Determination of noise immission from sound sources close to the ears

Hammershøi, Dorte; Møller, Henrik

Published in:
Acustica United with Acta Acustica

DOI (link to publication from Publisher):
10.3813/AAA.918014

Publication date:
2008

Acta Acustica united with Acustica
Vol. 94 (2008) 114 – 129

DOI 10.2392/AAA.918014

Determination of Noise Immission From Sound Sources Close to the Ears

Dorte Hammershøi, Henrik Møller
Acoustics, Department of Electronic Systems, Aalborg University, Fredrik Bajers Vej 7 B5,
9220 Aalborg Ø, Denmark. dh@es.aau.dk

Summary
When a sound exposure stems from a sound source that is close to the ear of the exposed person, the noise is described in terms of the *free-field related* or *diffuse-field related* sound pressure level, i.e. the level of a free or a diffuse-sound field that would result in the same exposure of the person's ear as that stemming from the close sound source. The at-ear sound exposure level is measured either by MIRE technique (*m*icrophones *i*n *r*eal *e*ars) or by a manikin, and the free-field related or diffuse-field related sound pressure levels are obtained by subtracting the free-field-front or the diffuse-field head-related transfer function (HRTF) expressed in dB. The use of either, the eardrum, the open entrance, or the blocked entrance as measurement point for the MIRE-technique is evaluated. The results are the same, wherever in the ear canal the measurements are made. There is good agreement between human HRTFs measured at different laboratories, and for eardrum, open-entrance and blocked entrance, standard HRTF data have been derived, which may be used instead of HRTFs measured for each subject. The resulting statistical uncertainty depends on the choice of measurement point, and whether individual or standard HRTF data are used. Generally, measurements at the blocked entrance are practical and produce results with low statistical uncertainty. The results from manikin-measurements do not agree well with results from humans (MIRE), when HRTFs from the actual manikin or from the manikin standards (IEC 60959 and ITU-T P.58) are used. A better agreement is obtained with HRTFs constructed by multiplying human blocked-entrance data with the transfer function of the standardized coupler for manikins. This method is therefore described (and data tabled) in ISO 11904-2. A comparison between humans, manikins, and the manikin standards suggest, that standards do not specify an average human and should be revised.

PACS no. 43.50.Hg, 43.58.Si, 43.15.+s, 43.64.Ha, 43.58.Vb

1. Introduction

Human noise exposure is usually described from measurements at the position of the exposed person but with the person absent, i.e. by characteristics of the un-obstructed exposing sound field. For certain sound sources, the coupling between the source and the ear is so close that such measurement does not make sense and possibly cannot be carried out at all. This applies to sound sources placed close to the ears, in particular headphones and earphones.

For these cases, the exposure of the ear can be measured, e.g. by means of miniature or probe microphones, or using a manikin. This gives a more direct indication of the actual exposure of the hearing organ, but values cannot be directly compared to traditional values. The ear measurements are therefore "transferred" to traditional values by determining the un-obstructed free-air[1] sound field, which would result in the same ear exposure. When this sound field has been found, it may be subject to the same processing as normally used in noise assessments, for instance A-weighting.

Measurements can be made with miniature or probe microphones in humans ears (the *m*icrophone *i*n *r*eal *e*ars technique, the MIRE technique) or with an acoustical manikin (the manikin technique). Both methods have been standardized by the International Standardization Organization, ISO, [1, 2]. The present study was inspired by discussions in the responsible working group, and some of the data material obtained in the study is included in the standards. The principle has been practiced earlier, first probably by Rice *et al.* [3, 4].

1.1. General procedure

The basic idea of the method is to find the free-air sound pressure, P_{FA}, which would result in the same sound pressure at the ear, P, as observed from the noise. The terms

Received 31 January 2007, revised 30 August 2007,
accepted 11 September 2007.

