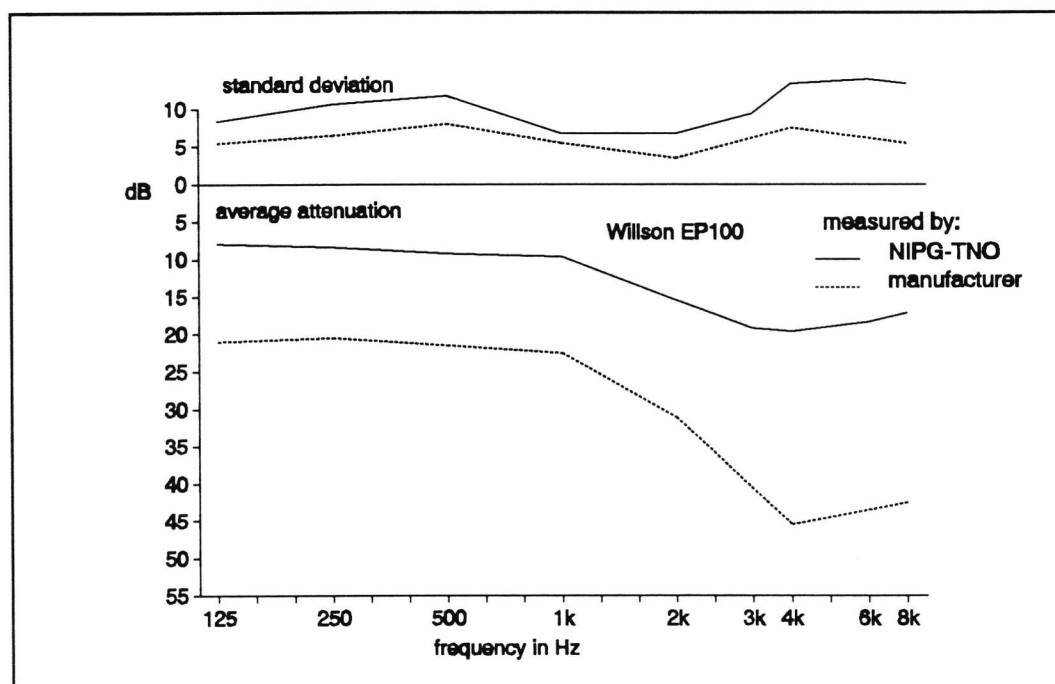
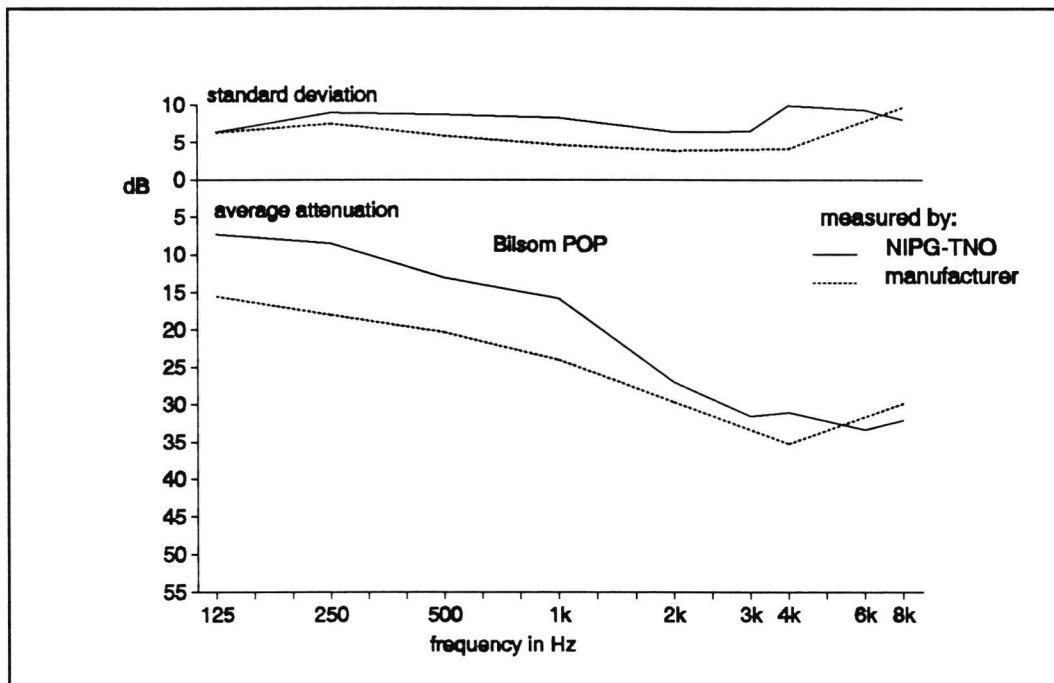


Figure 11. Average attenuation and standard deviation for Bilsom POP glass fiber earplugs, as measured by NIPG-TNO and as given by the manufacturer.



For an analysis aiming at simplifying the method for measuring the attenuation of hearing protectors, the attenuation values of 86 hearing protection devices which were determined according to the reference muff method were available and those values of 150 hearing protection devices (worn by 75 persons in two ears each) which were determined according to the deep muff method. The total of 236 individually determined attenuation characteristics were compared with the 13 spectra, mentioned before. The following aspects were considered to be important in arriving at a selection of the test frequencies to be used in the simplified measuring methods:

1. correlation between the individual values of the attenuation in dB(A) and the attenuation at a certain frequency, for a given noise situation;
2. correspondence of the relations for the different noise situations between the attenuation in dB(A) and the attenuation at a certain frequency;
3. reproducibility.

Ad 1. Per spectrum (noise situation), there is a spread in the individual measurement results when $D(A)$ is plotted against the attenuation at a certain frequency ($D(fr)$). This is illustrated in Figures 12 and 13 for spectrum 3. In Figure 12, the attenuation at 500 Hz measured by means of the reference muff method for all hearing protectors in question is plotted against the attenuation in dB(A). Figure

13 gives the results for all hearing protectors measured by means of the deep muff. The lines which show the best fit were determined by the statistical method of least squares and are also shown in the figures.

The correlation coefficient r was used to characterize the spread between $D(A)$ and $D(fr)$. This is justified from a statistical point of view, since the relationship between $D(A)$ and $D(fr)$ is linear (see, for example, Figures 12 and 13). The frequency at which the highest correlation coefficient between $D(A)$ and $D(fr)$ occurs, supplies the best estimate of $D(A)$ for a specific standard spectrum. The calculated correlation coefficients are given in Table 2.

Figure 12. The attenuation, expressed in dB(A), for spectrum 3 as a function of the attenuation at 500 Hz for all hearing protectors, as determined by the reference muff method.

