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Uncertainties in noise-induced permanent threshold shift

TNO Prevention and Health
COP

Wassenaarseweg 56
PO Box 2215
2301 CE Leiden
The Netherlands

Phone +31 71 5 18 18 18
Fax +31 71 5 18 19 20

author:
W. Passchier-Vermeer

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SUMMARY

This report discusses the assessment of noise-induced permanent threshold shift and of noise-induced hearing handicap in populations exposed to occupational noise as well as in individual occupational noise-exposed subjects. It is focused on methods for the allocation of hearing threshold level shifts to noise (noise-induced hearing threshold shift: N) and to age (age-related threshold shift: A) in individual subjects. In this report the population data given in the International Standard ISO 1999 are the basis for the methods discussed for allocating A and N in individual subjects. The methods are illustrated by using the hearing threshold levels averaged over the four frequencies 0.5, 1, 2, and 3 kHz, because this average is most frequently used in the USA to estimate hearing handicap.

Uncertainties in the allocation of N and A in individual subjects are due to uncertainties in population assessments of noise-induced threshold shift and due to uncertainties related to individual differences.

In the report two factors that contribute to uncertainties in **population** assessments are outlined. One factor concerns the question of appropriate age-related data-bases and the other concerns the correlation of hearing threshold levels at different frequencies.

In the report four age-related data bases are mentioned. Since it is unclear what age-related data base is applicable for what population, the variation induced by this incertainty has to be taken into account in individual assessments of N and A. In the report it is shown that for longer exposure times and for noise exposure levels of more than 90 dB(A), the use of different age-related data bases may cause differences in the estimated percentages noise-induced threshold shift in populations of 10 to 15%.

Usually, hearing handicap is calculated by assuming a perfect correlation between the hearing threshold levels at different frequencies. To get some insight in the question of the real correlation of hearing threshold levels at different frequencies, for the purpose of this report, data have been analyzed of the hearing threshold levels of a population of occupational noise-exposed subjects and of a population not exposed to occupational noise. It was shown that correlations between hearing threshold levels in these two populations are far from perfect. This suggests that also in other populations these correlations may be far from perfect. As a consequence of this less than perfect correlation, the standard deviations of the average values of the hearing threshold levels in these two populations is only 81% of the standard deviation that would occur in the case of a perfect correlation between the hearing threshold levels at different frequencies. This reduced variation in

the average hearing threshold levels does have a substantial effect on the (95%) confidence intervals with which noise-induced hearing threshold level shift is allocated in individual subjects.

The methods proposed by Dobie (Dobie, 1990, 1992, 1993a, 1993b) to estimate noise-induced permanent threshold shift in **individual** subjects from the population data given in ISO 1999 have been outlined in this report and their consequences have been regarded. Dobie specifies three methods for the allocation of hearing threshold level shifts (and hearing handicap) to noise and to aging in individual subjects:

1 the method of median-based allocation, to be applied if a subject has been exposed to one occupational noise exposure level during a number of years and this occupational noise exposure level is known;
2 a method of allocation, to be applied if a subject has been exposed to one noise exposure level during a number of years and this noise exposure level is unknown;
3 a curve-walking method, to be applied if a subject has been exposed to different noise exposure levels during successive periods of his working career.

The most important problem for the individual assessment of noise-induced hearing threshold level shift is the lack of information about the correlation of A and N in individual subjects. In this respect, the strategy proposed by Dobie, namely to curtail the likely distributions of N by assuming that the correlation between A and N is somewhere in the range between zero (r=0.0) and a perfect correlation (r=1.0) is considered to be a reasonable approach to get more insight in the problem.

If <u>the noise exposure level of a subject is known</u>, three (point) estimates of his noise-induced permanent threshold shift have been derived in the report:

1 by using the median-based method of allocation as proposed by Dobie;
2 by assuming a perfect correlation between A and N;
3 by assuming no correlation between A and N.

For a subject with a hearing threshold level equal to the median population value, these three point estimates of N are equal. Differences do exist in these three point estimates if the hearing threshold level of a subject is above the median population value. There is no information available on which a preference for any of the three point estimates can be based.
Assuming the correlation between A and N to be perfect (r= 1.0), in other words, assuming that subjects are equally susceptible in acquiring noise-induced threshold shift and in acquiring age-related threshold shift, the allocation of A and of N in a subject with a known noise exposure level

would then be most accurately done not by the method of median-based allocation, but by a more elaborate method which takes the susceptibility of the subject into account. For more than average susceptible subjects the method which takes the susceptibility of the subject into account results in lower allocations to noise than the median-based method of allocation. Assuming a perfect correlation between A and N, A and N in an individual subject can be calculated with very small (95%) confidence intervals.
If a correlation between A and N is assumed to be in the range between a zero and a perfect correlation, which is more plausible than the assumption of a perfect correlation, then the 95% confidence interval of N in an individual subject depends on his noise exposure level and this confidence interval is shown to be large at the higher noise exposure levels in the case of zero correlation between A and N. In the case of zero correlation between A and N the 95% confidence interval of N for longtime occupational noise exposure (exposure during 40 years) is equal to 20 to 26 dB (dependent upon the age-related data base chosen) if the noise exposure level is 90 dB(A), and as large as 32 to 44 dB if the noise exposure level is 100 dB(A). The width of this confidence interval for N in an individual subject does not depend on the hearing threshold level of the subject.
It is highly recommended that not only point estimates of N, but also the 95% confidence intervals assuming zero correlation between A and N are taken into account in the assessment of the effects of occupational noise on the hearing threshold level of an individual subject.

The method of allocation of N and A suggested by Dobie for subjects with unknown noise exposure levels has shown to have serious weaknesses. The proposed procedure attributes all variation in hearing threshold levels of populations to the occupational noise exposure. Therefore the method gives a high estimate of the occupational noise exposure level, also when the hearing threshold level of the subject falls well within the distribution of hearing threshold levels of populations without occupational noise exposure.

Objections with respect to curve-walking methods, and especially the one proposed by Dobie, are:

- there is no empirical support for any curve-walking method. In the report an alternative to the method proposed by Dobie is suggested, which is more plausible than the curve-walking method proposed by Dobie. This other method of curve-walking gives other results with respect to allocation of noise-induced threshold shift due to subsequent occupational noise exposures, as has been illustrated in this report;

- a curve-walking method applied to a *combination* of hearing threshold level shifts at different frequencies may give incorrect results since noise-induced threshold shift as a function of exposure time differs from frequency to frequency. For instance, in the example with which Dobie illustrates his method, the application of his curve-walking method to a *combination* of hearing threshold level shifts is one of the reasons why the conclusion that the second noise exposure does not induce any threshold shift may be incorrect;
- any curve-walking method should take into account the (95%) confidence intervals of N. Since the correlation between A and N in individual subjects is unknown, for the calculation of such intervals a zero correlation should not be excluded.

1. INTRODUCTION

1.1 Scope and contents of the report

This report discusses the assessment of noise-induced permanent threshold shift and the assessment of noise-induced hearing handicap in populations exposed to occupational noise as well as in individual noise-exposed subjects.

Presently ISO 1999 'Acoustics-Determination of occupational noise exposure and estimation of noise-induced hearing impairment' (ISO, 1990) gives the most widely accepted calculation method for estimating noise-induced permanent threshold shift and hearing handicap in populations exposed to occupational noise. Section 1.2 of this Introduction presents an outline of ISO 1999, and in chapter 2 assessments in populations are discussed.

For certain applications estimates are required of effects of occupational noise on the hearing threshold levels of individual subjects. Various methods have been proposed to estimate these effects on individual subjects from the population data given in ISO 1999. Presumably the most elaborate methods for assessment of noise-induced permanent threshold shift in individual subjects have been presented by Dobie (Dobie, 1990, 1992, 1993a, 1993b). They are outlined in section 1.3 of this Introduction, and chapter 3 treats specific aspects and consequences of these methods.

The discussion in this report is mainly restricted to topics related to the assessment of noise-induced hearing threshold shift and hearing handicap in individual subjects. After the conclusion in chapter 4, definitions are presented in chapter 5. Where possible the definitions given in ISO 1999 have been duplicated, in specific cases with slight modifications that restrict the definitions to occupational noise exposure. Chapter 6 presents an overview of the publications of the present author on several aspects related to noise-induced hearing loss. This overview is restricted to her publications in the English language, with the exception of those reports that have been published in Dutch only. References are presented at the end of the report. In the Annex data and calculations related to chapter 2 are given.

1.2 Outline of ISO 1999

ISO 1999 gives a calculation method for the determination of hearing threshold levels (HTLs) of populations exposed to noise (steady-state, intermittent, and impulse/impact) during working hours. The noise exposure during working hours is characterised by the noise exposure level, L_{EX} in dB(A).

The hearing threshold levels of occupational noise-exposed populations can be estimated by using the following equation:

$$H_{0.x} = A_{0.x} + N_{0.x} - A_{0.x}N_{0.x}/120 \qquad [1]$$

in which:

$H_{o.x}$ is the hearing threshold level at a specified frequency which is just exceeded by x% of the individual hearing threshold levels of a population;

$A_{o.x}$ is the age-related hearing threshold level at a specified frequency which is just exceeded by x% of the hearing threshold levels in a population with individuals with hearing threshold levels that are without any influence of occupational noise exposure;

$N_{o.x}$ is the, actual or potential, increase at a specified frequency in the hearing threshold level $H_{o.x}$ at that frequency due solely to exposure to occupational noise.

$A_{0.x}N_{0.x}/120$ is sometimes called the compression term; according to ISO 1999 this term is only important if $A_{0.x} + N_{0.x}$ is more than approximately 40 dB.

In ISO 1999 relations are given between L_{EX} and noise-induced permanent threshold shift ($N_{0.x}$) of populations for six frequencies in the range from 0.5 to 6 kHz, and for exposure times of populations from 1 to 40 years. These relations are given for N_x with x in the range of 0.05 to 0.95 and for L_{EX} values from 75 to 100 dB(A).

ISO 1999 also specifies two data bases for age-related hearing threshold levels of reference populations: data base A and B. To these and other possibly adequate data bases will be referred in more detail in section 2.2 of this report.

Thus, ISO 1999 provides the basis for calculating hearing threshold levels of occupational noise-exposed populations. ISO 1999 also claims to provide the basis for calculating hearing handicap. Hearing handicap is described in ISO 1999 as the disadvantage imposed by hearing impairment sufficient to affect one's personal efficiency in the activities of daily living, usually expressed in terms of understanding of conversational speech in low levels of background noise.

For the calculation of hearing handicap usually combinations of HTL values at two or more frequencies are used. ISO 1999 leaves it to the user of the Standard to specify these frequencies. For example, the American Medical Association (1979) specifies percentage hearing handicap (HH) in terms of the average HTL values at 0.5, 1, 2, and 3 kHz of both ears. The onset of hearing handicap is assumed to start from 25 dB and above 25 dB hearing handicap increases with 1.5% per dB increase of the hearing threshold level averaged over 0.5, 1, 2, and 3 kHz. In the calculations the average hearing threshold level at the better ear (lower hearing threshold levels) is multiplied by 5, and the value at the worse ear by 1. In formula (with HH in percentiles):

$$HH = 1/16 \, [\, 5 \, (\text{sum } HTL_{\text{better ear}} - 100) + (\text{sum } HTL_{\text{worse ear}} - 100)] \qquad [2]$$

Usually, in calculating hearing handicap in occupational noise-exposed populations the sum or the average value of the hearing threshold levels at two or more frequencies is calculated from the data given in ISO 1999, on the basis of the assumption that the correlation between the HTL values at different frequencies has a correlation coefficient equal to 1.0 (e.g. in: Dobie, 1990, 1992, 1993a, 1993b, and an informative Annex of ISO 1999). As a matter of fact this is very unlikely to occur considering the many factors that influence these hearing threshold levels. The subject of the correlation between HTLs at different frequencies and ears is further discussed in section 2.3 of this report.
ISO 1999 defines risk of hearing handicap in a population as the fraction of the people in that population with a hearing handicap. The risk of hearing handicap due to noise is defined as the risk of hearing handicap in an occupational noise-exposed population minus the risk of hearing handicap in a population not exposed to occupational noise, but otherwise equivalent to the occupational noise-exposed population.