[1] The term *free-air* is used as opposed to the more intuitive *free-field*, since free-field is used to refer unambiguously to the sound field of a single plane wave with frontal incidence to the exposed person (here, in ISO 11904 and other standards)

are connected by the head-related transfer function, the HRTF, by

$$P = P_{FA} \cdot HRTF, \quad (1)$$

where it is assumed that the terms are in the frequency domain, and dependence on frequency is implied. In the examples of the present article (and in the standards), a frequency resolution of a third octave is used. If the measured sound is given as sound pressure level, L, and the HRTF is given as magnitude in dB, ΔL, this can be expressed as

$$L_{FA} = L - \Delta L. \quad (2)$$

The relevant free-air fields are considered to be 1) a free field with frontal sound incidence, and 2) a diffuse field. There are arguments in favour of using either one of these types of fields. Much of the current knowledge of hearing and specifications to weighting functions are found with free-field frontal sound incidence, but most of the experience with noise exposures and hearing damages are presumably from situations with near diffuse-field properties.[2]

The method thus includes two steps, 1) measurement of the sound at the ear during exposure to the noise in question, and 2) measurement of the head-related transfer function for the relevant free-air sound field. The exposure data may in principle be measured at any point in the human ear canal, if the HRTF is measured in the same point, since the transmission along the ear canal is then the same during both measurements, and it thus cancels in the computation of L_{FA}. Examples of well-defined measurement points are at the eardrum, and at the open or blocked entrance of the ear canal.

1.2. Arguments against the methods in general

Since it must be assumed that the effects of noise on humans–in particular a possible damage of the ear–is a result of the actual exposure at the eardrum, it may seem strange to measure this exposure precisely, and yet convert the values to free air and evaluate the exposure by means of free-air methods and criteria. The free-air methods and criteria will be less accurate in predicting the effects of the noise, and the conversion to such values will introduce additional uncertainty.

This detour is necessary, since nearly all legislation as well as nearly all our knowledge about effects of noise on humans is based on free-air measurements. Recent years' technological achievements in microphone technique might in the future lead to an increased insight into actual eardrum exposures and the relation to noise-induced hearing losses. This may eventually lead to criteria that are more accurate, but in the meantime, the conversion to free-air values is the only practical possibility.

1.3. Differences between humans

As opposed to traditional free-air exposure techniques, ear exposure measurements will depend on the individual. This raises the question: Should individual or mean values be aimed at?

Generally, noise measurement techniques have been developed for a population, and, in particular, our experience about effects of noise has been gathered from population studies. Thus, a measurement of the exposure is not expected to predict precisely the individual risk of hearing damage for a particular person. That would also require a deeper insight into, e.g., the inner ear sensitivity and possible interaction between ear canal resonances and middle ear resonances. These issues and their relations to effects of noise are practically unexplored at present.

As a consequence, it is at present considered relevant only to aim at a population mean for free-field or diffuse-field related sound pressure levels.

1.4. Purpose and approach of study

It is the purpose of the present work to exemplify, compare and discuss the different methods for determining free-air-related sound pressure levels. For the MIRE-technique, this specifically includes a study of the significance of choice of measurement point in the ear canal. For the manikin-technique, it includes a comparison of results with those of the MIRE-technique, which is considered as the natural reference.

Both techniques require measurements of HRTFs, either of humans or of manikins. Such measurements require special facilities and skills, and, in particular for the MIRE technique, they represent a substantial work, since HRTFs must be measured for each individual subject. It is therefore investigated, whether it is feasible to use average data for a worldwide population of humans rather than individual data, and what the consequences are in terms of statistical uncertainty of the result. It is part of the study to collect "literature" data and to see if there is reasonable agreement between investigations to derive such average data.

For the manikin technique, an alternative could be to replace the measured HRTF for the particular manikin used by the intended HRTF for the manikin, i.e. the nominal values of the manikin standard. A third solution might be to use HRTF data derived from human HRTFs, in the following denoted "human-like" manikin HRTFs. These would potentially be better in case of disagreement between HRTFs of the manikin/standards and those of humans. The impact on the final result and its accuracy is studied for all three alternatives.

[2] The consideration relating to free-field versus diffuse-field must not be confused with considerations of free-field versus diffuse-field microphones. These types of microphones are constructed in such way that their pressure sensitivity at high frequencies compensates for the microphone's impact on the given sound field. The microphone output thereby reflects the sound pressure of the un-obstructed sound field, as long as the sound field is, respectively, a free field with normal incidence at the microphone or a diffuse field. At relevant frequencies, the difference between a free-field and a diffuse-field microphone is many times smaller than the difference between a free-field-front and a diffuse-field HRTF.

The same 14 headphones are used in all situations, which make cross-comparisons and statistical calculations possible. Most of the headphones are traditional supra- and circum-aural Hi-Fi headphones, while a few are completely free of the ear (but still close).