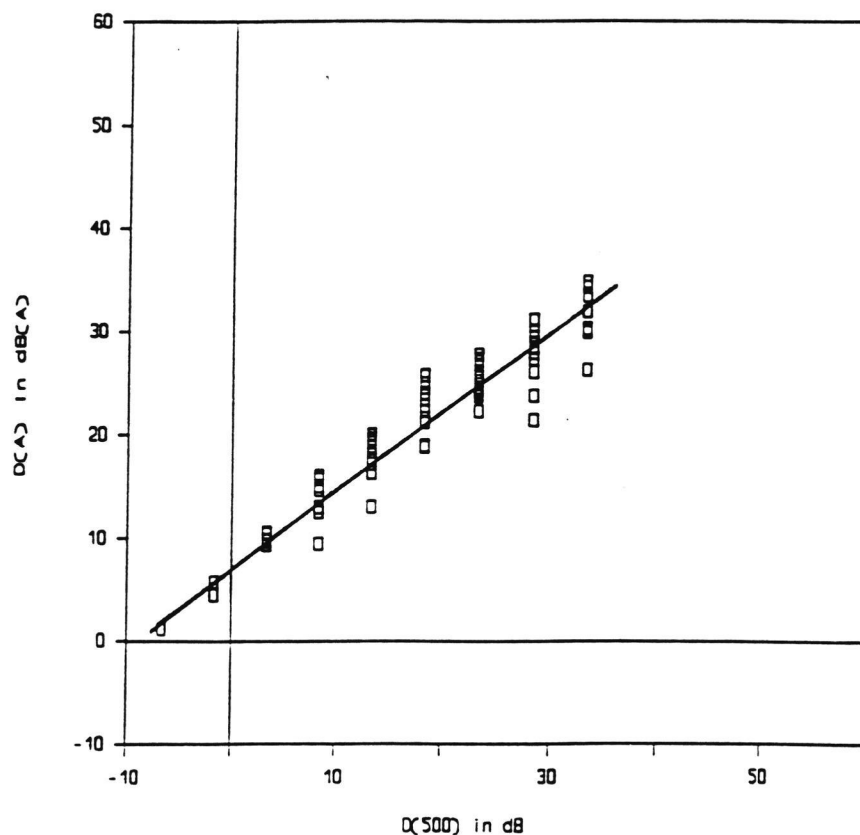


Figure 13. The attenuation, expressed in dB(A), for spectrum 3 as a function of the attenuation at 500 Hz for all hearing protectors as determined by the deep muff method.

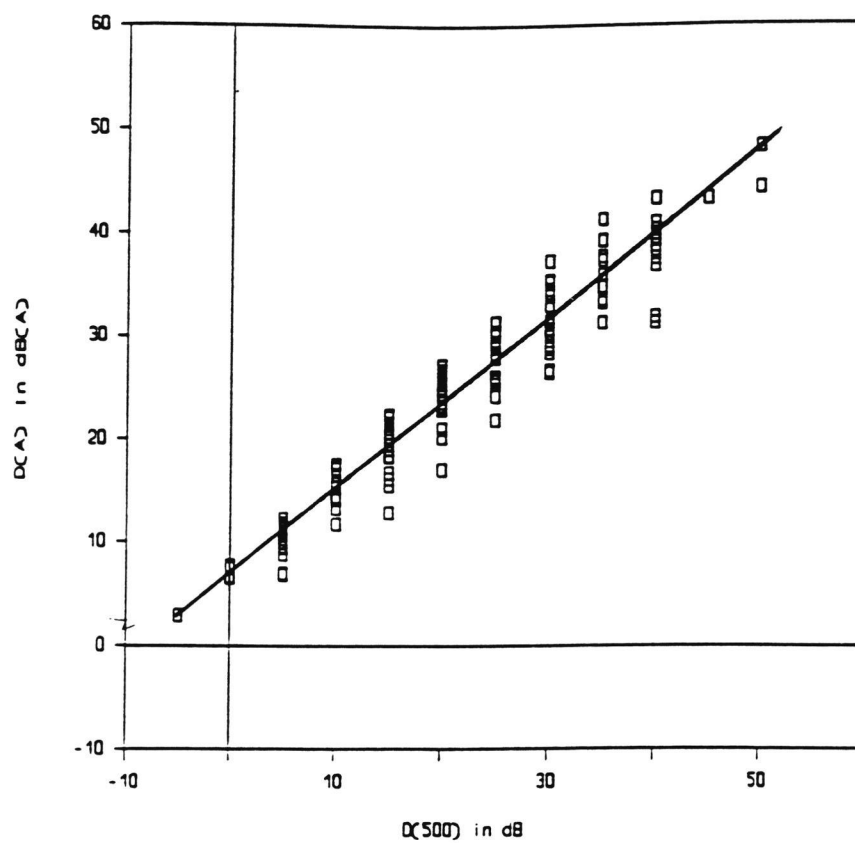


Table 2 Correlation coefficients between D(fr) and D(A) for frequencies of 125 till 8000 Hz, for the combination of 250 and 500 Hz and of 500 and 1000 Hz. Correlation coefficients for the separate spectra 1 to 11 and the spectra 13 and 16 and for the high frequency spectra (nr. 4, 8, 9 and 11), middle frequency spectra (nr. 1, 3, 5, 6, 7 and 10) and low frequency spectra (nr. 2, 13 and 16) together. Data for the reference muff and the deep muff methods are given separately.

reference muff											
	125	250	500	1000	2000	3000	4000	6000	8000	250+500	500+1k
4	0.56	0.69	0.91	0.83	0.87	0.77	0.85	0.69	0.77	0.90	0.91
8	0.51	0.64	0.82	0.78	0.83	0.75	0.87	0.78	0.86	0.81	0.83
9	0.58	0.74	0.93	0.85	0.92	0.78	0.80	0.59	0.64	0.93	0.93
11	0.51	0.65	0.79	0.79	0.95	0.76	0.85	0.69	0.75	0.79	0.82
average	0.54	0.68	0.86	0.81	0.89	0.76	0.84	0.69	0.76	0.86	0.87
1	0.69	0.77	0.94	0.83	0.81	0.74	0.76	0.56	0.60	0.96	0.93
3	0.66	0.76	0.95	0.84	0.84	0.76	0.77	0.56	0.61	0.96	0.94
5	0.71	0.78	0.93	0.83	0.82	0.73	0.75	0.53	0.57	0.95	0.92
6	0.73	0.80	0.89	0.80	0.82	0.73	0.79	0.61	0.66	0.94	0.89
7	0.57	0.73	0.99	0.85	0.80	0.76	0.74	0.55	0.60	0.97	0.96
10	0.60	0.79	0.97	0.84	0.81	0.75	0.74	0.54	0.59	0.98	0.94
average	0.66	0.77	0.95	0.83	0.82	0.74	0.75	0.54	0.61	0.96	0.93
2	0.73	0.77	0.93	0.81	0.79	0.72	0.73	0.53	0.56	0.95	0.91
13	0.68	0.91	0.90	0.78	0.78	0.71	0.71	0.50	0.55	0.98	0.91
16	0.83	0.79	0.87	0.76	0.73	0.67	0.69	0.48	0.51	0.91	0.85
average	0.75	0.82	0.90	0.78	0.77	0.70	0.71	0.50	0.54	0.95	0.89
deep muff											
	125	250	500	1000	2000	3000	4000	6000	8000	250+500	500+1k
4	0.87	0.92	0.97	0.81	0.78	0.84	0.80	0.76	0.78	0.97	0.94
8	0.85	0.89	0.92	0.80	0.80	0.87	0.87	0.82	0.85	0.94	0.91
9	0.86	0.91	0.96	0.81	0.80	0.82	0.78	0.74	0.75	0.97	0.94
11	0.74	0.75	0.79	0.77	0.92	0.86	0.88	0.82	0.83	0.79	0.82
average	0.83	0.87	0.91	0.80	0.83	0.85	0.83	0.79	0.80	0.92	0.90
1	0.92	0.96	0.96	0.79	0.72	0.79	0.75	0.71	0.72	0.99	0.93
3	0.91	0.95	0.97	0.80	0.74	0.80	0.75	0.71	0.73	0.98	0.94
5	0.92	0.96	0.95	0.79	0.73	0.79	0.74	0.70	0.72	0.98	0.92
6	0.93	0.97	0.94	0.78	0.72	0.78	0.74	0.71	0.72	0.98	0.91
7	0.87	0.92	0.99	0.80	0.71	0.79	0.75	0.71	0.72	0.99	0.95
10	0.88	0.96	0.97	0.80	0.71	0.79	0.74	0.71	0.72	0.99	0.94
average	0.91	0.95	0.96	0.79	0.72	0.79	0.75	0.71	0.72	0.99	0.93
2	0.93	0.96	0.95	0.79	0.71	0.78	0.74	0.70	0.71	0.99	0.92
13	0.89	0.99	0.93	0.77	0.68	0.76	0.72	0.68	0.70	0.99	0.90
16	0.95	0.96	0.93	0.77	0.70	0.77	0.72	0.69	0.70	0.98	0.87
average	0.92	0.97	0.93	0.78	0.70	0.77	0.73	0.69	0.70	0.99	0.90