1.3 Outline of the Dobie methods for hearing loss allocation estimates

Dobie (1990, 1992, 1993a, 1993b) specifies methods for the allocation of hearing threshold level shifts (and hearing handicap) to noise and to aging in individual subjects for three situations:

1. a subject is exposed to one occupational noise exposure level during a number of years, and this occupational noise exposure level is known;
2. a subject is exposed to one noise exposure level during a number of years, and this noise exposure level is unknown;

3. a subject is exposed to different known noise exposure levels during successive periods of his working career.

Dobie takes the population data given in ISO 1999 as a basis. He illustrates his methods of allocation by using the hearing threshold levels averaged over the four frequencies 0.5, 1, 2, and 3 kHz, because this average is most frequently used in the United States of America to estimate hearing handicap. In principle, however, his methods would not be restricted to the combination of frequencies mentioned. The methods specified by Dobie are outlined below.

1.3.1 Method of allocation when the occupational noise exposure level is known

First Dobie considers two possibilities of the relation between N and A, represented by:

- a perfect correlation (r=1.0) between individual values of N and A, which means equal susceptibility of a subject to threshold shift due to occupational noise exposure and to threshold shift related with aging. If this is true, equation 1 for populations is also applicable to individual subjects. Very susceptible subjects then come into the category with low x-values and less susceptible subjects have higher values of x;
- no correlation (r=0.0) between individual values of N and A. Dobie (1992) argues that a positive correlation between N and A is plausible. If this is true, the possible allocations of N and A in individual subjects are curtailed by a perfect correlation (r=1.0) and no correlation (r=0.0). In Dobie (1992) formulas are given for estimating the most likely distribution of A and N when r=0.0. For individual subjects with hearing threshold levels equal to the population median values a perfect correlation and no correlation will result in the same most likely allocation of A and N. For individual subjects with HTLs above the population median values, assuming no correlation will usually result in a larger most likely value for N than assuming r=1.0.

Dobie (1992) compares for each of six examples the two most likely N-values, assuming a perfect and assuming no correlation, in individuals with HTLs equal to the 10% population values with the most likely value of N in an individual with a median hearing threshold level. On the basis of this comparison Dobie proposed the <u>method of median-based allocation</u>: allocate a hearing threshold level of an individual subject to noise and age according to the proportions of A and N in which the median HTL, representative for the subjects age, gender, exposure time, and noise exposure level, would be allocated, regardless of the actual hearing threshold level of the subject (as long as it is between the 5th and 95th percentiles, where ISO 1999 is valid). Another argument for median-based allocation is given in Dobie (1993b) where confidence intervals of A and N are considered. This subject is treated more extensively in chapter 3 of this report.

1.3.2 Method of allocation when the occupational noise exposure level is unknown

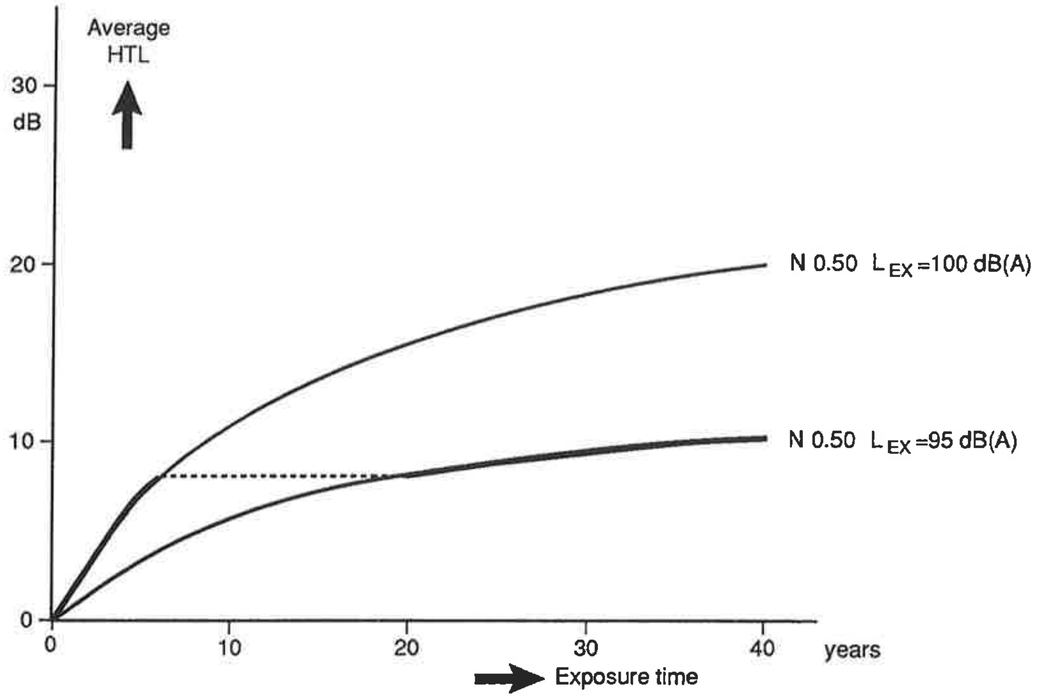
Dobie (1993a, 1993b) also specifies a method for allocation of hearing loss to noise and aging in individual subjects whose occupational noise exposure level is unknown. He suggests to compare the hearing threshold level of such a subject with the median A-value at the age of the subject of the representative age-related data base. The difference is attributed to the occupational noise exposure. The consequences of this method are treated in chapter 3.

1.3.3 Curve-walking method of allocation

Dobie (1993b) also suggests a method for the allocation of hearing loss of an individual who has been exposed during two or more successive periods to occupational noise, during each of these periods to a different noise exposure level: the so-called "curve-walking method of allocation". This method assumes that the noise-induced threshold shift of a subject moves in the first period along the median N-curve representative for the first noise exposure level. The subject takes his noise-induced threshold shift (N_1) with him to the second situation. He joins the median N-curve for that noise exposure level not at zero years but at the number of years matching the noise-induced threshold shift 'transferred' from the earlier exposure, and then moves along that curve. The noise-induced threshold shift (N_2) from the second exposure is then equal to the difference of the total accrued noise-induced threshold shift minus N_1.

This method is illustrated in figure 1 for someone exposed for 6 years to occupational noise with a noise exposure level of 100 dB(A), then followed by an exposure of 19 years to 95 dB(A). According to the curve-walking method of Dobie, N_1 (average value over the frequencies 0.5, 1, 2, and 3 kHz) is equal to 8 dB, and N_2 is equal to 2 dB. Furthermore, using age-related data base A, the median value of A for an age of 45 years (age being 20 years higher than the exposure time) is 5 dB. Consequently, the contribution of the first noise exposure to the hearing threshold level is 53%, of the second noise exposure 13%, and due to aging 33%, irrespective of the actual hearing threshold level of the subject.

Figure 1 Average values of the median noise-induced permanent threshold shifts at 0.5, 1, 2, and 3 kHz due to exposure to a noise exposure level of 95 and of 100 dB(A) as a function of exposure time. Illustration of the Dobie curve-walking method for a subject exposed during 6 years to 100 dB(A) followed by an exposure during 19 years to 95 dB(A).



2. UNCERTAINTIES RELATED TO POPULATION ASSESSMENTS

2.1 Lack of information

Taking the body of information given in ISO 1999, two specific questions remain to be answered before ISO 1999 can be used with respect to hearing handicap assessments in populations:

- what is the appropriate age-related data base for a specific population?
- what is the correlation between the hearing threshold levels at different frequencies and at different ears?

These questions will be treated in the sections 2.2 and 2.3.

2.2 Age-related data bases

In section 2.2.1 four age-related data bases will be specified. These data bases have been derived from different populations. Therefore differences in the values of the hearing threshold levels of these data bases do exist. In section 2.2.2 the consequences of these differences on the percentages noise-induced permanent threshold shift are given for examples of occupational noise-exposed populations.

2.2.1 Four examples

ISO 1999 specifies two data bases for hearing threshold levels associated with age: data base A and data base B. Data base A has been derived from otologically normal subjects who have no history of undue exposure to noise. The hearing threshold levels in data base A have been standardized in ISO 7029 relative to the median hearing threshold levels at an age of 18 years. In the informative Annex A of ISO 1999 these median hearing threshold levels at an age of 18 years have been set equal to zero dB. For frequencies other than 6 kHz this approach is usually taken as correct. Since this report only considers hearing threshold levels at 0.5, 1, 2, and 3 kHz, and not at 6 kHz, it seems to be appropriate to refer in this report to data base A with the median value at an age of 18 years taken equal to zero dB.

For data base B a set of data collected on a reference population not occupationally exposed to noise of the country under consideration is recommended in ISO 1999. An example of data base B is presented in the informative Annex B of ISO 1999 for an unscreened population. This example has been taken from the results of a large epidemiological survey carried out in the USA (National Center for Health Statistics, 1965). In this report this example of an age-related data base is referred to as data base B.

The following two other age-related data bases may also be relevant to be mentioned here:

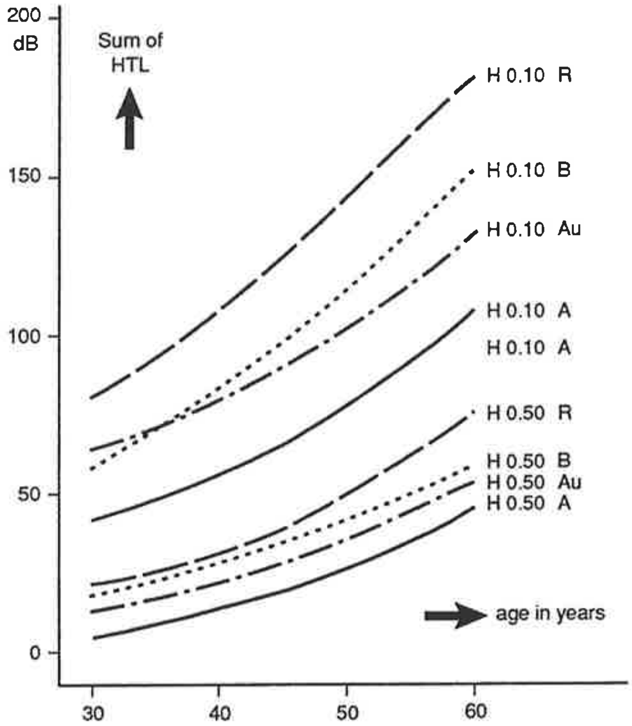
- a data base for otologically unselected populations without any substantial occupational noise exposure (Passchier-Vermeer, 1986, 1988a, 1990a, 1991c, 1994). Note 1 of Annex B of ISO 1999 refers to this data base. The values of this data base have been derived from an analysis of various relatively recent publications (Irion, 1983; Evans, 1982; Driscoll, 1984; Pfeiffer, 1985; Thierry, 1988; Passchier-Vermeer, 1984, 1987). Essentially this data base is equal to data base A with the following differences, which apply to the frequency range between 0.5 and 6 kHz:
  - the median hearing threshold level is 2 dB higher;
  - the hearing threshold level just exceeded in 10% of the population is 6 dB higher.

  Where appropriate, in this report this data base is referred to as data base Au (u: otologically unselected);
- a data base for 'the typical unscreened population' as proposed by Robinson (Robinson, 1988). This data base has been derived from results of studies mainly carried out in the past in the USA (Glorig 1965; Glorig 1957; Roberts, 1975; Roberts, 1970; Royster, 1979; Sutherland, 1978; Yaffe, 1961), together with one study in the UK (Martin, 1975). In this report to this data base will be referred as data base R.

In figure 2 the four age-related data bases A, Au, B and R are compared. The sum of the median hearing threshold levels at 0.5, 1, 2, and 3 kHz have been plotted as a function of age, as well as the sum of the hearing threshold levels just exceeded in 10% of the population at the four frequencies mentioned.

As already specified before, the difference between the sums of the median values in A and Au is equal to 8 dB, and the difference between the sums of the 10% values in A and Au is equal to 24 dB. The difference between the sums of the median values in B and R is 4 dB at ages up to 45 years and 18 dB at 60 years, whereas this difference derived from the 10% values is 24 dB, irrespective of age.

Figure 2 Sum of the median hearing threshold levels at 0.5, 1, 2, and 3 kHz, and the sum of the hearing threshold levels at these frequencies exceeded in 10% of the population, as a function of age for four age-related data bases (A: data base A from ISO 1999; Au: data base for an otologically unselected population, as proposed by Passchier-Vermeer; B: data base B from ISO 1999; R: data base proposed by Robinson for the typical unscreened population).