2. Methods

2.1. Human exposure data

Individual exposure data at blocked-entrance (L_{BE}) and open-entrance (L_{OE}) were obtained by multiplying (in the frequency domain) a source signal with human headphone transfer functions for the particular measurement point. Headphone transfer functions were obtained from a previous study [5] including 40 human subjects, and the source signal was chosen as an electrical pink noise signal (500 mV, 20 Hz-20 kHz). Here and elsewhere in the study, all calculations on signals and transfer functions were made with data representing single sinusoids with a resolution of 23 Hz (originally 187,5 Hz, interpolation carried out by zero-padding the impulse response), until data, in the final step, were converted to third-octave values for L and ΔL (power summation within each band).

Headphone measurements at the eardrum were not available, and in lack of these, pseudo-individual exposure data for eardrum, L_{ED}, were constructed based on two independent datasets (different subject groups). Each individual blocked entrance data from [5] was combined with a randomly selected individual blocked-entrance-to-eardrum data from [6] (12 subjects). The individual L_{ED} obtained this way is not correct for any specific person, but the mean and variance that can be derived from such values reflect those of correct values, if the two terms are uncorrelated.

2.2. Human HRTF data

Individual values for blocked and open entrance, ΔL_{BE} and ΔL_{OE} respectively, were obtained for a free field from [7]. For a diffuse field, similar values were obtained from the same data sets, and derived as explained in [8]. The subjects included in [7] and [5] were the same, thus the exposure and HRTF data were obtained for the same individuals.

2.3. Statistical variation with MIRE-technique

When ΔL is determined individually, the transmission along the ear canal will ideally cancel for each individual (see section 4.1). In this case, L_{FA} can–whatever the measurement point–be expressed in terms of blocked-entrance values:

$$L_{FA} = L_{BE} - \Delta L_{BE}. \quad (3)$$

The variance can be calculated as:

$$\sigma^2(L_{FA}) = \sigma^2(L_{BE} - \Delta L_{BE}). \quad (4)$$

If literature data are used, individual cancellation along the ear canal does not take place, and equation (3) does not apply. Statistical calculations must therefore be based on equation (2), and, since ΔL is a fixed value (which does not contribute to variance), the variance is:

$$\sigma^2(L_{FA}) = \sigma^2(L) \quad (5)$$

Note that $\sigma^2(L)$ refers to the variance in the actual measurement point, whereas equation (4) estimates variance from blocked entrance measurements and HRTFs – whether the measurement are made at blocked entrance or not.

2.4. Literature HRTFs

Initiated by the interest for using tabulated data with the MIRE-technique, an invitation to submit data was sent generally through national standardization bodies and by direct contact to known, relevant laboratories. The following datasets were received.

2.4.1. Free-field HRTFs

Hellström and Axelsson [9] measured eardrum HRTFs for 19 subjects for 24 directions in the horizontal plane, and for each azimuth at three elevations (−45°, 0° and 45°). Additional data measured in the same way are presently unpublished, but the total set of individual free-field-front HRTFs for 220 subjects (384 ears, since not all subjects had both ears measured) have kindly been made available in personal communication [10].

Møller *et al.* [7] measured blocked-entrance HRTFs for 40 subjects (both ears) for 97 directions covering the whole sphere. Open-entrance HRTFs were measured for the same 40 subjects (both ears) for sound coming from the front and back, left and right, and directly above. Open-entrance HRTFs from all 97 directions were determined by multiplying blocked-entrance HRTFs with the pressure division at the entrance, P_{OE}/P_{BE} (same investigation, average of 5 directions). The original free-field-front blocked-entrance and open-entrance HRTFs (given in terms of impulse responses) have been converted into individual third-octave values for the present investigation.

Hammershøi and Møller [6] measured eardrum, open-entrance and blocked-entrance HRTFs for 12 subjects (left ear only), with sound coming from the front, from the left side, and from the back. The original free-field-front HRTFs (given in terms of impulse responses) have been converted into individual third-octave values for the present investigation.

Sandvad [11] measured blocked-entrance HRTFs for 38 subjects (both ears) for 193 directions covering the whole sphere. The original free-field-front HRTFs (given in terms of impulse responses) have been converted into individual third-octave values for the present investigation.