To anticipate on what will be discussed later, in Table 2 the spectra are divided into three categories: high-frequency, middle-frequency, and low-frequency. This division is based on the difference between

the C-weighted and the A-weighted sound level ($L_C - L_A$), according to the model of a version of ISO/DIS 4869-2.2. If $L_C - L_A$ is smaller than 1 dB, then a high-frequency spectrum is involved (spectra 4, 8, 9 and 11). If $L_C - L_A$ is between 1 and 9 dB it concerns a middle-frequency spectrum (spectra 1, 3, 5, 6, 7, and 10) and if $L_C - L_A$ exceeds 9 dB a low-frequency spectrum (spectra 2, 13, and 16). In Table 2, the correlation coefficients for each of the frequencies considered are averaged per measuring method and per type of spectrum. It shows that, in the case of the deep muff method, the highest average correlation coefficient is observed twice at 500 Hz and once at 250 Hz. In the case of the reference muff method, the correlation for the low- and middle-frequency spectra is also the greatest at 500 Hz; for the high-frequency spectra, it is the highest at 2000 Hz, followed in second place by 500 Hz. To establish whether the correlation is higher when a combination of frequencies is used, correlation coefficients have been calculated for the average attenuation at 250 and 500 Hz and also for the average attenuation at 500 and 1000 Hz. The results are listed in the last two columns of Table 2. For the combination of 250 and 500 Hz, the correlation coefficient is only slightly higher in almost all cases than for a single frequency, and for the combination of 500 and 1000 Hz it is almost always somewhat lower.

All in all, it appears convincing that in using one frequency for all situations the highest correlation between $D(A)$ and $D(fr)$ is obtained by the use of the frequency 500 Hz.

Ad 2. It is the aim of the simplified measuring method to be able to use the measured attenuation at one (or more) frequencies to arrive at an estimate of $D(A)$, preferably independent of the sound situation (in this case represented by the thirteen spectra) in which the hearing protection is worn. An important aspect of the method is the agreement of the relationship between $D(fr)$ and $D(A)$ for the different spectra. The quality of this agreement can be evaluated by examination of the regression lines, determined by the method of least squares. Thus, best-fitting lines have been calculated for each spectrum in the form of $D(A) = A_{yx} + B_{yx} D(fr)$. A frequency is suitable as test frequency if the various best-fitting lines (13 in all) do not diverge too much at this frequency. To illustrate this, the thirteen best-fitting lines have been plotted in Figures 14 and 15 for the frequency of 500 Hz, both for the deep muff and for the reference muff method. In particular, the Figures 14 and 15 demonstrate the difference between the best-fitting lines at 500 Hz for the four high-frequency spectra and those for the nine middle- and low-frequency spectra.

Figure 16 shows the six average regression lines for 500 Hz. Averaging took place after dividing the individual regression lines by measuring method and by spectrum shape.

Figure 14. The lines with the best fit for $D(A)$ versus $D(500)$ for the thirteen spectra, the attenuation measured by the reference muff method. The solid lines pertain to the six middle-frequency spectra, the broken lines to the four high-frequency spectra, and the dotted lines to the three low-frequency spectra.

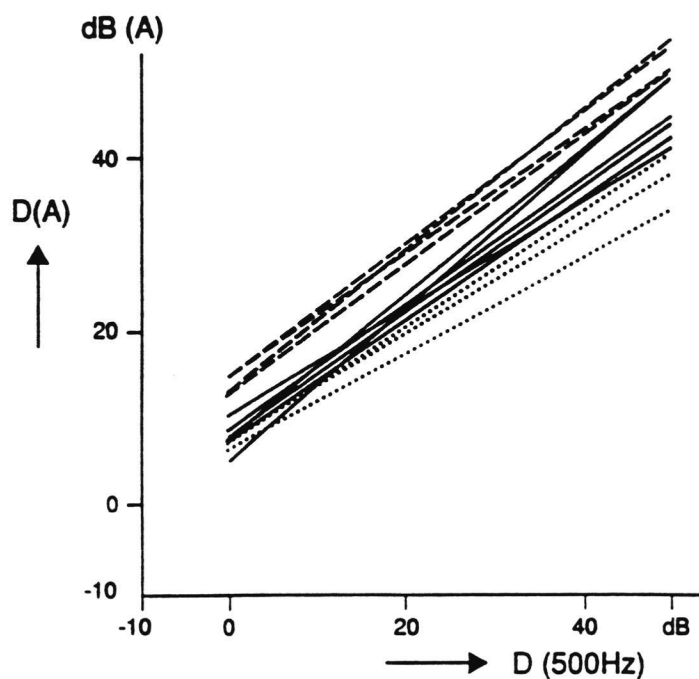


Figure 15. The lines with the best fit for $D(A)$ versus $D(500)$ for the thirteen spectra, the attenuation measured by the deep muff method. The solid lines pertain to the six middle-frequency spectra, the broken lines to the four high-frequency spectra, and the dotted lines to the three low-frequency spectra.

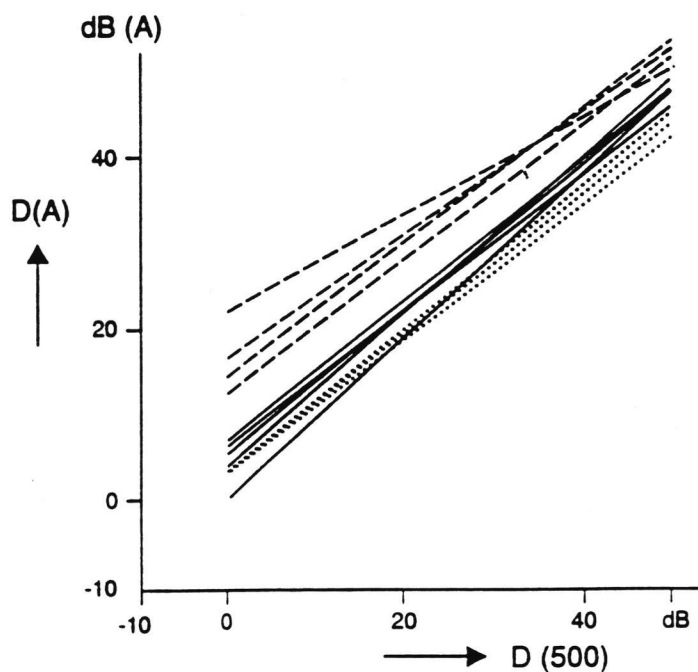
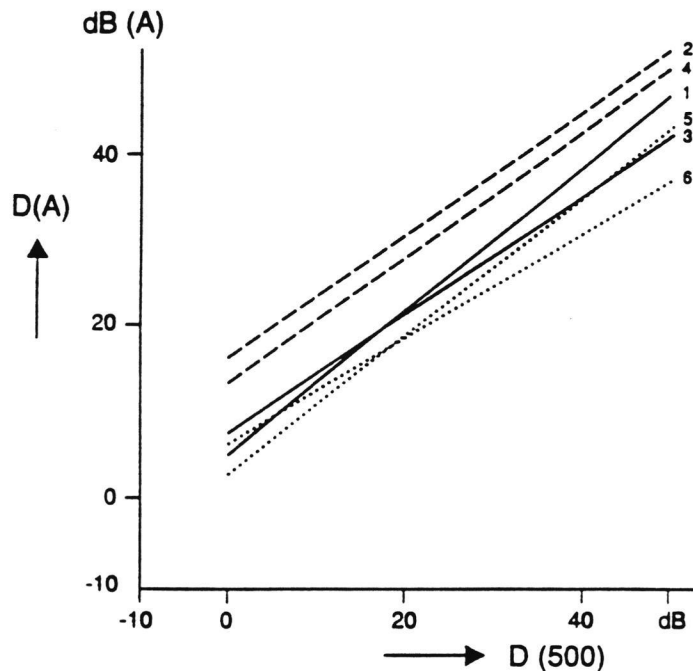