According to the opinion of the present author, it is unclear at the moment which age-related data base is appropriate for which population. Some authors (Dobie, 1993b) favor to use data base B for a population of freetime 'hunters', and data base A for other populations. This approach, however, does not resolve the problem, since it is not clear who has to be considered to be a 'hunter'. There are some indications that data base Au might be the appropriate age-related data base for present otologically unselected populations (Passchier-Vermeer, 1990a). Based on an analysis of data on 56 occupational noise-exposed (sub)populations (with mean ages between 30 and 50 years and mean exposure times between 10 and 30 years), Passchier-Vermeer (1990a) showed that the median hearing threshold levels at 4 kHz agree on average very closely with the predicted values in ISO 1999, when data base Au was taken as age-related data base for otologically unselected populations. The values of the hearing threshold levels at 4 kHz exceeded in 10% of the populations appeared to be on average somewhat higher than predicted by ISO 1999; the small discrepancy observed was considered negligible for the purpose of estimating hearing threshold levels of populations (Passchier-Vermeer, 1990a). Since in this investigation data base Au was taken as appropriate age-related data base for the otologically unselected populations, it might be argued that data base Au represents at the moment the best available data base for otologically unselected populations. It should be kept in mind, however, that the observations have been restricted to 4 kHz and might not be applicable to other frequencies, nor to age groups outside the age range considered in the analysis.

2.2.2 The effect of the selection of an age-related data base on percentage noise-induced permanent threshold shift

As mentioned in section 1.2, hearing threshold levels of populations exposed to occupational noise can be estimated from data given in ISO 1999 about the effects of occupational noise exposure on hearing threshold levels of populations and the data of a relevant age-related data base. Since there are differences at a given age between the hearing threshold levels of the several age-related data bases, also the estimated hearing threshold levels of occupational noise-exposed populations depend upon the choice of an age-related data base. Moreover, the relative contribution of the occupational noise exposure to the hearing threshold levels varies with the choice of age-related data base. The following example of this variation concerns a population with a mean age of 50 years, and an exposure time of 30 years. The relative contribution of the occupational noise exposure to the sum of the median hearing threshold levels at the four frequencies 0.5, 1, 2, and 3 kHz, and to the sum of the hearing threshold levels exceeded in 10% of the population have been calculated. The results are given in the figures 3 and 4.

Figure 3 Percentage shift of the median hearing threshold level (average value at 0.5, 1, 2, and 3 kHz) caused by exposure to occupational noise, as a function of noise exposure level for a population with a mean noise exposure time of 30 years and a mean age of 50 years. Parameter is the age-related data base (A: data base A from ISO 1999; Au: data base for an otologically unselected population, as proposed by Passchier-Vermeer; B: data base B from ISO 1999; R: data base proposed by Robinson for the typical unscreened population).

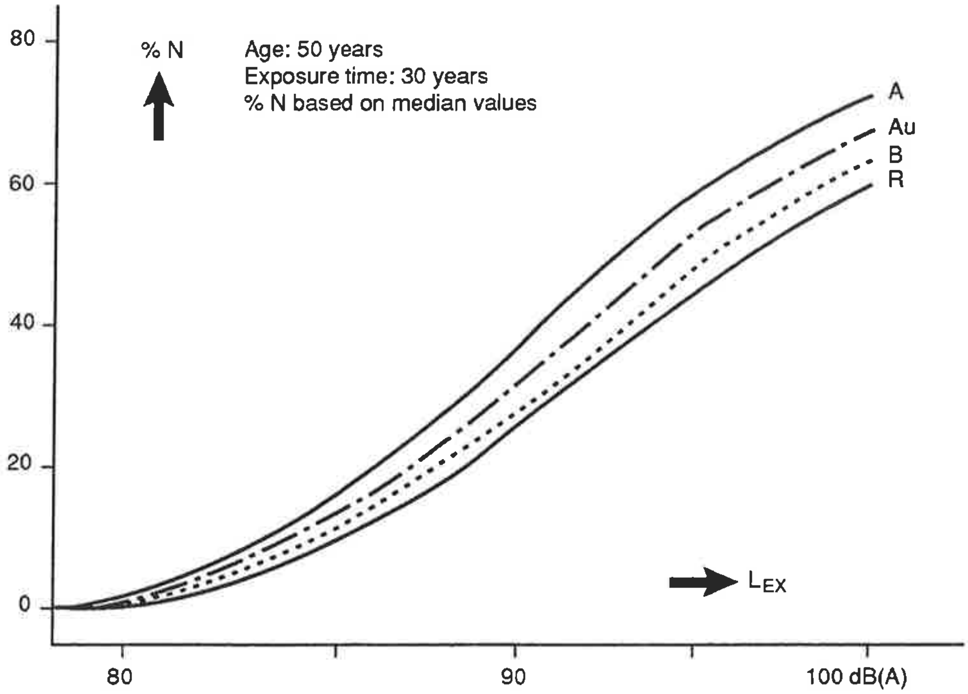
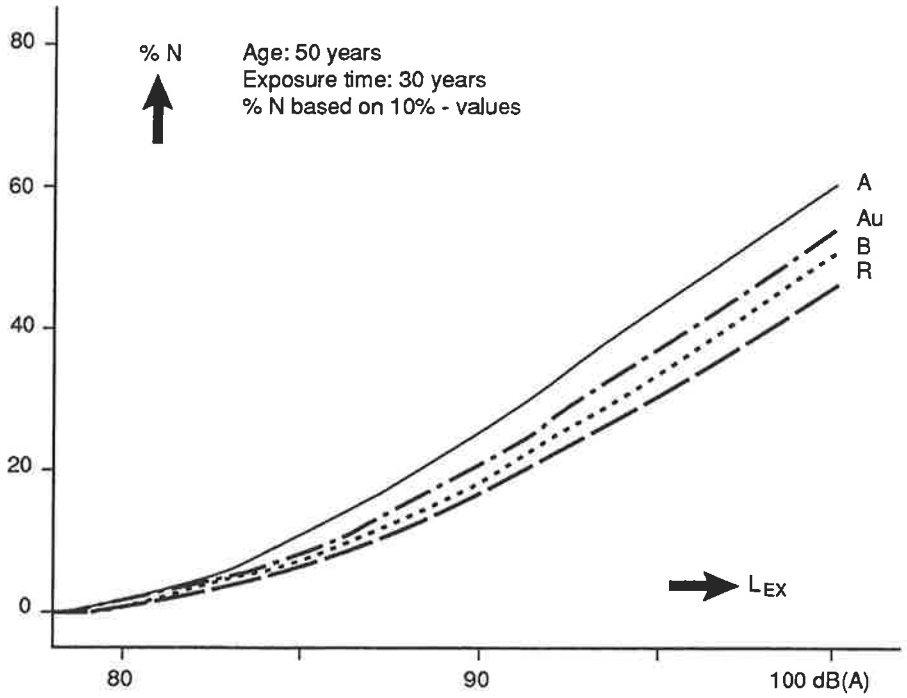


Figure 4 Percentage shift of the hearing threshold level not exceeded in 10% of the population (average value at 0.5, 1, 2, and 3 kHz) caused by exposure to occupational noise, as a function of noise exposure level for a population with a mean noise exposure time of 30 years and a mean age of 50 years. Parameter is the age-related data base (A: data base A from ISO 1999; Au: data base for an otologically unselected population, as proposed by Passchier-Vermeer; B: data base B from ISO 1999; R: data base proposed by Robinson for the typical unscreened population).



As expected, the relative contribution of occupational noise-exposure to the hearing threshold levels of populations is largest if data base A is used, and smallest if data base R is used.

2.3 Correlation between hearing threshold levels at different frequencies and ears

In the Annex of this report the consequences of varying degrees of correlations between the hearing threshold levels at the four frequencies 0.5, 1, 2, and 3 kHz have been estimated for eighteen examples of male populations. Calculations have been carried out using the following correlation coefficients between the HTL values at adjacent frequencies: 1.0, 0.7, 0.5, and 0.0. Results have been presented graphically in the figures A1 to A6 for the correlation coefficients 1.0 and 0.0. The figures show the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz exceeded in 10%, and in 50% of the population as a function of age. In all plausible models, the median values of these summations are independent of the correlation coefficients used. Therefore, the median values in the figures are supposed to be equal for each correlation coefficient. In figure A7 the results for the age-related data bases A and B have been compared. The figure shows that the values exceeded by 10% of the sums of the HTL values of data base A, with r=1.0, are about the same as those of data base B with r= 0.0.

In the pertinent literature there is no useful information on the correlation between individual HTL values of occupational noise-exposed populations and those of reference populations at different frequencies and at different ears. The results of the early analysis by Beasley (1940) cannot be used since they are not based on present standardized audiometric test methods and since they have not been specified in appropriate sub-populations. To get some insight in the correlation between hearing threshold levels at different frequencies and ears, the author has analyzed for the purpose of this report available data on the hearing threshold levels of an occupational noise-exposed population. This, otologically unselected, population consists of 587 male carpenters, aged 16 to 65 years (Passchier-Vermeer, 1992b). For the purpose of this report, an analysis has also been carried out on data of an otologically unselected population not exposed to occupational noise (Passchier-Vermeer, 1992b). Since the model presented in ISO 1999 has been based on results of populations splitted up into subgroups (according to age, and consequently also according to exposure time), both groups have also been splitted up into subgroups according to age. Detailed information is given in the Annex.

The results show that the correlations between the hearing threshold levels at different frequencies of the occupational noise-exposed population as well as of the reference population are far from perfect. For both groups the correlation coefficients of HTLs at adjacent frequencies are on average 0.7. The correlation coefficients of the sums of the HTLs at 0.5 and 1 kHz, and the sums of the HTLs at 2 and 3 kHz are 0.5 for the noise exposed population, and 0.6 for the reference population. These results have been applied in the Annex to the eighteen examples of male populations mentioned before. Results have been given in the figures A8 to A14 as curves with parameter exp. In each of the figures the differences between the 10% and 50% values, if the empirical determined correlation coefficients between the HTLs at different frequencies have been taken as a basis, are 81% of these differences for a correlation with a correlation coefficient of 1.0. In the Annex the correlation coefficients of the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz at the right, and that sum at the left ear have been given for the group of carpenters and the reference group. This correlation appears to be relatively high: correlation coefficients are between 0.83 and 0.91. If hearing handicap is based upon the sum of 5 times the average value of the HTLs at 0.5, 1, 2, and 3 kHz of the better ear, and 1 times that value for the worse ear, such as specified by AMA, and a correlation coefficient of 0.8 to 0.9 is used, then this sum is up to 5% less than with a correlation coefficient taken equal to 1.0. Therefore, the slightly less than perfect correlation between the hearing threshold levels at both ears does not seem to have a relevant impact on the estimated hearing handicap of populations, if calculated according to the AMA formula of hearing handicap.

3. UNCERTAINTIES RELATED TO INDIVIDUAL ASSESSMENTS

3.1 Introduction

As outlined in section 1.3 Dobie specified methods for the allocation of hearing threshold shifts to noise and aging in individual subjects for three situations. In this chapter aspects related to these three methods will be treated in different sections.

3.2 Method of allocation when the noise exposure level is known

There is no straightforward method for deriving noise-induced hearing threshold shift in individual subjects from population data, such as presented in ISO 1999. Therefore, ISO 1999 itself is very clear by stating that 'the Standard shall not be used to predict or assess the hearing impairment or hearing handicap of individual persons.'
If ISO 1999 is used for assessments in individuals, $N_{0.x}$ is usually incorrectly interpreted as the noise-induced permanent threshold shift exceeded in x% of the individual subjects of an occupational noise-exposed population. The incorrectness of this approach has been recognized by the present author as early as 1968, when the basis of the statistical model later used in ISO 1999 has been presented (Passchier-Vermeer, 1968). That report presents noise-induced shifts of the median hearing threshold levels, and data about the hearing threshold levels not exceeded in 25 and 75% of noise-exposed populations. It states in its summary: 'Calculation of the exact values of the noise-induced hearing losses not exceeded in 75 and in 25% of the persons is impossible, as it is not known exactly what would have been the hearing levels of a person when he had not been exposed to occupational noise. However, it is possible to calculate the noise-induced shifts of the hearing threshold levels not exceeded in 25 and in 75% of the people.' If $N_{0.x}$ is interpreted as the noise-induced permanent threshold shift exceeded in x% of the individual subjects of an occupational noise-exposed population, a perfect correlation is assumed between A and N in individual cases, a hypothesis for which there is no empirical evidence.
As already pointed out, Dobie takes in principle a more realistic approach by also assuming no correlation between A and N in individual subjects. Dobie (1992) states that 'although the correlation between A and N is clearly unknown, it seems more likely to be positive than negative. If age-related threshold shift includes "sociocusis" due to sounds of everyday life, susceptibility to

this component of age-related threshold shift should be correlated with susceptibility to noise-induced threshold shift. In addition, it seems likely that because at least the major site of action for both noise-induced and age-related threshold shift is the cochlear hair cell, susceptibility may be shared as well. In the absence of any firm basis for estimating a degree of correlation, it seems most reasonable to assume a value between 0 and 1.' This reasoning has some weak points, especially when hearing threshold levels in the lower frequency range are considered. Usually, conductive hearing loss, when it is present in an individual, gives elevated hearing threshold levels in this frequency range. On the other hand it has been demonstrated (Nilsson, 1983; Chung, 1978) that conductive hearing loss may prevent the ear from noise-induced threshold shift. Therefore, a negative correlation between A and N at the lower frequencies is likely to exist in a specific (sub)population. However, since it is unknown to what extent conductive hearing loss, and hence a possible negative correlation between A and N, does exist in occupational noise-exposed populations, the consequences of this observation are unclear.