Bronkhorst [12] measured eardrum HRTFs for eight subjects (both ears) using 976 directions covering the whole sphere. Langendijk and Bronkhorst [13] improved the methods and determined eardrum HRTFs for 31 subjects (both ears). Drullman and Bronkhorst [14] measured blocked-entrance HRTFs for 69 subjects using the same setup. These data [13, 14] were converted into third-octave values (originally frequency responses with 97.7 Hz resolution), and the mean free-field-front HRTF and its standard deviation across subjects were kindly made available in personal communication [15].

Hartung [16] measured blocked-entrance HRTFs for 190 directions covering the whole sphere. Some uncertainty exists on the calibration of these data, though. HRTFs measured in largely the same setup–and with a known calibration–exist for three subjects (six ears). These data have been converted into third-octave values and kindly made available in personal communication [17].

Storey and Dillon [18] measured eardrum and blocked-entrance HRTFs for 20 subjects (one ear) for 0° and 45° azimuths in the horizontal plane. Their free-field-front HRTFs in third-octave values from 100 Hz to 10 kHz were kindly made available in personal communication [19].

Free-field-front HRTFs were also measured by Wiener and Ross [20] (6-12 ears, eardrum), Wiener [21] (6 ears, open entrance), Yamaguchi and Sushi [22] (7 subjects, eardrum and open entrance, 3 subjects blocked entrance), Robinson and Whittle [23] (16 subjects, outside open entrance), Jahn [24] (6 subjects, eardrum), Shaw [25] (10 subjects, open entrance), Blauert [26, 27] (12 subjects, close to the open entrance), Mehrgardt and Mellert [28] (20 subjects, open entrance), Morimoto and Ando [29] (3 subjects, open entrance), Pösselt *et al.* [30] (11 subjects, blocked entrance), Schmitz and Vorländer [31] (10 subjects, close to the open entrance), Okabe and Miura [32] (28 subjects, open entrance). A compilation of data from six investigations [20, 21, 22, 23, 24, 25] was carried out by Shaw [33], and later presented in tabular form by Shaw and Vaillancourt [34]. All of these data are given in forms not suitable for conversion to third-octave values. However, except for the data by Morimoto and Ando [29], which were presented in a very small figure, a comparison was presented by Møller *et al.* [7] and–in most cases–fair agreement was found with the data of Møller *et al.* [7].

Free-field HRTFs have also been presented by Burkhard and Sachs [35] (24 subjects, open entrance), Platte [36] (4-6 subjects, close to the open entrance), Genuit [37] (6 subjects, close to the open entrance), and Wenzel *et al.* [38] (eardrum), however not for the frontal direction.

2.4.2. Diffuse-field HRTFs

Killion *et al.* [39], measured eardrum HRTFs in a diffuse sound field for 20 subjects (both ears). The original individual data for 16 of the 20 subjects (one ear or subject mean) have kindly been made available in personal communication ([40], kindly facilitated by E. A. G. Shaw).

Møller *et al.* [8] computed diffuse-field open-entrance and blocked-entrance HRTFs using the HRTFs for 97 directions of 40 subjects (both ears) from Møller *et al.* [7]. For the present investigation both diffuse-field HRTFs (originally frequency responses with 187.5 Hz resolution) have been converted into third-octave values.

Blocked-entrance HRTFs of the investigation by Sandvad [11] for 38 subjects (both ears) and 193 directions were used to compute individual diffuse-field HRTFs using the same methods as described in Møller *et al.* [8], the only difference being the higher number of directions.

Eardrum and blocked-entrance HRTFs for 976 directions from the investigations by Langendijk and Bronkhorst [13] and Drullman and Bronkhorst [14] for both ears of 31 and 69 subjects, respectively, (see also section 2.4.1) were used to compute individual diffuse-field HRTFs. These were subsequently converted into third-octave values and the mean and standard deviation across subjects were kindly made available for the present investigation [15].

Individual diffuse-field blocked-entrance HRTFs from the investigation of Hartung [16] were computed and subsequently converted into third-octave values for 3 subjects, and kindly made available in personal communication [17].

Finally, Storey and Dillon [18] measured eardrum and blocked-entrance HRTFs in a diffuse field for 18 subjects (one ear). Their individual data in third-octave values from 100 Hz to 10 kHz were kindly made available in personal communication [19].