Figure 16. The average regression lines for $D(A)$ on $D(500)$; averaging according to the shape of the spectra. Formulas of the regression lines are:

1. $D(A) = 5.3 + 0.83 D(500)$; deep muff method, middle-frequency spectra;
2. $D(A) = 16.5 + 0.71 D(500)$; deep muff method, high-frequency spectra;
3. $D(A) = 7.5 + 0.70 D(500)$; reference muff method, middle-frequency spectra;
4. $D(A) = 13.4 + 0.073 D(500)$; reference muff method, high-frequency spectra;
5. $D(A) = 2.3 + 0.82 D(500)$; deep muff method, low-frequency spectra;
6. $D(A) = 6.7 + 0.59 D(500)$; reference muff method, low-frequency spectra.



The spread of the regression lines at frequencies other than 500 Hz is not smaller than at 500 Hz. Therefore, there is no reason to prefer other frequencies over 500 Hz as test frequency.

The regression lines given in Figure 16 show the attenuation of a hearing protector not to be determined solely by the attenuation it produces at 500 Hz. For instance, if a hearing protector is worn and $D(500)$ is virtually zero, then, in the case of middle-frequency spectra, an attenuation of 5 to 7 dB(A) is obtained as a result of the attenuation at frequencies other than 500 Hz.

Ad 3. With respect to the applicability of a method in practice, it is important that its reproducibility is high. Probably, the reproducibility of the attenuation measurements is different from frequency to frequency. It has been shown that 500 Hz should be given preference as test frequency, possibly in

combination with 250 Hz and/or 1000 Hz. Therefore, in the project, the measurements were repeated, not only at 500 Hz but also at the two other frequencies mentioned.

5 THE SECOND STEP TO A SIMPLIFIED TEST METHOD: REPEAT MEASUREMENTS

Apart from the repeat measurements of the attenuation of the hearing protection devices, the sound field of the test signals in the minicabin of the mobile van was also examined again. The results of the measurements turned out to be nearly identical to those of the earlier measurements during the experimental phase (see Table 3 of Report 93.018 and Table 2 of Report 93.021).

Of the 173 workers from the first field study 150 participated in the second one. For various reasons (see NIPG-TNO Report 93.021), the measurement results of only 134 of these 150 workers could be compared with each other: 74 workers with hearing protection devices which were tested by the reference muff method, and 60 workers with hearing protection devices which were tested by the deep muff method. In Table 3, the results are given for the 74 workers with their hearing protection tested by the reference muff method.

Table 3 Comparison of attenuation values of the hearing protection devices, which were tested twice by the reference muff method. The average differences, the standard deviations of the differences and the results of the Student-t-test ($P=0.025$, two-sided tested). 74 measurements were included.

	Frequency in hertz		
	250	500	1000
mean difference in attenuation (in dB)	1,1	1,1	1,6
standard deviation (in dB)	6,0	5,8	7,3
t-value	1,64	1,60	1,92
statistical significance	no	no	no

On average, the attenuation measured during the second test was 1 dB less in comparison with the first test. These differences are not statistically significant at any of the three frequencies used.

The standard deviation in the differences between the attenuations in the first field study and those in the second field study varied from 5.8 dB at 500 Hz, 6.0 dB at 250 Hz to 7.3 dB at 1000 Hz. These standard deviations have approximately the same order of magnitude as those obtained for hearing threshold level measurements by conventional audiometric test methods. For the measuring method used in the project (manual audiometry at fixed frequencies), the standard deviation in the difference between two hearing threshold levels (i.e. in the attenuation) is 4.2 dB at frequencies of 250-1000 Hz [Passchier-Vermeer, 1988]. The standard deviation in the difference between two attenuation values is $\sqrt{2}$ times as large as that in a single attenuation value, that is, 6.0 dB. With respect to the practical

application of the method, this has the very important consequence that a possible variation in the attenuation produced by a hearing protection device is so slight that it contributes little or nothing to the standard deviation in the attenuation differences. Taking into account the conventional measurement error encountered in hearing threshold levels measurements, it can therefore be concluded that:

- the attenuation of the hearing protection devices measured by the reference muff method (ear muffs, muffs mounted on a helmet, and plugs connected by a headband) will not differ much in the individual worker from one measurement to the next; and
- the measurements with the reference muff are optimal with respect to the fact that no greater measurement accuracy can be obtained in view of the nature of the measurements.

Since the standard deviations of the attenuation differences at 250 Hz and at 500 Hz are slightly smaller than those at 1000 Hz, the former frequencies deserve slight preference over 1000 Hz as test frequency with respect to the reproducibility of the test method.

Table 4 shows the results of the measurements obtained in the second field study by the deep muff method. At all three frequencies, the attenuation in the second measurement is, on average, statistically significant smaller than that of the first measurements. In addition, the standard deviations in the differences of the attenuation values are greater than would be expected from conventional hearing threshold levels measurements.

Table 4 Comparison of the differences in the attenuation values of the hearing protection devices tested twice by the deep muff method. The average differences, the standard deviations of the differences and the results of the student t-test are given ($P=0.025$, two-sided tested). It concerns 122 measurements.

	Frequency in hertz		
	250	500	1000
average difference in attenuation (in dB)	3.0	3.0	2.1
standard deviation in attenuation (in dB)	8.6	9.2	8.6
t-value	3.83	3.63	2.70
statistical significance	yes	yes	yes

Table 5 shows the results obtained with the deep muff method, divided according to the type of hearing protector. A comparison of the results obtained for the various hearing protectors included in the study shows that the average differences and the standard deviations are smaller for the ELCEA custom moulded plugs, except at 1000 Hz, and for the glass fiber ear plugs than they are for the Varifoon custom moulded plugs and the foam ear plugs.

Table 5 Comparisons of the differences in the attenuation values of the hearing protection devices tested twice by the deep muff method.

Hearing protection devices	Number of measurements	Frequency in hertz		
		250	500	1000
<u>Custom moulded plug ELCEA</u>	22			
mean difference in attenuation (in dB)		1.8	-0.7	3.6
standard deviation in attenuation (in dB)		6.1	6.6	9.1
t-value		1.39	-0.48	1.88
statistical significance		no	no	no
<u>Custom moulded plug Varifoan</u>	26			
mean difference (in dB)		4.2	5.4	3.8
standard deviation (in dB)		9.1	9.1	7.9
t-value		2.38	3.02	2.49
statistical significance		yes	yes	yes
<u>Foam ear plug EAR</u>	50			
mean difference (in dB)		4.1	3.5	1.9
standard deviation (in dB)		8.9	9.9	8.3
t-value		3.27	2.50	1.62
statistical significance		yes	yes	no
<u>Glass fiber plug Bilsom Pop</u>	18			
mean difference (in dB)		1.9	3.9	0.6
standard deviation (in dB)		6.7	6.8	6.6
t-value		1.23	2.43	0.35
statistical significance		no	yes	no

In the third field study, the attenuation measurements by the deep muff method were repeated. Of the 61 workers tested in the second field study, 53 were tested again in the third field study. Of this number, one worker with a different (brown) ELCEA custom moulded plugs and two with Willson pre-moulded ear plugs were not taken into account in the determination of the average attenuation. In addition, the results of one worker who wore the grey ELCEA custom moulded plugs were excluded from the complete analyses (see Section 5 of NIPG-TNO Report 93.021). The results for the average attenuation values are thus based on 49 workers, i.e., 98 sets of attenuation measurements. These results from the three field studies are listed in Table 6. The analysis of the individual attenuation values is based on 51 workers, i.e., 102 sets of attenuation measurements.