If it is true that the correlation between A and N is not negative, then the observation of Dobie is correct that it is possible to curtail noise-induced hearing loss in individual subjects by assuming in calculations the correlation between A and N to have correlation coefficients between 0.0 and 1.0.

If a perfect correlation does exist between A and N, both these components of the hearing threshold level of an individual subject could in principle be calculated exactly, when shortcomings in the appropriate age-related data bases and in the occupational noise exposure characteristics are ignored.

In the case of no correlation (r=0.0) between A and N, the following two characteristics can be calculated in order to specify the noise-induced component of a hearing threshold level of a subject:

- the most probable value of N;
- a confidence interval, in which the true N-value is located with a specified probability.

The most probable value of N in the case of zero correlation between A and N depends upon the population distribution of A (i.e. upon the choice of age-related data base, and upon the age of the subject), the distribution of individual N-values in the population, and the hearing threshold level of the subject. For someone with a hearing threshold level equal to the median population value, representative for his age and noise exposure characteristics, the most likely value of N is equal to the median N-value of the population. For other hearing threshold levels of a subject, however, the most likely value of the individual N is usually not equal to the corresponding population value. Examples are given below to illustrate this observation.

Dobie (1993a) presents a method for determining confidence intervals for hearing loss allocation estimates. Dobie focuses on obtaining confidence intervals for which the probability is 50% that they include the true value, 'because hearing loss allocation estimates are useful mainly, if not exclusively, in medical-legal settings where the standard of proof is "more probable than not".' The procedures described in Dobie (1993a) are conservative, that is, the real confidence intervals will usually be narrower than those obtained with the procedures described. In this respect, Dobie considers the most important factor ensuring conservatism the use of a four-frequency average hearing threshold level with a correlation coefficient of 1.0 between values at different frequencies. This last subject has been treated in detail in section 2.3 of this report. In the example of the occupational-noise exposed carpenters, the standard deviations of the average HTL values over four frequencies, when the empirical values of the correlation coefficients were used, were reduced to 81% of the standard deviations applicable when a correlation between the HTL values at different frequencies of 1.0 was assumed. In the following this reduction to 81% is taken into account, thus ensuring more realistic confidence intervals.

Usually not 50% but 95% confidence intervals are calculated. Using this probability of 95% and the reduction of 81% mentioned before, the method presented in the Dobie publication has been applied to several cases, including the example given in the Dobie publication. That example concerns a 60 year old man, who worked for 30 years in a noise exposure level of 90 dB(A), and who has a hearing threshold level of 30 dB (averaged over 0.5, 1, 2, and 3 kHz). According to the method of median-based allocation, the contribution of noise exposure to his hearing threshold level is 11.1 dB. Assuming a perfect correlation between A and H, noise exposure contributes 7.5 dB to his actual hearing threshold level. Assuming no correlation, the most likely estimate of the noise exposure contribution is 10.2 dB and of the age contribution 19.8 dB. The 95% confidence intervals of the noise-induced and age-related contributions have, in the case of no correlation between A and N, each a width of 18 dB and are 1-19 dB and 11-29 dB, respectively. This implies that for zero correlation, noise exposure contributes from 3 to 63% to the hearing threshold level, and the age-related contribution is from 37 to 97%, each with a probability of 95%.

Another example, which will be used in section 3.4 of this report, concerns a 30 year old man exposed for 10 years to occupational noise with a noise exposure level of 100 dB(A). The 95% confidence interval of the noise-induced hearing threshold level shift (averaged over four frequencies) is 17 dB in the case of zero correlation between A and N. (In this example the standard deviation in A is 7.2 dB and in N equal to 13.2 dB, as calculated from ISO 1999, taking data base A as age-related data base.) If the subject would have a hearing threshold level equal to the median value representative for his age and noise exposure characteristics, the 95% confidence interval for the noise-induced shift in hearing threshold level would be 2.5-19.5 dB in the case of zero correlation. According to the method of median-based allocation this contribution would have been 11 dB, as has already been demonstrated in figure 1.

It seems particularly instructive to look at confidence intervals of N for long exposure times. In the following an exposure time of 40 years and an age of 60 years is chosen. For a noise exposure level of 90 dB(A) the 95% confidence interval in the case of zero correlation between A and N has a width of 20 dB, if data base A is taken as age-related data base, and a width of 26 dB, if data base B is used. For a noise exposure level of 100 dB(A) these widths are 32 and 44 dB, respectively. For subjects having a hearing threshold level equal to the 10% population value (the compression term as specified in equation 1 taken into account) the following data are applicable, assuming no correlation between A and N:

- noise exposure level 90 dB(A); the most likely value of N, if data base A is used, is equal to 9 dB, and the 95% confidence interval is 0-19 dB, which constitutes 0-56% of the actual hearing threshold level. The most likely value of N, if data base B is used, is 10 dB, and the 95% confidence interval is 0-23 dB (0-51% of the hearing threshold level);
- noise exposure level 100 dB(A); the most likely value of N, if data base A is used, is equal to 38 dB, and the 95% confidence interval is 22-54 dB (38-94% of the hearing threshold level). The most likely value of N, if data base B is used, is 34 dB, and the 95% confidence interval is 12-56 dB (20-93%).

These results can be compared with those obtained if a perfect correlation between A and N is assumed and with the results if the median-based method of allocation is used. Assuming a perfect correlation between A and N, the corresponding values of N would be 8 dB for an exposure for 40 years to 90 dB(A), and 29 dB for an exposure during 40 years to 100 dB(A), irrespective of the data base used (where appropriate, in the calculations the compression term has been applied). If the median-based method is applied, these values of N are for a noise exposure level of 90 dB(A) equal to 10 and 15 dB, if data base A and data base B, respectively, are used. For 100 dB(A) these values are 33 and 35 dB, respectively. Note that all these values fall obviously within the 95% confidence intervals of N calculated for zero correlation between A and N.

The results of this section can be summarized as follows. When the noise exposure level of a subject is known, three point estimates of the noise-induced permanent threshold shift can be made:

1. using the median-based method of allocation as proposed by Dobie;
2. assuming a perfect correlation between A and N;
3. assuming no correlation between A and N.

For a subject with a hearing threshold level equal to the median population value, these point estimates are equal. For a subject with a higher hearing threshold level these three point estimates are usually different. These differences are relatively small when compared with the 95% confidence interval of N, when no correlation between A and N is assumed.
Assuming a perfect correlation between A and N, the 95% confidence intervals of N are very small. These intervals increase in width with decreasing correlation coefficient. Assuming zero correlation between A and N, the width of the 95% confidence interval does not depend on the hearing threshold level of a subject. The width of this interval is therefore the same in a subject with a hearing threshold level equal to the median population value, representative for his age and noise exposure characteristics, and in a subject with a higher hearing threshold level.

3.3 Method of allocation when the noise exposure level is unknown

If the noise exposure of a subject is unknown, Dobie suggests to compare the hearing threshold level of the subject with the median value at his age of the relevant age-related data base, and to attribute the difference to occupational noise exposure. This difference can then be related to his hearing threshold level, and the assumed percentage noise-induced hearing threshold level shift be calculated. As an example, in table 1 these percentages have been calculated for a subject aged 50 years, for several sums of the hearing threshold levels at 0.5, 1, 2, and 3 kHz, and for the four age-related data bases specified before.

Table 1 Percentage noise-induced hearing threshold level increase relative to the median value of the sum of HTL at 0.5 1, 2, and 3 kHz of an occupational noise-exposed subject with mean age of 50 years using four different data bases.

Value of the sum of HTL at 0.5, 1, 2, and 3 kHz in dB	% N using data base			
	A	Au	B	R
36	25	3	0	0
50	46	30	16	2
100	73	65	58	51
150	82	77	72	67

The table shows, for instance, for the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz being equal to 100 dB, the percentage noise-induced shift of his hearing threshold level to be 51 to 73%, depending on the age-related data base used.

From the relevant curve in figure 3 at the exposure time of 30 years, from each of the % N values in table 1 L_{EX} can be estimated. The result is given in table 2.

Table 2 L_{EX} values estimated from the median value of the sum of HTL at 0.5, 1, 2, and 3 kHz of an occupational noise-exposed subject with mean exposure time of 30 years and mean age of 50 years.

Value of the sum of HTL in dB	L_{EX} values (in dB(A)) estimated from the median value of the sum of HTL at 0.5, 1, 2, and 3 kHz using data base			
	A	Au	B	R
36	87	82	≤77	≤77
50	92	90	87	80
100	100	99	98	97
150	>100	>100	>100	>100

This table shows that for a 50 years old, 30 years occupational noise-exposed subject with a sum of hearing threshold levels at 0.5, 1, 2, and 3 kHz of 100 dB, the estimated noise exposure level varies from 97 dB(A) (when age-related data base R is used) to 100 dB(A) (for data base A). The variation of the L_{EX} values is much larger for smaller values of the sum of the hearing threshold levels.

Contrary to an unknown noise exposure, assume that the L_{EX} value of the occupational noise exposure would have been 90 dB(A). Then, applying the method of median allocation, according to figure 3 the percentage noise-induced threshold shift varies from 25 to 37, depending on the age-related data base chosen. For an L_{EX} value of 100 dB(A) the percentage noise-induced threshold shift varies from 60 to 72.

This means that, for this specific example with the sum of HTL equal to 100 dB, when the noise exposure is unknown, the calculated percentage noise-induced threshold shift is classified as if it were from an exposure to an L_{EX} value of 97 to 100 dB(A)! It could be questioned whether a sum of a hearing threshold level at 0.5, 1, 2, and 3 kHz of 100 dB at an age of 50 years is, or is not, an extraordinary high value. Taking the four age-related data bases, it is estimated that the following percentages of subjects of these populations have hearing threshold levels of at least 100 dB: data base R: 24%, data base B 16%, data base Au: 11%, and data base A less than 5%. Therefore, it could be argued that a subject with such a hearing threshold level very well fits within the populations represented by the data bases R, B and Au, which are supposed to have had no substantial occupational noise exposure.

3.4 Curve-walking method of allocation

Since the present author is not aware of scientific evidence for the curve-walking method as suggested by Dobie, several other alternatives could be suggested. One of them, which is based upon equal susceptibility to noise-induced and to age-related threshold shift during each of the successive noise exposure periods of a subject, is demonstrated below. According to this method, the noise-induced threshold shift of a subject is assumed to move in the period of the first occupational noise exposure along the N-curve representative for his susceptibility and noise exposure level, resulting in a noise-induced threshold shift of N_1. Denote the difference between N_1 and the value of N, representative for his susceptibility, due to an exposure of equal length to the second noise exposure level, by Δ. Then the subject carries this extra noise-induced hearing threshold level shift with him during the second noise exposure. During both noise exposures, the age-related threshold shift of the subject moves along the A-curve representative for his age and his susceptibility. Although there is also no scientific evidence for this method of curve-walking, the method is more plausible. The extra amount of noise-induced hearing threshold level shift Δ could for instance be regarded as the extra amount of hearing threshold shift when data base B is considered relative to data base A. Several authors (e.g. Dobie (1992)) consider the difference between the values in data base A and B partly to be due to exposure to noise during everyday life.