2.5. Manikins

Three manikins, intended to conform with the manikin-standards (IEC 60959 [41] and ITU-T P.58 [42]) were included.

The Knowles Electronics Manikin for Acoustic Research (KEMAR) was originally designed from anthropometrical data, and it formed the basis for the geometrical description in IEC 60959. The pinnae are anatomically shaped, and four different sizes are available. In the present study it was tested with the most common ones, DB065/066.

The Brüel and Kjær type 4128 manikin has anatomically shaped pinnae, but has head and torso of simplified geometries. The pinnae used in the present study were DZ 9626/27.

All parts of the HMS II manikin from HEAD acoustics are of simplified geometry. A box with electronic equipment makes up the part of the torso below the shoulders.

The particular version of the HMS II used in the present study was intended for binaural recordings, so it only had 4-mm ear canals terminated by the microphones rather than the IEC 60711 occluded ear simulators and ear canal extensions. Thus “eardrum” measurements were not available, but for comparison, measurements were transferred to “eardrum” by means of (1) the difference between blocked entrance and “eardrum” of an IEC 60711 coupler (see section 2.7 and Figure 2), and (2) similar data for the HMS II ear canal and microphone, i.e. difference between blocked entrance and 4-mm measurements.

2.6. HRTFs of manikins

The manikin HRTFs were obtained from a previous study (previously unpublished, methods presented in [43]). The