Table 6 Average attenuation values and standard deviations, plus the number of attenuation measurements per protector. All values in dB.

Field investigation	model/brand	number n	average attenuation			standard deviation		
			250	500	1000	250	500	1000
1	Custom moulded plug	14	11.1	11.8	19.6	6.3	9.9	12.3
2	ELCEA grey		8.9	12.1	16.4	8.1	9.0	10.8
3			12.1	14.1	16.8	9.9	8.0	7.7
1	Custom moulded plug	22	21.4	26.1	30.0	8.0	9.3	10.6
2	Varifoon		16.6	19.3	25.9	8.4	10.5	9.8
3			16.6	21.4	25.2	10.2	9.8	9.5
1	Foam plug	46	21.8	24.0	25.3	8.7	10.8	9.1
2	EAR		17.3	20.1	22.9	8.3	8.6	8.1
3			16.8	19.1	22.3	8.6	9.2	9.0
1	Glass fiber plug	16	7.2	11.9	15.6	9.2	8.3	8.6
2			5.3	7.8	13.8	5.1	5.9	6.5
3			6.6	8.4	13.8	7.6	7.2	6.7

The results are shown graphically in Figures 17 to 20. The assumed attenuation is again the average attenuation minus one time the standard deviation.

Figure 17. Average attenuation (ma), assumed attenuation (aa), and standard deviations of the attenuation values from the three field studies: ELCEA grey custom moulded plug.

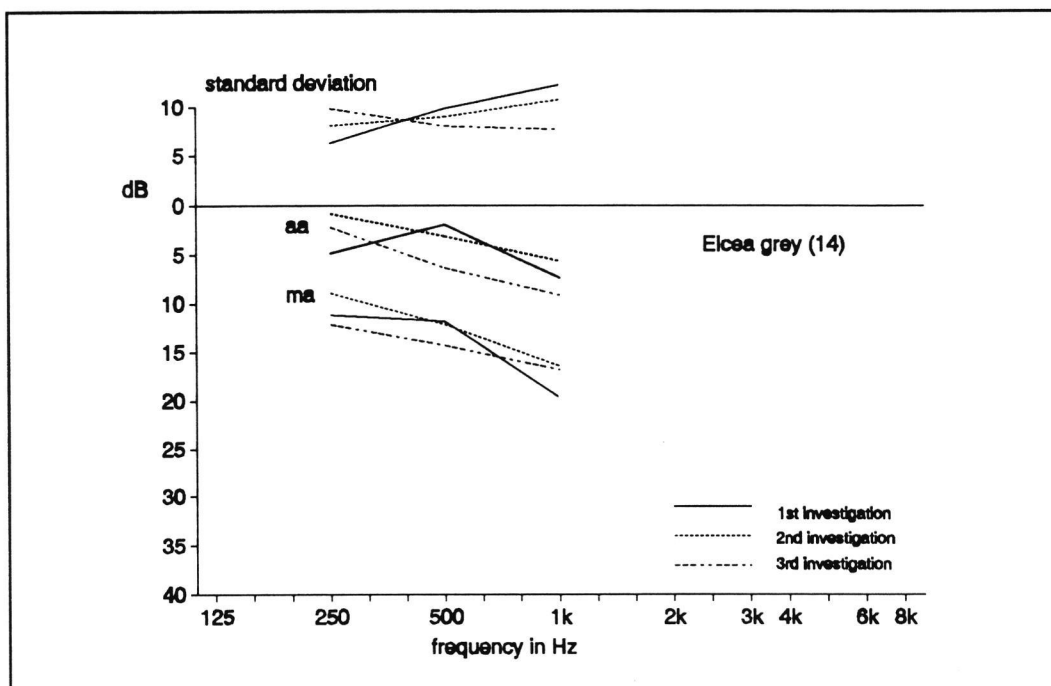


Figure 18. Average attenuation (ma), assumed attenuation (aa), and standard deviations of the attenuation values from the three field studies: Varifoon custom moulded plug.

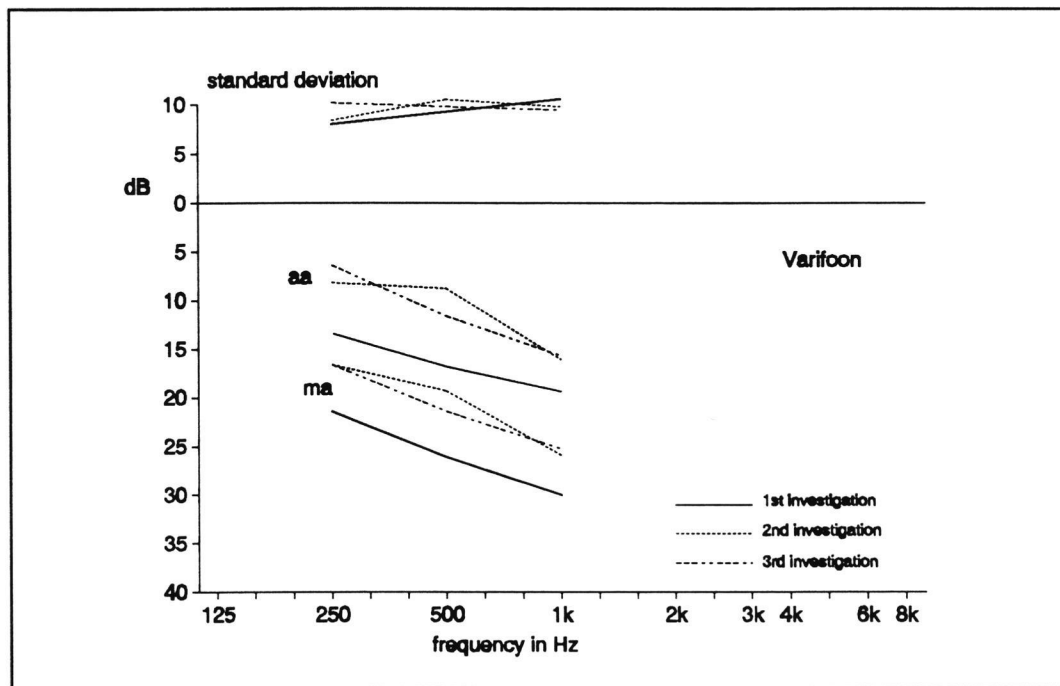


Figure 19. Average attenuation (ma), assumed attenuation (aa), and standard deviations of the attenuation values from the three field studies: EAR foam plug.