The method is illustrated in figure 5 for a subject with average susceptibility, and in figure 6 for a subject with a susceptibility corresponding with the 10% population values. Taking the example given in section 1.3.3 (figure 1), and again taking data base A as age-related data base, the hearing threshold level of an average susceptible subject is 18.5 dB, and the contribution of the first noise exposure to the hearing threshold level is 43%, of the second noise exposure 30%, and the age-related component is 27%. Of the more susceptible subject the hearing threshold level is 40.5 dB, and the respective contributions are 41, 17, and 42%. According to the Dobie curve-walking method of allocation these contributions are 53, 13 and 33%, irrespective of the hearing threshold level of the subject. In this example, the Dobie method allocates a larger N to the first noise exposure and less to the second noise exposure, compared with the other method. Obviously, the methods give different results with respect to the allocation of the two components of noise-induced hearing threshold shift in individual subjects.

Figure 5 Average values of the median noise-induced permanent threshold shifts at 0.5, 1, 2, and 3 kHz due to exposure to a noise exposure level of 95 and of 100 dB(A) as a function of exposure time. Illustration of a curve-walking method that assumes equal susceptibility for noise-induced and age-related threshold shift during both periods of occupational noise exposure. Curve-walking of a subject with average susceptibility, exposed for 6 years to 100 dB(A) followed by and exposure for 19 years to 95 dB(A).

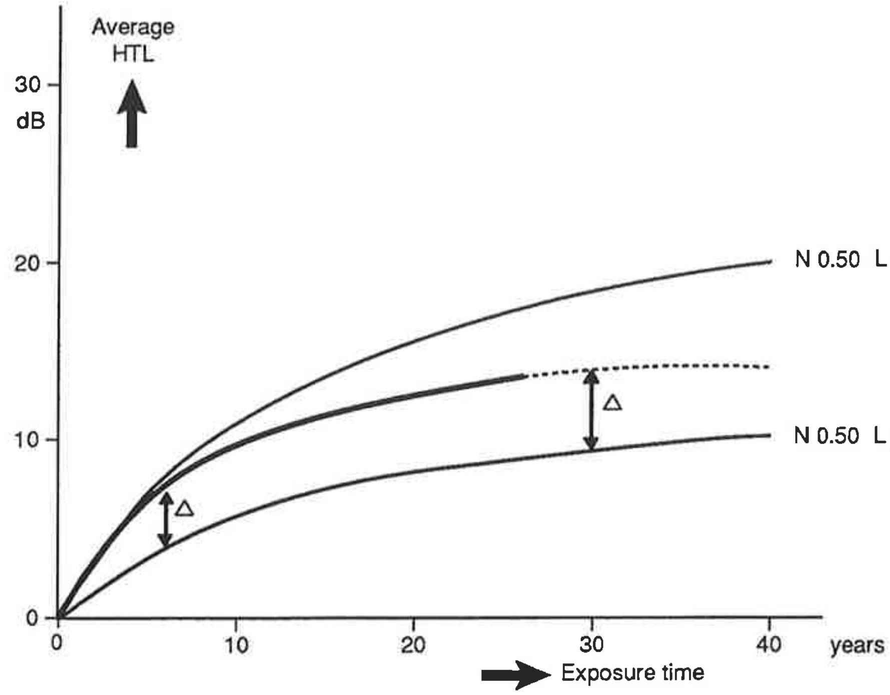
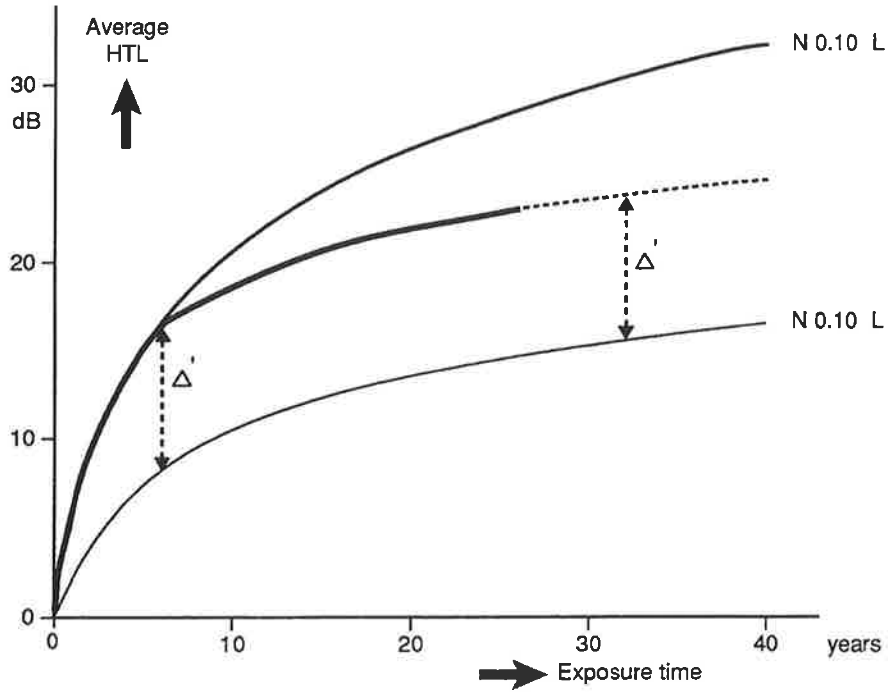


Figure 6 Noise-induced permanent threshold shifts not exceeded in 10% of the population (average values over 0.5, 1, 2, and 3 kHz) due to exposure to a noise exposure level of 95 and of 100 dB(A) as a function of exposure time. Illustration of a curve-walking method that assumes equal susceptibility for noise-induced and age-related threshold shift during both periods of occupational noise exposure. Curve-walking of a subject with an susceptibility equal to the 10% population values, exposed for 6 years to 100 dB(A) followed by and exposure for 19 years to 95 dB(A).



The methods of curve-walking given above have been illustrated with values averaged over the four frequencies 0.5, 1, 2, and 3 kHz, as was done in Dobie (1993b). However, using an average value over four frequencies is incorrect, since noise-induced hearing threshold level shift as a function of exposure time differs from frequency to frequency. This incorrect application is illustrated with the example given in Dobie (1993b) (example 9). A subject spent 10 years at an occupational noise exposure level of 100 dB(A), followed by an occupational noise exposure to 95 dB(A). The median value of N after 10 years of exposure to 100 dB(A) is 11 dB when averaged over the four frequencies 0.5, 1, 2, and 3 kHz. Since this value of 11 dB is higher than the median value of N reached from an exposure to 95 dB(A), even after an exposure time of 40 years, according to the Dobie method of curve-walking, no noise-induced threshold shift is to be expected from this subsequent exposure to 95 dB(A). However, taking the median values of N at the separate frequencies, these values are for an exposure during 10 years to 100 dB(A) equal to 4, 6, 8, and 26 dB at 0.5, 1, 2, and 3 kHz. Looking at the median values of N due to a 40 years exposure to 95 dB(A), it appears that these values are indeed lower at 0.5, 1 and 3 kHz than those for an exposure during 10 years to 100 dB(A). However, the median value at 2 kHz of 8 dB is reached after 18 years of exposure to 95 dB(A), and in the course of time an additional noise-induced threshold shift of 6 dB is to be expected at 2 kHz, assuming that the curve-walking method according to Dobie is correct for single frequencies. Therefore, taken this example only, it is show that the curve-walking method is incorrect, when applied to combinations of frequencies.

Ignoring the facts that the curve-walking method of allocation should not be applied to values averaged over frequencies and also that there is no empirical support for the method, in the light of the 95% confidence intervals for individual assessment of noise-induced hearing threshold level shift, the applicability of the method to individual subjects should be seriously questioned. Take for instance the example with which Dobie illustrated his method (see also figure 1 of this report). As was calculated in 3.2, the 95% confidence interval of N in the case of zero correlation between A and N is 2.5-19.5 dB for an average susceptible subject exposed for 10 years to 100 dB(A). A large part of this confidence interval is below the median N value to be expected due to an exposure for 10 years to a noise exposure level of 95 dB(A). Therefore, the true value of N for that subject may very well be below that median value. It should therefore not at all be excluded that the subject will acquire further noise-induced hearing loss during the second noise exposure period.

4. DISCUSSION AND CONCLUSION

This discussion focuses on methods for the allocation of noise-induced hearing threshold level shift in individual subjects exposed to occupational noise. Uncertainties in the allocation of N in individual subjects are due to uncertainties in population assessments of noise-induced threshold shift, and due to uncertainties related to individual differences. In this chapter, first the uncertainties in population assessments will be discussed. Thereafter, the uncertainties relevant for the methods of allocation of N in individual subjects will be discussed for each of the allocation methods outlined in chapter 3.

With respect to uncertainties in **population assessments** the availability of an appropriate age-related data base and the correlation of hearing threshold levels at different frequencies are the main factors that hamper the applicability of the data in ISO 1999 for hearing handicap assessments. According to the opinion of the present author, it is unclear at the moment what age-related data base is appropriate for what population. Therefore, the variation induced by uncertainties in the selection of an age-related data base has to be taken into account in individual assessments of noise-induced hearing loss. In chapter 2 of this report the estimation of the relative contribution of occupational noise exposure to the hearing threshold levels of populations has been shown to depend on the age-related data base chosen. For example, figure 3 shows percentages of N determined at the median hearing threshold levels of populations to differ by 10 to 15% for the higher noise exposure levels, depending on the age-related data base used. (Just as in the preceding chapters of this report, all numerical examples given in this discussion refer to hearing threshold levels averaged over the frequencies 0.5, 1, 2, and 3 kHz.)
In addition to this, the lack of information about the correlation between the hearing threshold levels at different frequencies has to be taken into account. In the examples of the population of carpenters and of the reference population this correlation turned out to be far from perfect, suggesting that in other populations this correlation might also be far from perfect. In these examples, the standard deviation in the hearing threshold levels averaged over four frequencies is only 81% of the standard deviation that would occur in case of a perfect correlation between the hearing threshold levels at different frequencies. This reduced variation in the average hearing threshold levels does have a substantial effect on the (95%) confidence intervals with which N is allocated in individual subjects. Therefore an extensive investigation, covering a wide range of noise exposure levels, exposure times, and ages, is recommended in order to obtain reliable information on this subject.

Noise-induced risks in occupational noise-exposed populations are usually determined by subtracting values representative for a reference population from values representative for the noise-exposed population. For instance, noise-induced risk of hearing handicap is assessed in this way. According to ISO 1999 this noise-induced risk is defined as the percentage of subjects with a hearing handicap in an occupational noise-exposed population minus the percentage of subjects with a hearing handicap in a population not exposed to occupational noise, but otherwise equivalent to the occupational noise-exposed population. Possibly, such a difference is less affected by both above mentioned uncertainties than the separate values are.

The most important problem for the **individual assessment** of noise-induced hearing threshold level shift is the lack of information about the correlation of A and N. Longitudinal investigations might in principle give some insight in this problem, but unfortunately the presently available epidemiological investigations (Abel, 1984; Bergström, 1986; Brühl, 1994a, 1994b; Chung 1982; Dieroff, 1978; Erlandsson, 1983; Rösler, 1994; Schwetz, 1989; Touma, 1992) fail in this respect. Furthermore, the increased use of hearing protection by occupational noise-exposed subjects reduces the possibility to collect the required, unbiased information (Passchier-Vermeer, 1994; Passchier et al., 1994). In these circumstances, the strategy proposed by Dobie, namely to curtail the likely distributions of N by assuming that the correlation between A and N is somewhere in the range between zero (r=0.0) and a perfect correlation (r=1.0) is considered to be a reasonable approach to get more insight in the problem.

If the noise exposure level of a subject is known, three point estimates of his noise-induced permanent threshold shift have been specified in section 3.2.:

1 by using the median-based method of allocation as proposed by Dobie;

2 by assuming a perfect correlation between A and N;

3 by assuming no correlation between A and N.

For a subject with a hearing threshold level equal to the median population value, these three point estimates of N are equal. Differences do exist in these three point estimates if the hearing threshold level of a subject is above the median population value. There is no information available on which a preference for any of the three point estimates can be based.
If the correlation between A and N would be perfect (r= 1.0), in other words, if subjects would be equally susceptible in acquiring noise-induced threshold shift and in acquiring age-related threshold shift, the allocation of A and of N in the HTL range where ISO 1999 is applicable would only be hampered by uncertainties with respect to the population data. Knowing the exact values of the

noise exposure characteristics and the age of a subject, knowing the population data of the appropriate age-related data base, and knowing the correlation between the HTLs at different frequencies, then A and N in that subject could be allocated with very small 95% confidence intervals. Allocation of A and N in a subject with a known noise exposure level would then be most accurately done not by the method of median-based allocation, but by the more elaborate method which takes the susceptibility of the subject into account. An estimation of the differences in the results of both methods for the 10% most susceptible subjects can be obtained by comparing the curves in figure 3 and 4 of this report. These differences are estimated to be 12 to 15% for an exposure time of 30 years and noise exposure levels of at least 90 dB(A), the median-based method of allocation resulting in higher allocations to noise than the method assuming equal susceptibility.