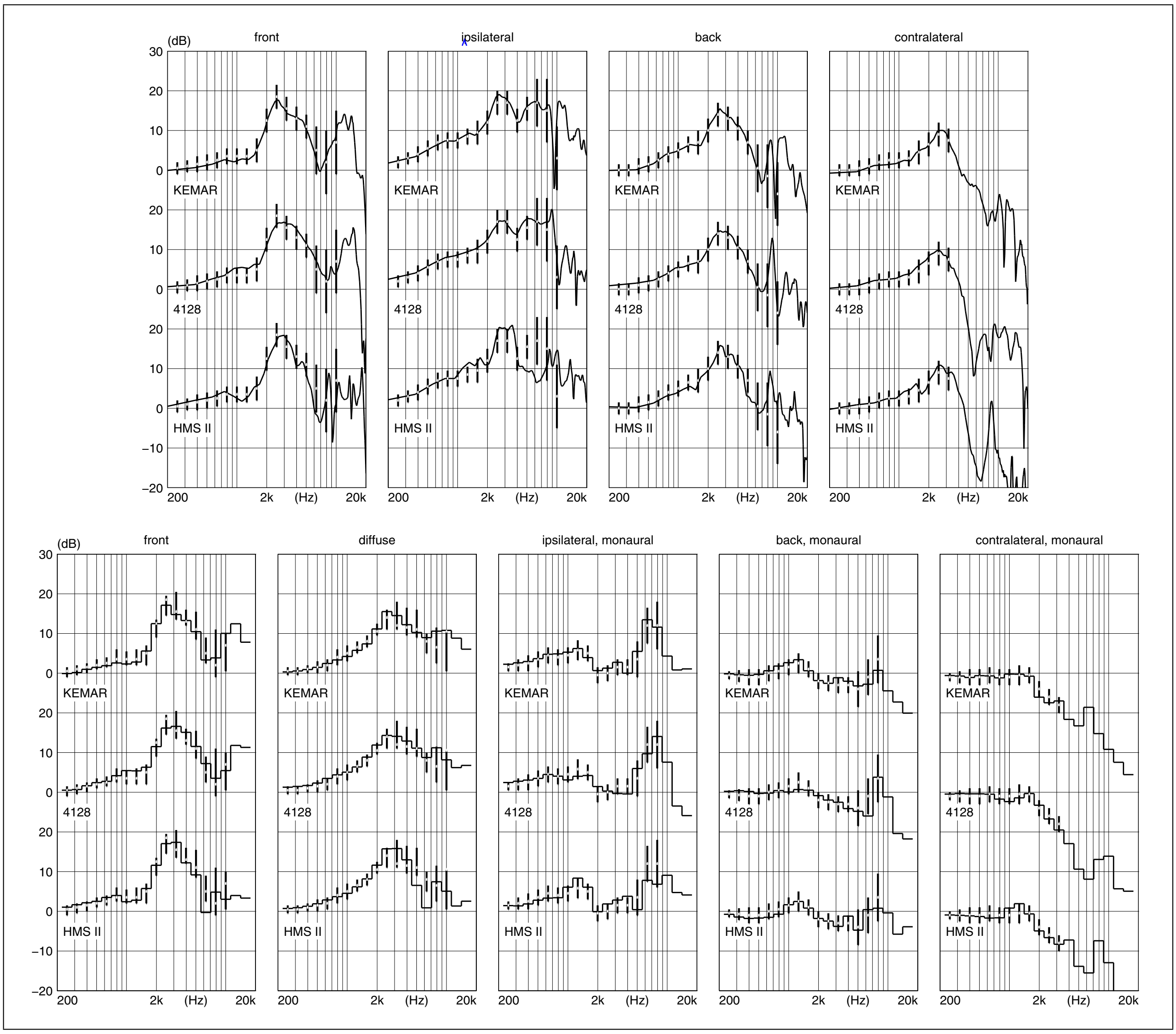

Figure 1. Top: Manikin HRTFs (heavy lines) and requirements of IEC 60959 (vertical bars, nominal value at white dot). Bottom: Third-octave noise-band manikin HRTFs (heavy lines) and requirements of ITU-T P.58 (vertical bars, nominal value at white dot).

HRTFs of the three manikins are shown in Figure 1 together with requirements from the standards.

From Figure 1 (top) it is seen that the transfer functions of the KEMAR are very close to the nominal values of the IEC 60959 requirements (except for the ipsilateral and back directions at 10 kHz, where narrow dips in the HRTFs impede comparison). The manikin thus seems to fulfil the requirements very well. For the 4128 there is also nice agreement with the requirements, although the transfer functions are not close to the nominal values at every single frequency (just within tolerances for the front direction at 1, 1.25 and 2.5 kHz). For the HMS II the main structures of the requirements are generally recognized, but the transfer functions do not often coincide with the nominal values of the IEC 60959, and they are outside the tolerances for the front direction at 6.3 kHz, and for the ipsilateral direction at 5, 6.3 and 10 kHz.

From Figure 1 (bottom) it is seen that the transfer functions of the KEMAR also fulfill the requirements of the ITU-T P.58 well, although they are just within the tolerances for some directions (the front direction at 800 Hz, 1 kHz, and 10 kHz, for the back (monaural) at 3.15 kHz, and for the contralateral (monaural) at 2 kHz). Most of the transfer functions of the 4128 meet the requirements of the ITU-T P.58, although they are just within tolerances for some directions (front direction at 1 kHz, for the diffuse field at 630 Hz and 8 kHz, for the ipsilateral (monaural) at 2, 3.15 and 4 kHz, and for the contralateral (monaural) at 3.15 kHz). For the back direction (monaural), the transfer function of the 4128 is outside tolerances at 6.3 kHz. Transfer functions of the HMS II fulfil the requirements of the ITU-T P.58 for most frequencies, however they are just within tolerances in several cases, and outside the tolerances for the front direction at 6.3 kHz, for the diffuse field at 5 and 6.3 kHz, and for the ipsilateral (monaural) at 4 kHz.

Table I. Alternative data for ΔL (free-field, upper value, and diffuse-field, lower value) for use with manikins (mean human blocked-entrance data from Møller *et al.* [7] transferred to "manikin eardrum" using mean values of Figure 2, as described in section 2.7).

Frequency $[Hz]$	≤ 100	125	160	200	250	315	400	500	630	800	1000
$\Delta L_{FF}[dB]$	0.0	0.4	0.8	1.2	1.5	1.5	1.7	2.1	2.5	2.2	1.7
$\Delta L_{DF}[dB]$	0.0	0.3	0.6	0.9	1.2	1.4	1.8	2.3	3.2	4.0	4.6
Frequency $[Hz]$	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000	
$\Delta L_{FF}[dB]$	3.8	8.4	12.9	15.6	15.6	14.2	10.6	4.0	2.0	-0.3	
$\Delta L_{DF}[dB]$	6.0	8.1	11.4	15.0	14.2	11.9	9.8	8.5	11.0	7.1	