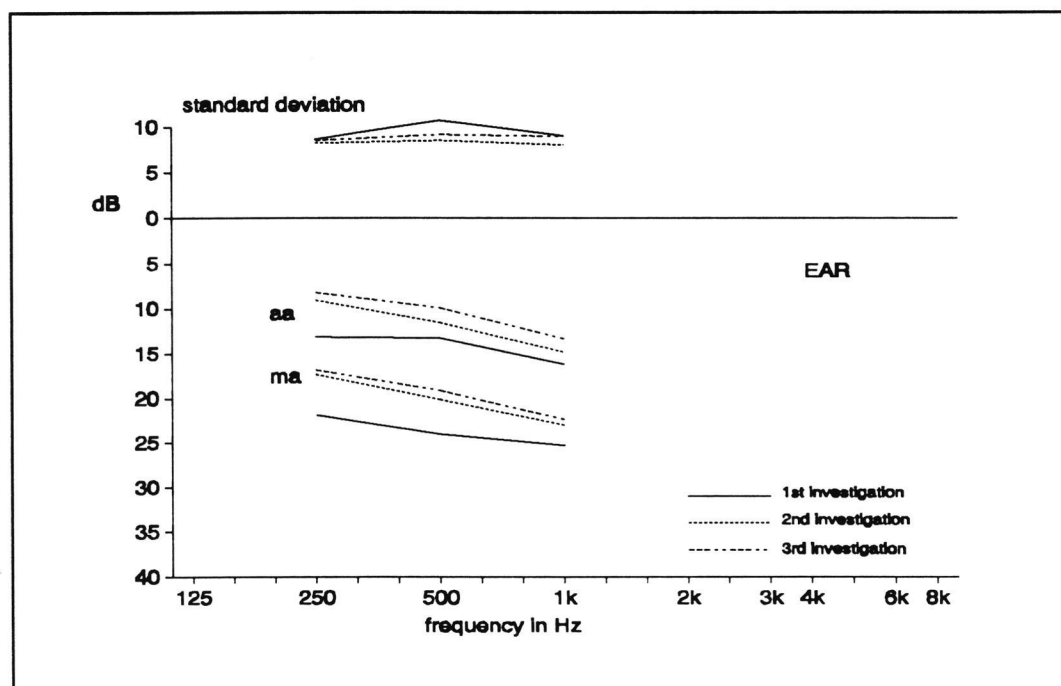
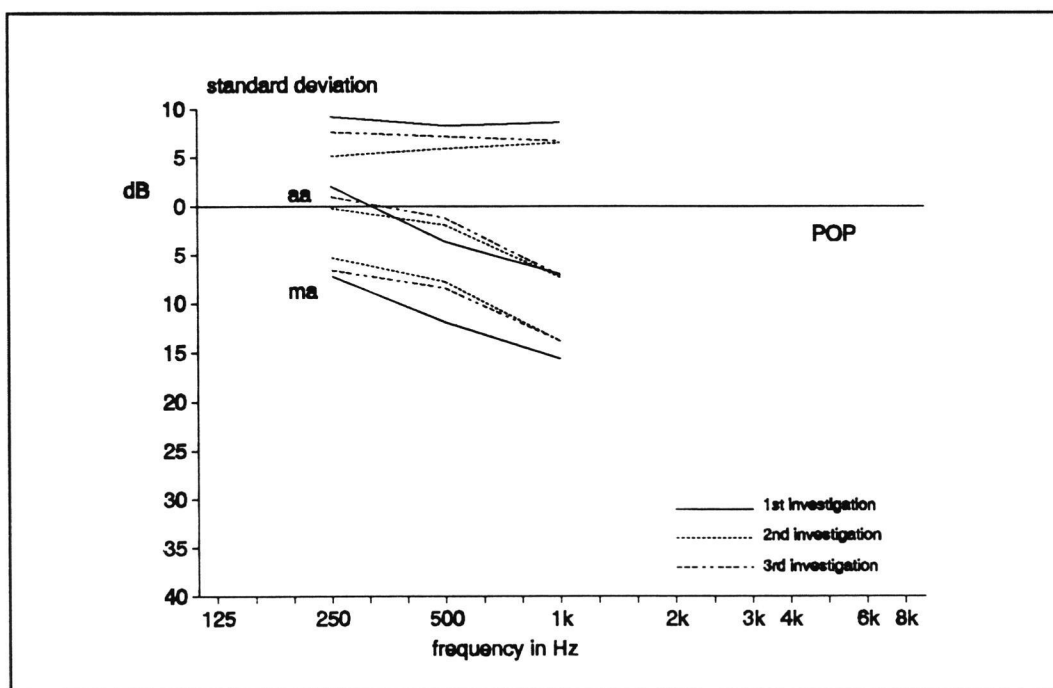


Figure 20. Average attenuation (ma), assumed attenuation (aa), and standard deviations of the attenuation values from the three field studies: glass fiber plug.



In the top section of Table 7, the differences between average attenuation values and the standard deviations in the attenuation values are given for all hearing protectors tested three times. Apparently, there are no statistical significant differences between the results of the second and the third field study at all three frequencies. There are differences, however, between the first field study and the last two studies.

Table 7 Average differences and standard deviations of the differences in the individual attenuation values and in the individual hearing threshold levels in the various field investigations (all values in dB) and the results of the Student-t test; S=significant, NS=not significant. n = 102.

DIFFERENCES IN ATTENUATION:		250 Hz	500 Hz	1000 Hz	250 Hz	t-test 500 Hz	1000 Hz
1-2	average	3.4	3.8	2.4	3.77	4.18	2.79
	s.d.	9.1	9.1	8.6	S	S	S
2-3	average	-0.5	-0.4	0.5	-0.70	-0.51	0.66
	s.d.	7.7	7.7	7.4	NS	NS	NS
1-3	average	2.8	3.4	2.8	3.22	3.81	3.40
	s.d.	9.0	9.0	8.5	S	S	S
HEARING THRESHOLD LEVELS WITHOUT HEARING PROTECTION		250 Hz	500 Hz	1000 Hz	250 Hz	t-test 500 Hz	1000 Hz
1-2	average	-0.2	-1.3	-0.9	-0.43	-3.29	-1.73
	s.d.	4.5	4.2	5.1	NS	S	NS
2-3	average	0.3	0.3	0.6	0.67	0.74	1.29
	s.d.	4.4	4.6	4.6	NS	NS	NS
1-3	average	0.1	-1.0	-0.3	0.21	-2.03	-0.52
	s.d.	4.6	5.1	5.6	NS	S	NS
HEARING THRESHOLD LEVELS WITH HEARING PROTECTION		250 Hz	500 Hz	1000 Hz	250 Hz	t-test 500 Hz	1000 Hz
1-2	average	3.2	2.4	1.5	3.63	2.82	1.96
	s.d.	8.9	8.7	7.7	S	S	NS
2-3	average	-0.2	-0.0	1.1	-0.31	-0.06	1.49
	s.d.	7.8	8.1	7.2	NS	NS	NS
1-3	average	2.9	2.4	2.5	3.53	2.52	3.24
	s.d.	8.5	9.5	8.0	S	S	S

To analyze more thoroughly the differences found among the various field studies, the three hearing threshold levels measurements carried out without hearing protection being worn, were compared with each other and also the three hearing threshold levels measurements which were performed while wearing hearing protection. The results are given in the last sections of Table 7. The table shows the hearing threshold levels measured during the second and third field studies, both with and without hearing protection, not to be significantly different from each other. Concerning the measurements without hearing protection, there are on average differences in the hearing threshold levels of only 1 dB at most, while the standard deviations have values which should be expected on the basis of conventional hearing threshold levels measurements. From this it follows that the reproducibility of the hearing threshold levels measurements without hearing protection is approximately the same as that of conventional hearing threshold levels measurements. The situation is different for the measurements with hearing protection. The standard deviations in the hearing threshold levels with hearing protection

are in the order of 8 to 9 dB, which is much higher than the values encountered in conjunction with usual hearing threshold levels measurements.

If it is assumed that a hearing threshold levels measurement with a hearing protection device in the auditory canal is just as accurate as the same measurement without a hearing protector (which is acceptable on the basis of the results from the experimental phase of the project), then the larger standard deviation in the hearing threshold levels measurements with hearing protectors is the result of the variation in the attenuation of the hearing protectors. The measuring method used is thus not to blame for the greater dispersion in the hearing threshold levels measured with hearing protectors. The standard deviation which is the consequence of the variation in the attenuation of a hearing protector is estimated to be approximately 6 dB (see NIPG-TNO Report 93.021 for the calculations).

On the basis of the repeat measurements of the attenuation of insert type hearing protectors, the following conclusions can be drawn:

- the attenuation of the hearing protectors measured by the deep muff method (custom moulded, pre-moulded, foam and glass fiber ear plugs) differs in the individual worker from one measurement to another, the standard deviation in the attenuation being approximately 6 dB;
- the measurements by the deep muff method are optimal, with respect to the fact that no greater measurement accuracy can be obtained in view of the nature of the measurements.