If a correlation between A and N is assumed to be in the range between a zero and a perfect correlation, then the 95% confidence interval of N in an individual subject depends on his noise exposure level and this confidence interval is large at the higher noise exposure levels for a zero correlation. It has been calculated that in the case of zero correlation between A and N the 95% confidence interval of N for longtime occupational noise exposure (exposure during 40 years) is equal to 20 to 26 dB (dependent upon the age-related data base chosen) if the noise exposure level is 90 dB(A), and as large as 32 to 44 dB if the noise exposure level is 100 dB(A). The width of this confidence interval for N in an individual subject does not depend on his hearing threshold level.

It is highly recommended that not only point estimates of N, but also the 95% confidence intervals assuming zero correlation between A and N are taken into account in the assessment of the effects of occupational noise on the hearing threshold level of an individual subject.

The method of allocation of N and A suggested by Dobie for subjects with unknown noise exposure levels has been shown to give a high estimate of this noise exposure level, also if the hearing threshold level of the subject falls well within the distribution of HTLs of populations without occupational noise exposure. This procedure attributes all variation in hearing threshold levels of populations to the occupational noise exposure. It also implies that for anyone with a hearing threshold level larger than the median value at his age of the relevant age-related data base, occupational noise exposure may be assumed to have had an effect. In this respect, the uncertainty of what age-related data base is applicable for what population is important. If for a certain population data base B would be the appropriate data base, but instead data base A would be used, then 70% of the subjects of that population have a hearing threshold level for which occupational noise exposure is hold partially responsible. This uncertainty with respect to the choice of an age-related data base is a serious problem for a method such as proposed by Dobie.

Objections with respect to curve-walking methods, and especially the one proposed by Dobie, are:

- there is no empirical support for any curve-walking method. There are other methods of curve-walking than proposed by Dobie which are equally plausible or perhaps more plausible. Other methods may result in other results with respect to allocation of noise-induced threshold shift due to subsequent exposures, as has been illustrated in this report;
- a curve-walking method should not be applied to a combination of HTL or N values at different frequencies;
- any curve-walking method should take into account the (95%) confidence intervals of N. Since the correlation between A and N in individual subjects is unknown, for the calculations of such intervals a zero correlation should not be excluded.

In conclusion:

- if the noise exposure level of a subject is known, allocation of noise-induced hearing threshold level shift based on the population data presented in ISO 1999 should not only take into account point estimates of N but also the (95%) confidence interval, assuming a zero correlation between A and N. There is no information available on which a preference for any of the three point estimates specified in this report can be based;
- if the noise exposure level of a subject is unknown, the Dobie method of allocating N has shown to have serious weaknesses;
- if a subject is exposed to different noise exposure levels during successive periods, any curve-walking method should take into account the (95%) confidence intervals associated with noise-induced threshold shift in individual subjects.

5. DEFINITIONS

1. Hearing threshold level of an individual, HTL = H (in dB)

The hearing threshold level at a specified frequency of an individual is his threshold of hearing at that frequency determined relative to ISO audiometric zero, as specified in ISO 389.

2. Hearing threshold level of a population, $H_{o.x}$ (in dB)

The hearing threshold level $H_{o.x}$ at a specified frequency of a population is the value which is just exceeded in x% of the individual hearing threshold levels of the population at that frequency.

3. Hearing threshold level of an individual associated with age, A (in dB)

The hearing threshold level at a specified frequency of an individual observed solely in association with age without any influence of occupational noise exposure.

4. Hearing threshold level of a population associated with age, $A_{o.x}$ (in dB)

The hearing threshold level $A_{o.x}$ at a specified frequency observed in association with age in a population with individuals with hearing threshold levels that are without any influence of occupational noise exposure.

5. Noise-induced permanent threshold shift of an individual, NIPTS = N (in dB)

The permanent shift, actual on potential, of the hearing threshold level at a specified frequency caused solely by exposure to occupational noise, in the absence of other causes.

6. Noise-induced permanent threshold shift of a population, $N_{o.x}$ (in dB)

The increase, actual or potential, in the hearing threshold level $H_{o.x}$ at a specified frequency of a population estimated to be caused solely by exposure to occupational noise, in the absence of other causes, as specified in ISO 1999.

In ISO 1999 $N_{o.x}$ is specified according to the following formula:

$$H_{0.x} = A_{0.x} + N_{0.x} - A_{0.x}N_{0.x}/120$$

7. Noise exposure level normalized to a nominal 8 h working day, $L_{EX,\ 8h} = L_{EX}$ (in dB(A))

The equivalent continuous A-weighted sound pressure level ($L_{Aeq,Te}$) given by the equation:

$$L_{EX} = L_{Aeq,Te} + 10 \lg (T_e/T_o)$$

with:

T_e is the effective duration of the working day;

T_o is the reference duration of 8 hours.

6. RELATED PUBLICATIONS

The present author investigated several aspects related to noise-induced hearing loss. Starting from 1967 relations between occupational noise exposure and noise-induced shifts in hearing threshold levels have been specified (Passchier-Vermeer, 1967, 1968a, 1968b, 1969, 1971, 1973, 1974, 1975, 1976, 1978, 1986, 1988a, 1988b, 1990a, 1990b, 1991c, 1992a, 1992b (in Dutch only); Passchier-Vermeer, Berg van den and Rövekamp, 1986; Passchier-Vermeer, Eijk van den, 1968; Passchier-Vermeer, Hof van and Rövekamp, 1991 (in Dutch only). This list of publications has been restricted to those in the English language, with the exception of the reports which have been published in Dutch only; most of the English publications are also available in Dutch). Questions related to age-related data bases have also been the subject of several publications (Passchier-Vermeer, 1977, 1984 (in Dutch only), 1986, 1987 (in Dutch only), 1988a, 1990a, 1994a; Passchier-Vermeer, Berg van den and Rövekamp, 1986; Spoor and Passchier-Vermeer, 1969). Where appropriate, research has been carried out with respect to noise measurement methods and audiometric test methods (Passchier-Vermeer, 1982a, 1983; Passchier-Vermeer, Berg van den and Leeuw, 1980; Passchier-Vermeer, Berg van den and Rövekamp, 1981; Passchier-Vermeer, Eijk van den, 1974). As a member of ISO/TC 43/SC 1/WG 19, the working group that prepared ISO 1999 (ISO 1990), papers have been presented which dealt with (draft) ISO 1999 (Passchier-Vermeer, 1982b, 1982c). The results of a field investigation into the effectiveness of personal hearing protection has also been published (Passchier-Vermeer, Berg van den and Crijns, 1994). In more recent years the question of noise-induced hearing loss from noise sources outside the workplace has been the subject of some English publications (Passchier-Vermeer, 1991a, 1991b, 1993b). On behalf of the Health Council of the Netherlands a background study has been published (Passchier-Vermeer, 1993a), in which the present state of knowledge about the effects of noise on health, including the subject of effects on hearing has been outlined.

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ANNEX

1. CORRELATION BETWEEN HEARING THRESHOLD LEVELS AT DIFFERENT FREQUENCIES

1.1 Calculations with theoretical values of correlation coefficients

Let σ_i^2 be the variance in the hearing threshold levels at frequency i (i in kHz) (i=0.5, 1, 2, and 3).

Let σ_{ij}^2 be the variance in the values representing the sum of the hearing threshold levels at frequencies i and j.

In general σ_{ij}^2 will depend upon the degree of correlation between the hearing threshold levels at frequency i and those at frequency j. This given by the formula:

$$\sigma_{ij}^2 = \sigma_i^2 + \sigma_j^2 + 2r_{ij}\,\sigma_i\,\sigma_j \qquad \text{[A1]}$$

with:
r_{ij}: the correlation coefficient of the hearing threshold levels at frequency i and those at frequency j.

Let σ_{ijkl}^2 be the variance related to the sum of the hearing threshold levels at four frequencies and be specified as follows:

$$\sigma_{ijkl}^2 = \sigma_{ij}^2 + \sigma_{kl}^2 + 2r_{ijkl}\,\sigma_{ij}\,\sigma_{kl} \qquad \text{[A2]}$$

with:

σ_{ij}^2: variance in the sum of the HTLs at frequencies i and j;
σ_{kl}^2: variance in the sum of the HTLs at frequencies k and l;
$i \neq j \neq k \neq l$;

r_{ijkl}: the correlation coefficient of the correlation between the sum of the HTL values at the two frequencies i and j and the sum of the HTL values at the two frequencies k and l.

In this Annex the consequences of an imperfect correlation between the hearing threshold levels at the four frequencies 0.5, 1, 2, and 3 kHz have been calculated for eighteen examples. These examples refer to male groups. They concern six reference populations not occupationally exposed to noise (data bases A and B, both at ages 30, 45 and 60 years) and twelve occupational noise-exposed populations (parameters: ages 30, 45 and 60 years, exposure times 10, 25 and 40 years, L_{ex} values 90 and 100 dB(A), age-related data bases A and B). Calculations have been carried out taking in each calculation the same value for each of the correlation coefficients r_{ij}, r_{kl} and r_{ijkl}: 1.0, 0.7, 0.5 and 0.0. In principle the correlation coefficients could be even negative, but no energy has

been spent by the present author to calculate the consequences of a negative correlation between the HTL values at different frequencies.
The results are presented in table A1. In this table the values are given of the sum of the HTL values at 0.5, 1, 2, and 3 kHz, not exceeded in 50 and 10% of the populations for the four values of the correlation coefficients specified before. The median values in table A1 of the sums are equal for each correlation coefficient.
The results are presented graphically in the figures A1 to A6 for the correlation coefficients taken equal to 1.0 and equal to 0.0. In figure A7 the results for both age-related data bases are compared.

Table A1 Eighteen examples of results of hearing threshold level calculations, dependent upon the correlation between hearing threshold levels at separate frequencies. The examples are for male groups, exposed for 10, 25 and 40 years to equivalent sound levels of 90 and 100 dB(A). Two age-related data bases (A and B) have been used. The age of the groups is supposed to be 20 years less than the exposure time. Examples are given for ages 30, 45 and 60 years, exposure times of 10, 25 and 40 years.

Noise exposure level L_{EX} in dB(A)	Age-related reference data base	Exp. time in years	Age in years	Sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz. Values exceeded by				
				50%	10%			
					r=1.0	r=0.7	r=0.5	r=0.0
-	A	-	30	5	42	36	33	24
-	A	-	45	20	66	59	55	44
-	A	-	60	45	108	99	93	78
-	B	-	30	18	58	52	48	38
-	B	-	45	35	104	95	88	73
-	B	-	60	58	152	145	130	108
90	A	10	30	15	61	55	50	39
90	A	25	45	35	89	81	70	64
90	A	40	60	63	137	127	120	103
90	B	10	30	28	75	68	64	52
90	B	25	45	50	123	113	107	90
90	B	40	60	76	181	167	157	133
100	A	10	30	49	120	110	103	86
100	A	25	45	86	162	151	144	125
100	A	40	60	107	203	190	180	158
100	B	10	30	62	133	123	116	98
100	B	25	45	97	190	177	168	146
100	B	40	60	126	231	216	206	181

Figure A1 Distribution of the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz as a function of age. Values are given not exceeded by 50% of the sums (H 0.50) and not exceeded by 10% of the sums (H 0.10), with the correlation coefficient between the HTLs at the different frequencies as parameter.The figure refers to no occupational noise exposure and age-related data base A.

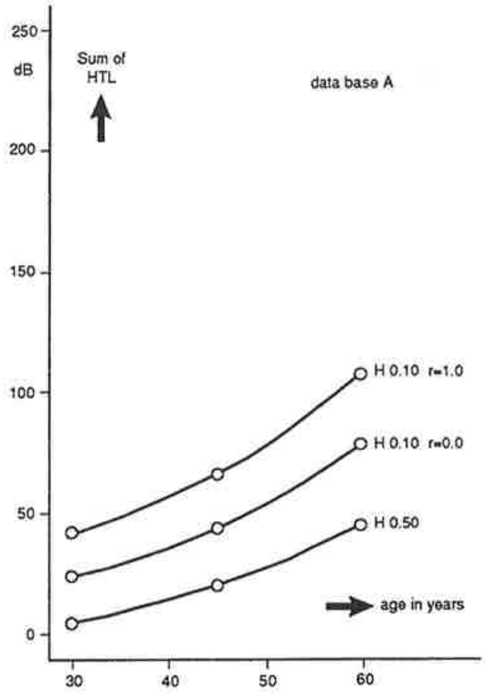


Figure A2 Distribution of the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz as a function of age. Values are given not exceeded by 50% of the sums (H 0.50) and not exceeded by 10% of the sums (H 0.10), with the correlation coefficient between the HTLs at the different frequencies as parameter. The figure refers to no occupational noise exposure and age-related data base B.