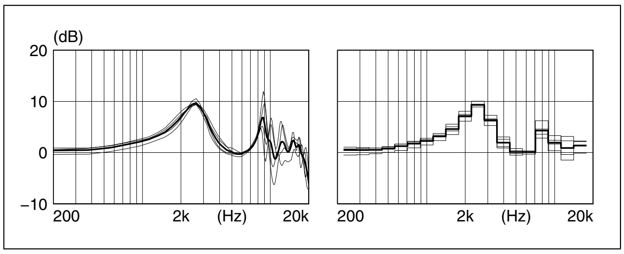

Figure 2. Sound transmission in IEC 60959/ITU-T P.58 ear-canal simulation consisting of IEC 60711 occluded ear simulator and ear-canal extension. Transmission from blocked-entrance pressure to pressure measured by IEC 60711 microphone for pure tones (left frame) and third-octave noise bands (right frame). Thin lines indicate measurements on four different ears (mounted in manikins, simulated diffuse field), heavy lines indicate means.

2.7. Human-like manikin HRTFs

The immediate choice of human data to use with manikins would be human eardrum HRTFs. However, the measurement of L includes the transmission in the ear simulator, and if that deviates from the average transmission in human ear canals, the two will not cancel in the subtraction. Besides, for humans a significant variation exists due to variance in the ear-canal transmission [6] and possibly uncertainty of the exact measurement point. A similar variation does not exist for manikins, since their ear-canal transmission is determined by the configuration for the common IEC 60711. It was therefore decided to use a procedure that uses the transfer function of the coupler as part of the HRTF. This was done by combining human blocked-entrance HRTFs with the transfer function of the IEC 60711 coupler.

Four examples of the transmission from the blocked entrance of the artificial ear canal to the pressure measured by the IEC 60711 microphone are shown in Figure 2 (our data, not previously published). As expected this transmission is approximately the same for different samples of the ear canal and coupler, except for narrow peaks and dips at high frequencies.

ΔL was therefore obtained by adding (in dB) average human blocked-entrance HRTFs (from [7]) and the transfer function of the manikin ear simulator (Figure 2).

2.8. Manikin exposure data

Manikin exposure data were obtained using a procedure similar to that used with human data (section 2.1), using

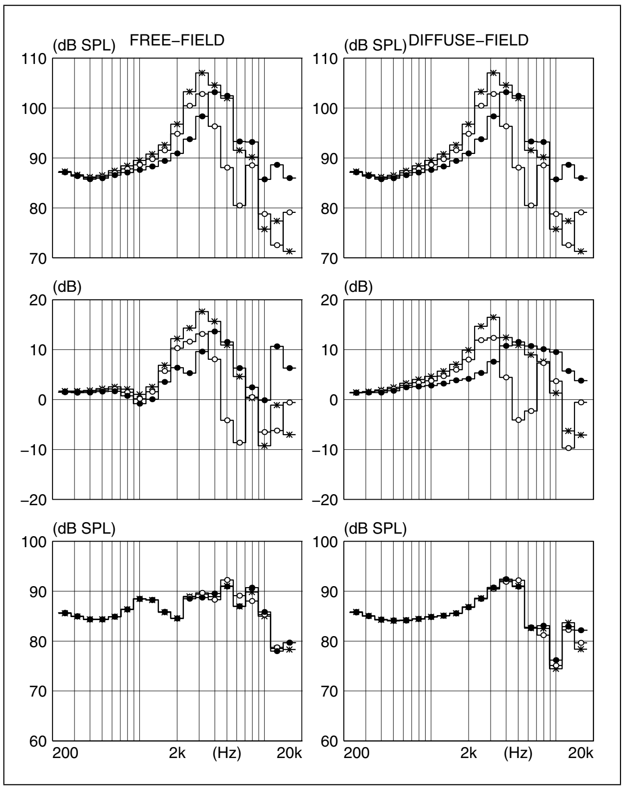

Figure 3. Top panels (identical) show exposure data for the Sony MDR 102 headphone, measured at eardrum (stars), open entrance (circles) and blocked entrance (dots) for subject AVH. Middle panels show the individual free-field (left) and diffuse-field (right) HRTFs. Bottom panels show the resulting free-air related levels. A-weighting and summation give free-field related A-weighted levels of 99.7, 99.9 and 99.7 dB and diffuse-field related A-weighted levels of 99.5, 99.6 and 99.6 dB (for eardrum, open entrance and blocked entrance, respectively).

headphone transfer functions measured with the manikins' built-in microphones (not previously published, methods similar to [5]).