With respect to the choice of the frequency or frequencies of the test signals for a simplified measuring method, it was established in this section that, in the case of measurements with the reference muff, the standard deviation in the attenuation values at 250, 500, and 1000 Hz are approximately the same. The same applies to the measurements by the deep muff method. On the basis of these results, there is no reason to prefer any one of these frequencies over the other two for the purpose of a simplified measuring method.

6. DISCUSSION

6.1 Determination of the test frequency for the simplified method

In Section 4, three aspects important for the selection of the test frequencies for a simplified test method were considered. These aspects were the correlation between $D(fr)$ and $D(A)$, the agreement between the regression lines of $D(A)$ versus $D(fr)$ for the various standard spectra, and the reproducibility of $D(fr)$. The results of Sections 4 and 5 show, with respect to the first two aspects, the test frequency of 500 Hz to deserve preference and with respect to the third aspect, the three test frequencies 250, 500, and 1000 Hz to be approximately of equal value. All in all, therefore, preference should be given to 500 Hz, if a single test frequency is to suffice. A combination of the test frequencies 500 and 1000 Hz yields a lower correlation than the test frequency of 500 Hz alone. The combination of these two frequencies is therefore not preferable. The other combination considered was that of the test frequencies 250 and 500 Hz. With this combination, the correlation coefficient increases by 0.01 in comparison with the coefficient when 500 Hz is the only test frequency. For two other reasons, not discussed previously, it is not desirable to include 250 Hz as a test frequency for use by occupational health services.

The first reason involves the possibility that high background levels in the audiometric test room would mask a test signal at 250 Hz. Although no masking of the test signals at 250 Hz occurred in the minicabin used by NIPG-TNO, the lowest frequency is the most critical one with respect to masking and in the everyday practice of occupational health services this may lead to unexpected problems. The other reason pertains to the physiological noise which may occur at 250 Hz, especially during measurement of the attenuation of hearing protectors worn in the auditory canal. By blocking off the auditory canal with a hearing protector, the level of physiological noise close to the eardrum is amplified. This amplification of physiological noise may mask the test signal, with the result that the measured value obtained for the hearing threshold levels is too high. Therefore, the resulting calculation of the attenuation value yields a value which may also be too high. Berger [Berger, 1983a] has shown that, as a result of physiological noise, the average attenuation at 250 Hz is measured 2 to 3 dB too high.

At 500 Hz, this effect is almost completely absent. In summary, it can therefore be concluded that 500 Hz is the most desirable test frequency for use in a simplified method for determining the attenuation of hearing protectors in practice.

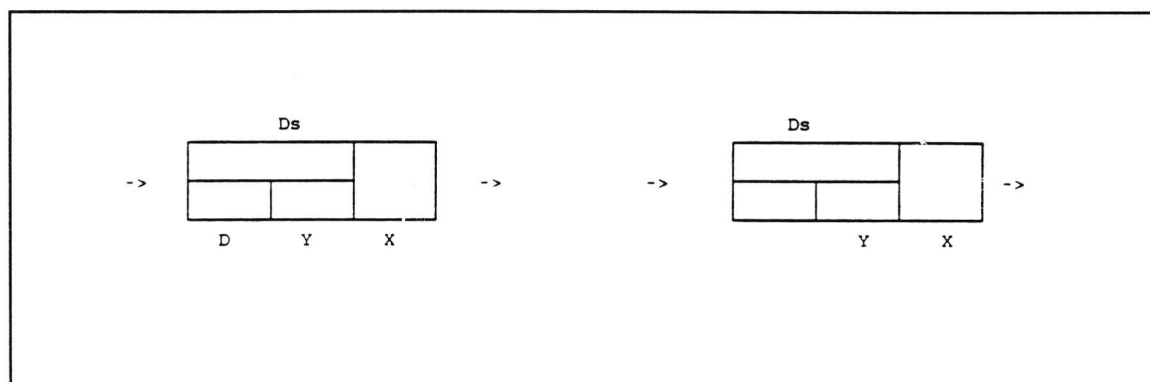
Two other reasons of a more general nature suggest 500 Hz to be a good choice as test frequency. These reasons pertain to the first two conditions which a simplified test method should fulfil: the method should be applicable to (almost) any worker, regardless of the state of his hearing, and the method should be applicable to (almost) any type of hearing protector.

In an evaluation of the applicability of test signals to workers, the following two phenomena must be taken into account:

- the possible conduction of test signals via the skull of the worker; and
- due to the bandwidth of the test signal, workers with highly frequency-dependent hearing losses may hear some test signals not at the center frequency of the test signal in question but rather at a lower or higher frequency.

With respect to the conduction of test signals via the skull, the following aspect is important. There are in principle two parallel routes along which the test signal can be conducted to the inner ear, namely, the route via the auditory canal and the middle ear and the route via the skull. The attenuations which occur are shown schematically in Figure 21.

Figure 21. Schematic diagrams of the various ways in which test signals can be attenuated. Left side: impedance with hearing protector; right side: impedance without hearing protector. D_s = skull attenuation; Y = attenuation of the middle ear; X = attenuation of the inner ear.



If, when a hearing protector is being worn, the attenuation (D) of this device plus the bone conduction loss (Y) in the middle ear is greater than the skull attenuation (D_s), then the test signal will be heard

via the skull and the inner ear. If D is greater than $D_s - Y$, it is therefore impossible to determine D . The attenuation of the skull is to some degree frequency-dependent and is in the range of 40 to 57 dB. The attenuation at high frequencies of some hearing protectors approaches these values. For the reference muff used in the project, for example, the average difference between D_s and the attenuation D at 2000-8000 Hz is only 1 to 7 dB, while at 1000 Hz the difference is 11 dB. Even if the bone conduction loss Y is small, one must therefore take into account skull conduction at high frequencies when this muff is worn. At 500 Hz, the difference between the attenuation of, for example, the reference muff (28 dB) and the skull attenuation (57 dB) is nearly 30 dB, so that skull conduction begins to play a role at this frequency once the conduction loss reaches 30 dB. For these reasons, it is therefore possible to measure the attenuation of the hearing protection of many more workers at low frequency, and therefore 500 Hz deserves to be given preference as a test frequency over higher frequencies.

With respect to the hearing of the narrow band of noise at a frequency other than the center frequency in question, the following should be remarked. In the project, the narrow bands of noise were used, which are normally used in audiometry and which have a decrease in level of 24 dB/octave. This implies that, for a worker with a difference in his hearing threshold levels of 25 dB between two frequencies one octave apart, if the center frequency of the test signal corresponds with the frequency at which the highest hearing threshold level of the worker occurs, the signal will not be heard at the center frequency, but rather at the adjacent frequency with the lower hearing threshold level. In fact, therefore, the hearing threshold level is not determined at the center frequency of the test signal, but at other frequencies in the offered signal which the worker in question is more available to hear. If 1/2-octave band intervals are used (at the test frequencies of 2000, 3000, 4000, 6000 Hz), the same is applicable at a difference of only 12 dB between hearing threshold levels.

With respect to 500 Hz as the center frequency of the test signal, the following should be said: It can be derived from Table 1 that, in practice, the average difference in the mean attenuation of the hearing protectors at 500 Hz and at 250 Hz is 3 dB; for the attenuations at 500 Hz and 1000 Hz, this average difference is -4 dB. In practice this means that, if the hearing threshold level of a worker at 500 Hz is 25 dB or more higher than at 250 Hz, the estimate of the attenuation of a hearing protector at 500 Hz from a measurement with a test signal with mid-frequency of 500 Hz, is on average 3 dB too low; and, if the hearing threshold levels at 500 Hz is 25 dB or more higher than at 1000 Hz, the estimate of the attenuation is 4 dB too high. Therefore, as a result of the bandwidth of the test signal, there may

be a slight error in the estimated attenuation at 500 Hz. Fortunately, both phenomena hardly ever occur in workers, so that this seems to be irrelevant for the practical situation.