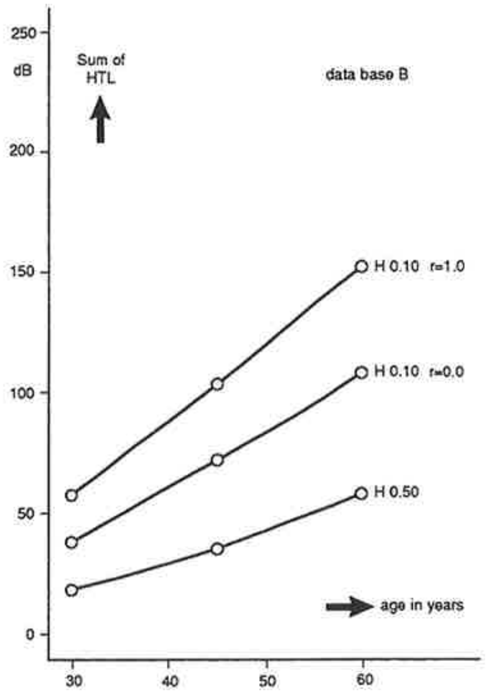


Figure A3 Distribution of the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz as a function of age. Values are given not exceeded by 50% of the sums (H 0.50) and not exceeded by 10% of the sums (H 0.10), with the correlation coefficient between the HTLs at the different frequencies as parameter. The figure refers to occupational noise exposure: 90 dB(A), age related data base A and exposure time 20 years less than age.

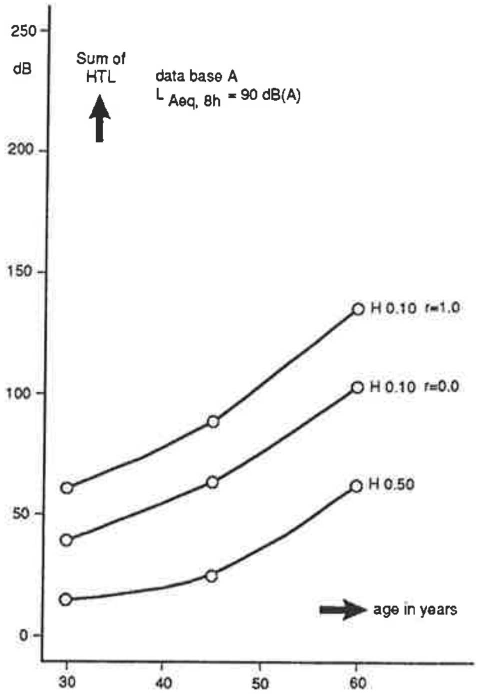


Figure A4 Distribution of the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz as a function of age. Values are given not exceeded by 50% of the sums (H 0.50) and not exceeded by 10% of the sums (H 0.10), with the correlation coefficient between the HTLs at the different frequencies as parameter. The figure refers to occupational noise exposure: 90 dB(A), age related data base B and exposure time 20 years less than age.

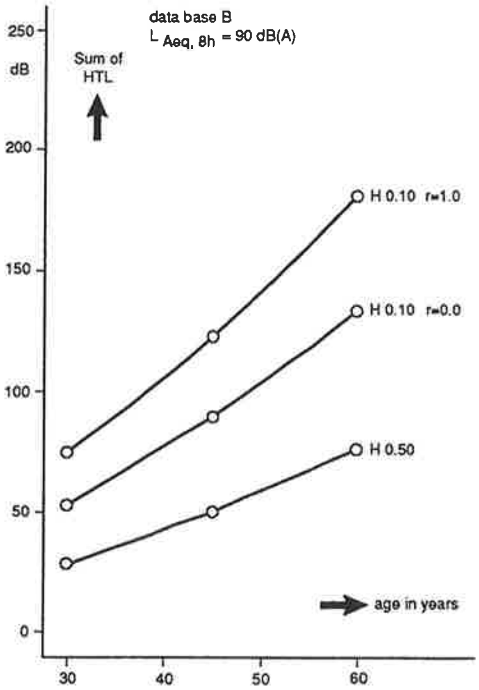


Figure A5 Distribution of the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz as a function of age. Values are given not exceeded by 50% of the sums (H 0.50) and not exceeded by 10% of the sums (H 0.10), with the correlation coefficient between the HTLs at the different frequencies as parameter. The figure refers to occupational noise exposure: 100 dB(A), age related data base A and exposure time 20 years less than age.

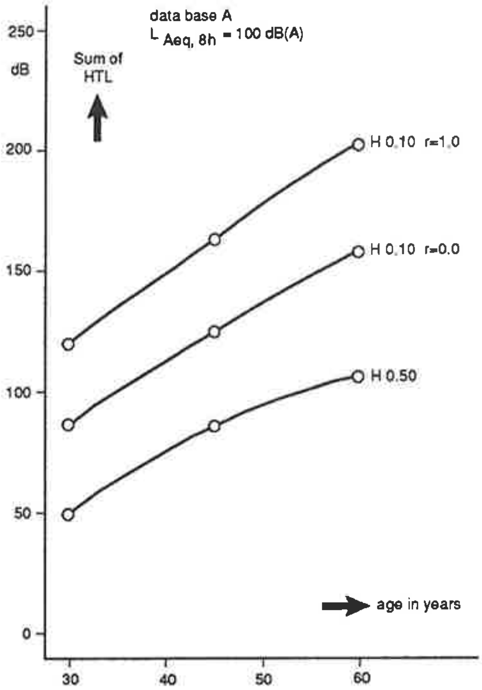


Figure A6 Distribution of the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz as a function of age. Values are given not exceeded by 50% of the sums (H 0.50) and not exceeded by 10% of the sums (H 0.10), with the correlation coefficient between the HTLs at the different frequencies as parameter. The figure refers to occupational noise exposure: 100 dB(A), age related data base B and exposure time 20 years less than age.

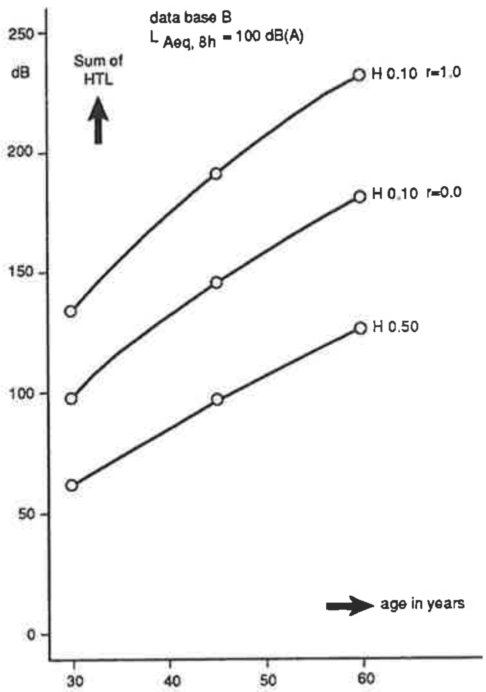
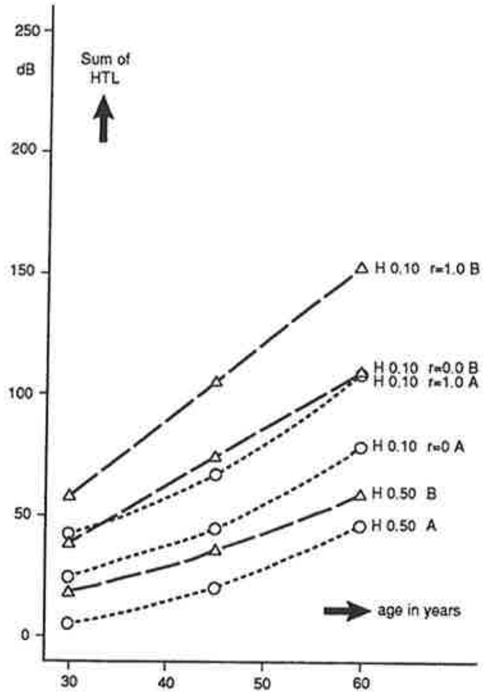


Figure A7 Distribution of the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz as a function of age. Values are given not exceeded by 50% of the sums (H 0.50) and not exceeded by 10% of the sums (H 0.10), with the correlation coefficient between the HTLs at the different frequencies as parameter.The figure refers to no occupational noise exposure and age-related data bases A and base B.



1.2 Calculations with empirical values of correlation coefficients

Data have been analysed of a population of 587 occupational noise-exposed carpenters and a reference population of 234 subjects not exposed to noise during working hours. Thes populations have been splitted up into subgroups according to age. In table A2 the number of subjects in each subgroup has been given. Since the number of subjects in the youngest and oldest reference subgroup is supposed to be too small for calculation of reliable correlation coefficients, no data on correlation coefficients are given for those subgroups.

Table A2 Number of subjects in each subgroup of a group of carpenters (occupational noise-exposed population) and a group of subjects not exposed to occupational noise.

	Age in years					
	≤ 20	21-30	31-40	41-50	≥51	total
Occ. noise-exposed population	54	132	211	126	64	587
Reference population	(12)	82	72	52	(16)	206 (234)

The tables A3 and A4 present the results of the correlation analysis of the HTL values at 0.5 and 1 kHz and of HTL values at 2 and 3 kHz respectively. Data are given for the right and left ear separately. Obviously, there is not much of a general trend in the results. Therefore an average value for the occupational noise-exposed group and for the reference group has been calculated. These average values appear to be somewhat larger for the occupational noise-exposed group than for the reference population.

Table A3 Correlation coefficient of HTLs at 0.5 kHz and HTLs at 1 kHz for male subgroups. Grouping according to age.

	Age in years ≤ 20	21-30	31-40	41-50	≥ 51	average value
Occupational noise-exposed subgroups						
L	0.79	0.73	0.74	0.77	0.65	
R	0.60	0.65	0.81	0.73	0.77	
average*	0.70	0.69	0.78	0.75	0.71	0.73
Reference subgroups						
	≤ 20	21-30	31-40	41-50	≥ 51	
L	-	0.70	0.67	0.75	-	
R	-	0.74	0.55	0.70	-	
average*	-	0.72	0.61	0.73	-	0.69

* average value of the two values above.

Table A4 Correlation coefficient of HTLs at 2 kHz and at 3 kHz for male subgroups. Grouping according to age.

	Age in years ≤ 20	21-30	31-40	41-50	≥ 51	average value
Occupational noise-exposed subgroups						
L	0.76	0.60	0.67	0.78	0.86	
R	0.81	0.72	0.64	0.75	0.76	
average*	0.79	0.66	0.66	0.77	0.81	0.74
Reference subgroups						
	≤ 20	21-30	31-40	41-50	≥ 51	
L	-	0.67	0.25	0.81	-	
R	-	0.51	0.76	0.67	-	
average*	-	0.59	0.51	0.74	-	0.61

* average value of the two values above.

Table A5 gives the correlation coefficients of the sum of the HTL values at 0.5 and 1 kHz and that sum at 2 and 3 kHz. Again average values have been calculated.

Table A5 Correlation coefficient of the sum of the HTLs at 0.5 and 1 kHz and the sum of the HTLs at 2 and 3 kHz for male subgroups. Grouping according to age.

	Age in years ≤ 20	21-30	31-40	41-50	≥ 51	average value
Occupational noise-exposed subgroups						
L	0.79	0.42	0.41	0.38	0.48	
R	0.64	0.48	0.46	0.51	0.45	
average*	0.72	0.45	0.44	0.45	0.47	0.51
Reference subgroups						
	≤ 20	21-30	31-40	41-50	≥ 51	
L	-	0.65	0.32	0.64	-	
R	-	0.76	0.50	0.57	-	
average*	-	0.71	0.41	0.61	-	0.58

* average value of the two values above.

Table A6 summarizes the results obtained in the tables A3 to A5.