6.2 Exclusion criteria

Unfortunately, it is not possible by means of the simplified methods described above to determine the attenuation of hearing protectors in every single worker. This possibility depends on the hearing of the workers in question. The determination of the attenuation (D) of a hearing protector in the case of a worker with a bone conduction loss Y is possible only if $D + Y < D_s$ (see figure 21). In the determination of the hearing threshold levels with and without hearing protection, measurements were conducted in which $D + X + Y$ or $X + Y$ were determined; from these measurements there is no information available on the separate component Y of the hearing threshold levels. To solve this, the following procedure should be followed to conclude whether it is possible to determine the attenuation of a hearing protector in the case of a specific worker. It is assumed that the skull attenuation at 500 Hz is 55 dB. Berger [Berger, 1983b] gives an average value of 57 dB at 500 Hz.

First, it is assumed that there is little difference between the hearing in the two ears of a worker. The following two possibilities are then to be distinguished:

1. The measured hearing threshold levels, when the hearing protection is worn, does not exceed 55 dB. Then skull conduction can be ignored and the attenuation of the hearing protector can be determined from the difference between the hearing threshold levels with and without the hearing protector by the use of the deep muff method and from the difference between the hearing threshold levels with the hearing protector and that with the reference muff by the use of the reference muff method.
2. The measured hearing threshold level with hearing protection exceeds 55 dB. In this case, components X and Y of the hearing threshold levels are determined by comparison of the results of bone conduction audiometry and air conduction audiometry. If it turns out that the measured hearing threshold levels with hearing protection minus the air conduction loss X does not exceed 55 dB, then the attenuation can again be determined by the method described above. If this difference in the measured hearing threshold level and X is greater than 55 dB, the attenuation cannot be estimated from the measuring results, since during the determination of the hearing threshold level in the presence of hearing protection conduction through the skull is measured, because $D_s < D + Y$.

There is also the possibility that there is a considerable difference in the hearing threshold levels of the two ears of a worker. Here, too, skull conduction sometimes plays an important role. In the case of the reference muff method, the test signal is transmitted simultaneously to both ears. Therefore, during the measurement of the two-sided hearing threshold level in the presence of hearing protection and during the measurement when the reference muff is worn, it is the lowest of the two hearing threshold levels of one ear which is determined in both cases. Possible skull conduction between the two ears is thus irrelevant. It should be realized, however, that in fact only the attenuation of the hearing protector at the better ear is determined. This is, after all, a defect from which any method suffers in which the test signals are transmitted to both ears simultaneously.

In the case of the deep muff method, skull conduction during the measurement of the attenuation of a hearing protector in the less acute ear can be of importance. That is, if the test signal is transmitted to the less acute ear (ear 1), it will be heard at the other ear (ear 2) if $D_1 + Y_1 + X_1$ is greater than $D_2 + X_2$. In that case, it will be necessary again to use a procedure such as that described earlier to determine whether the attenuation of the hearing protector can be determined in the less acute ear. If the measured hearing threshold level with hearing protection is more than 55 dB in the less acute ear, then by comparison of the results of bone- and air conduction audiometry, the components X_1 , Y_1 , X_2 , and Y_2 of the hearing threshold levels can be determined. If the measured hearing threshold level with hearing protection on the less acute ear is more than 55 dB plus the air-conduction loss X_1 of the better ear, then the determination of the attenuation of the hearing protector for the less acute ear is not possible.

The exclusion procedure can therefore be summarized as follows:

if any hearing threshold level at 500 Hz is measured which is higher than 55 dB, air- and bone-conduction losses of the two ears are established by means of a comparison of results of air- and bone-conduction audiometry. If the measured hearing threshold level with hearing protection minus the air-conduction loss exceeds 55 dB, then it is not possible to determine the attenuation of the hearing protector. In the case of measurement by the reference muff method this air-conduction loss concerns the smallest air-conduction loss of one of the two ears, and in the case of the measurement by the deep muff method it concerns - in the case of the estimation of the attenuation of the hearing protector on the less acute ear - to the air-conduction loss of the better ear. In that case, the attenuation of the hearing protector at the better ear can be determined without any problem by using the deep muff method.

6.3 Application of the simplified test method

Figure 16 shows the lines with the best fit for $D(A)$ versus $D(500)$ in six possible cases. It can be seen that the best-fitting lines are nearly independent of the method used and differ according to the shape of the spectra, i.e., whether they contain high, middle, or low frequencies. The average lines for the high-frequency, middle-frequency, and low-frequency spectra are:

$D(A) = 4.5 + 0.71 D(500)$: low-frequency spectrum;

$D(A) = 6.4 + 0.77 D(500)$: middle-frequency spectrum;

$D(A) = 15.0 + 0.72 D(500)$: high-frequency spectrum.

As a simple rule of thumb, it is possible to use:

$D(A) = 4 + 0.75 D(500)$: low-frequency spectrum;

$D(A) = 7 + 0.75 D(500)$: middle-frequency spectrum;

$D(A) = 15 + 0.75 D(500)$: high-frequency spectrum.

In this way, the A-weighted attenuation of a hearing protector can be estimated from its attenuation at 500 Hz. In the preceding, it has already been indicated that the standard deviation in the attenuation at 500 Hz is 6 dB in the case of the reference muff method and 8 dB in the case of the deep muff method. It follows from this according to the formulas given above that the standard deviations in $D(A)$ are 4.5 and 6 dB(A), respectively.

The attenuation of the hearing protectors in real working situations should at least be such that it guarantees that there is no chance of the worker in question to acquire noise-induced hearing loss. This implies that the equivalent sound level at the workplace in question minus the attenuation $D(A)$ of the hearing protector, should not exceed 80 dB(A). If also the standard deviation in $D(A)$ of approximately 5 dB(A) is taken into account, then the difference between the equivalent sound level and $D(A)$ should not be 75 dB(A). Written as a formula, this gives:

$$L_{\text{Eq},8h} - D(A) \leq 75 \text{ dB(A)}.$$

From the rules of thumb given above, it can be deduced that:

$D(500) > 4/3 (L_{\text{Eq},8h} - 79)$: low-frequency noise;

$D(500) > 4/3 (L_{\text{Eq},8h} - 82)$: middle-frequency noise;

$D(500) > 4/3 (L_{\text{Eq},8h} - 90)$: high-frequency noise.

These formulas should in no way be interpreted to mean that, for example, in the case of high-frequency sound with an equivalent sound level of less than 90 dB(A) no hearing protection is

needed because $D(500)$ does not need not to be larger than 0 dB. Even with an attenuation of 0 dB at 500 Hz, the attenuation at higher frequencies is, in this case, such that the attenuation taken over the entire spectrum is sufficient to prevent noise-induced hearing damage. The formula given above are considered to be applicable only for $D(500)$ values of at least 0 dB.

7. CONCLUSION

This report gives an outline of how and on what basis the method for measuring the attenuation of hearing protectors can be simplified for use in practical situations. The conclusions are based on situations encountered in the coal and steel industry. The noise situation is characterized in the project by eleven standard spectra and two additional spectra. Before the results can be applied to other industrial situations, it would be necessary to determine whether the thirteen spectra also cover these other industrial noise situations.

The simplified test methods have also been based on the individual, frequency-dependent attenuation characteristics of hearing protectors as used by workers of a specific factory (Hoogovens). It is not expected that this frequency dependence is different in other industrial circumstances. In addition, the attenuation values determined in the project lie within the ranges found in other practical situations. The conclusion thus appears to be justified that the simplified test methods developed can be applied in practice in all industrial situations.

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