Table A6 Average values of the correlation coefficients of HTLs at 0.5, 1, 2, and 3 kH and sums of HTLs at two adjacent frequencies for male subgroups. Averaged over age and over results from the right and the left ear.

Combination of frequencies	Occupational noise-exposed group	Reference group
0.5 / 1 kHz	0.73	0.69
2 / 3 kHz	0.74	0.61
0.5 + 1 / 2 + 3 kHz	0.51	0.58

Calculations have been carried out with respect to the 18 examples of populations presented at the beginning of this Annex, using the results of the correlation analysis on the group of carpenters and of the reference group: the correlation coefficient of the correlation between the single frequencies has been taken equal to 0.7 and that between the sums of two adjacent frequencies equal to 0.5. The results are given in the figures A8 to A14 as lines with parameter exp.

Figure A8 Distribution of the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz as a function of age. Values are given not exceeded by 50% of the sums (H 0.50) and not exceeded by 10% of the sums (H 0.10), with the correlation coefficient between the HTLs at the different frequencies as parameter (r= 0.0, r= 1.0 and exp.: r= 0.7 for single frequencies and r=0.5 for the sums of two frequencies).The figure refers to no occupational noise exposure and age-related data base A.

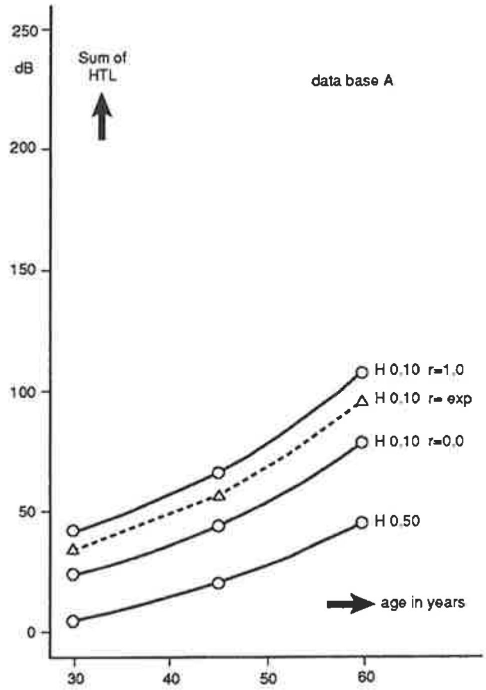


Figure A9 Distribution of the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz as a function of age. Values are given not exceeded by 50% of the sums (H 0.50) and not exceeded by 10% of the sums (H 0.10), with the correlation coefficient between the HTLs at the different frequencies as parameter (r= 0.0, r= 1.0 and exp.: r= 0.7 for single frequencies and r=0.5 for the sums of two frequencies). The figure refers to no occupational noise exposure and age-related data base B.

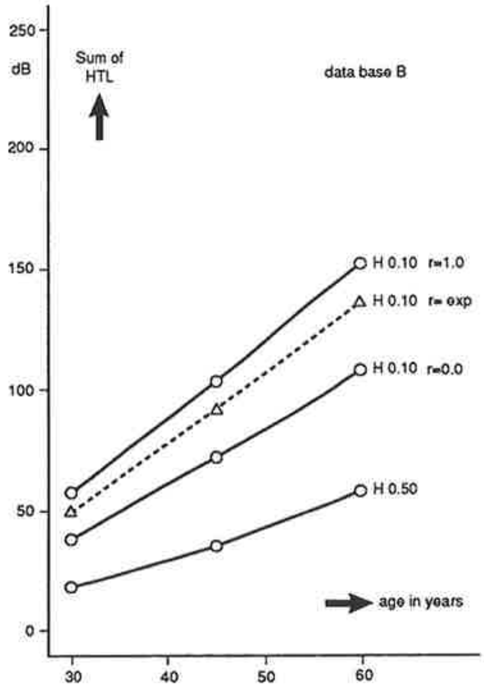


Figure A10 Distribution of the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz as a function of age. Values are given not exceeded by 50% of the sums (H 0.50) and not exceeded by 10% of the sums (H 0.10), with the correlation coefficient between the HTLs at the different frequencies as parameter (r= 0.0, r= 1.0 and exp.: r= 0.7 for single frequencies and r=0.5 for the sums of two frequencies).
The figure refers to occupational noise exposure: 90 dB(A), age related data base A and exposure time 20 years less than age.

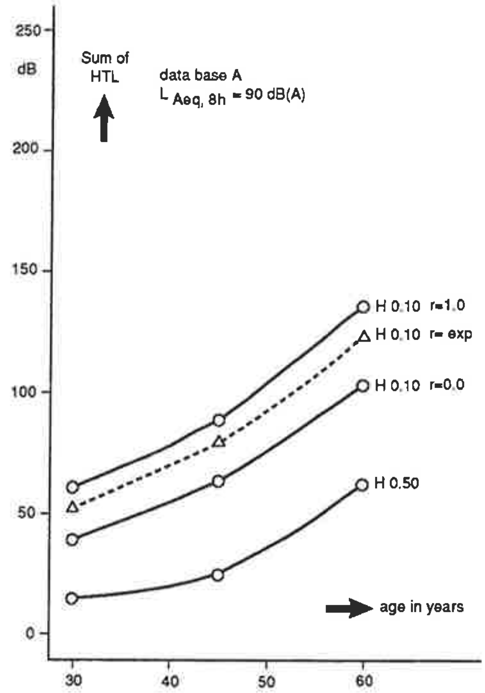


Figure A11 Distribution of the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz as a function of age. Values are given not exceeded by 50% of the sums (H 0.50) and not exceeded by 10% of the sums (H 0.10), with the correlation coefficient between the HTLs at the different frequencies as parameter (r= 0.0, r= 1.0 and exp.: r= 0.7 for single frequencies and r=0.5 for the sums of two frequencies).The figure refers to occupational noise exposure: 90 dB(A), age related data base B and exposure time 20 years less than age.

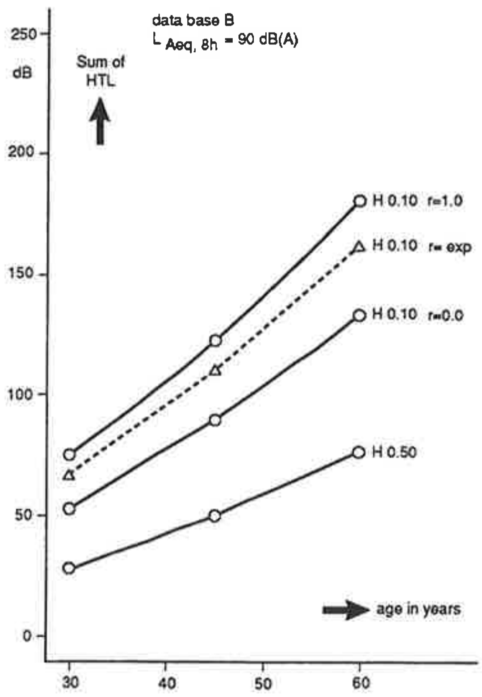


Figure A12 Distribution of the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz as a function of age. Values are given not exceeded by 50% of the sums (H 0.50) and not exceeded by 10% of the sums (H 0.10), with the correlation coefficient between the HTLs at the different frequencies as parameter (r= 0.0, r= 1.0 and exp.: r= 0.7 for single frequencies and r=0.5 for the sums of two frequencies).The figure refers to occupational noise exposure: 100 dB(A), age related data base A and exposure time 20 years less than age.

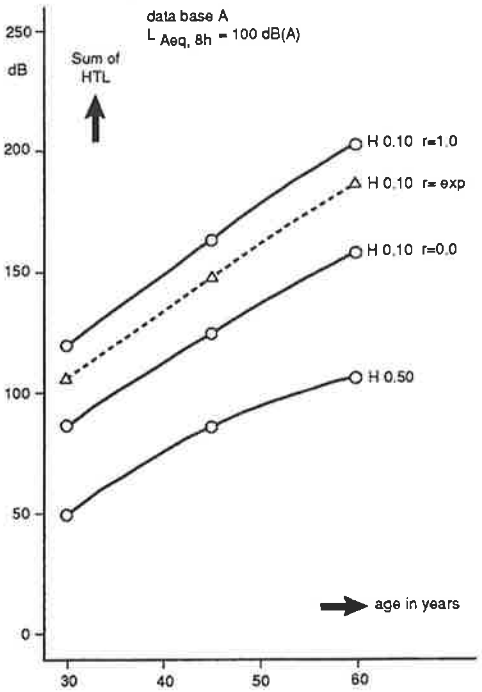


Figure A13 Distribution of the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz as a function of age. Values are given not exceeded by 50% of the sums (H 0.50) and not exceeded by 10% of the sums (H 0.10), with the correlation coefficient between the HTLs at the different frequencies as parameter (r= 0.0, r= 1.0 and exp.: r= 0.7 for single frequencies and r=0.5 for the sums of two frequencies).The figure refers to occupational noise exposure: 100 dB(A), age related data base B and exposure time 20 years less than age.

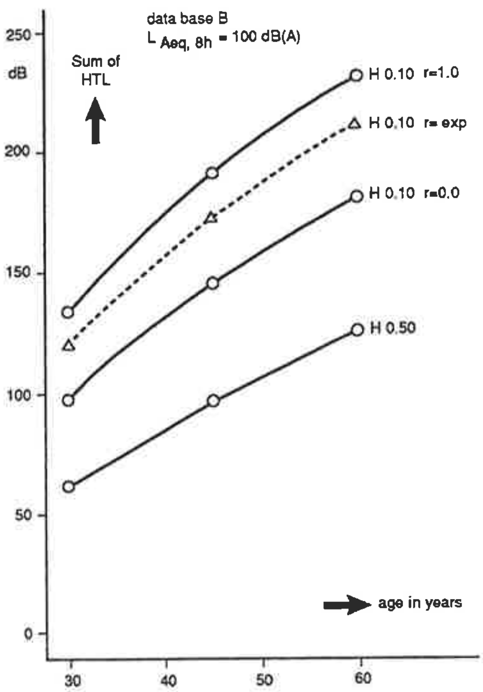
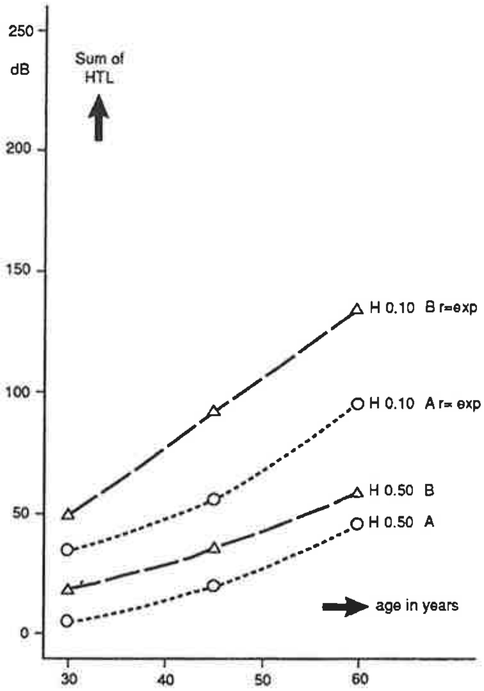


Figure A14 Distribution of the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz as a function of age. Values are given not exceeded by 50% of the sums (H 0.50) and not exceeded by 10% of the sums (H 0.10), with the correlation coefficient between the HTLs at the different frequencies as parameter (r= 0.0, r= 1.0 and exp.: r= 0.7 for single frequencies and r=0.5 for the sums of two frequencies).The figure refers to no occupational noise exposure and age-related data bases A and B.



2. CORRELATION BETWEEN HEARING THRESHOLD LEVELS AT DIFFERENT EARS

In table A7 the correlation coefficient of the sum of the hearing threshold levels at 0.5, 1, 2, and 3 kHz at the right and that sum at the left ear have been given for the groups of carpenters and the reference group. Apart from the youngest occupational noise-exposed subgroup, correlation coefficients vary from 0.83 to 0.91. Since it is very likely that social hearing handicap due to occupational noise and aging is not an issue at an age of 20 years or less, the low correlation coefficient for the youngest subgroup is not taken into account here.

Table A7 Correlation coefficient of the sum of HTL values at 0.5, 1, 2, and 3 kHz at the right ear and that sum at the left ear. Grouping according to age.

Subgroups	Age in years				
	≤ 20	21-30	31-40	41-50	≥ 51
Occupational noise-exposed	0.62	0.85	0.84	0.89	0.91
Reference	-	0.86	0.83	0.90	-

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