2.9. Uncertainty with manikin-technique

The validity of manikin-measurements was assessed by computing the difference between L_{FA} obtained with a manikin, and the grand mean of L_{FA} obtained from measurements with humans using individual HRTFs (blocked entrance data used).

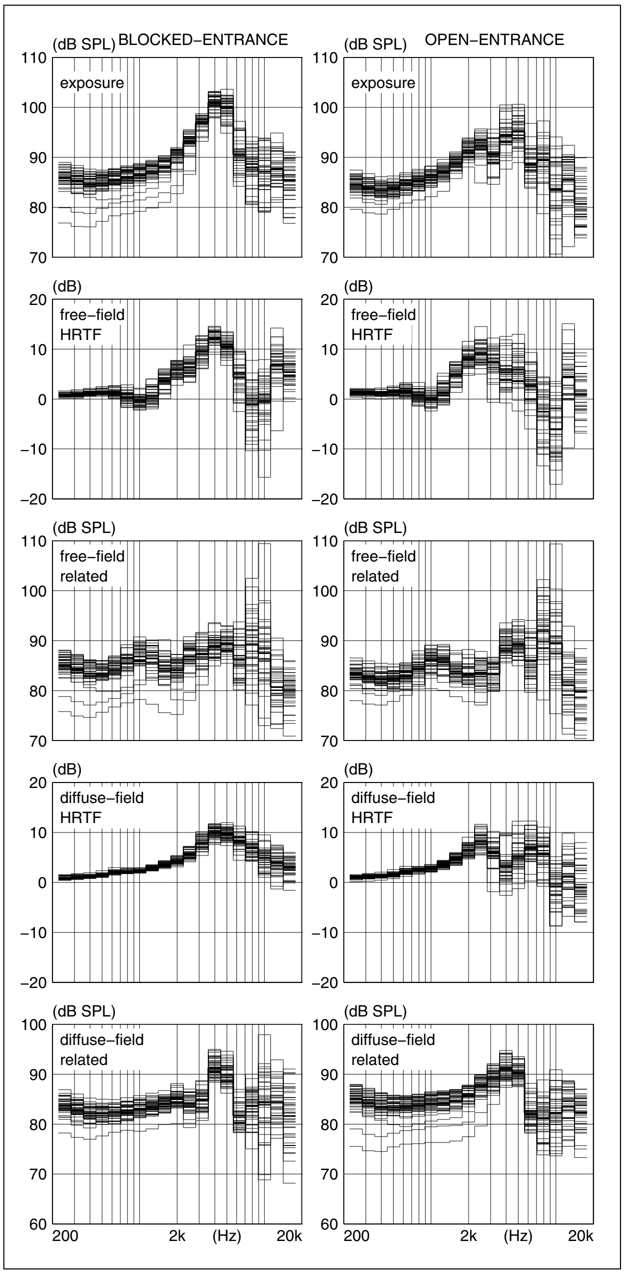

Figure 4. Blocked- and open-entrance data for 40 individuals (thin lines, means in heavy line). Top panels show exposure data for the Sony MDR 102 headphone, 2nd row shows the free-field HRTFs, 3rd row shows the resulting free-field related levels, 4th row shows the diffuse-field HRTFs, and bottom row shows the diffuse-field related levels. A-weighting and summation give free-field related A-weighted levels of 98.5 dB (blocked-entrance mean) and 98.3 dB (open-entrance mean), and diffuse-field related A-weighted levels of 98.5 (blocked-entrance mean) and 97.6 dB (open-entrance mean).

3. Results

3.1. MIRE-technique

An example of individual exposure data, HRTFs and resulting free- and diffuse-field related sound pressure levels is shown in Figure 3. Data are shown for eardrum, open entrance and blocked entrance. It is clearly seen how the

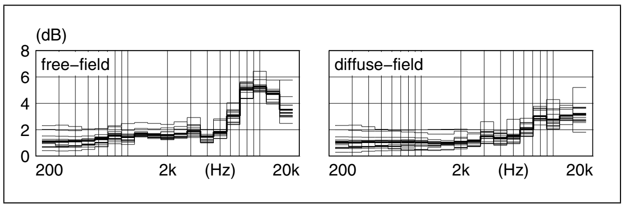

Figure 5. $\sigma(L_{FA})$ for 14 headphones (thin lines, mean in heavy line), when individual values are used for ΔL (equation 4).

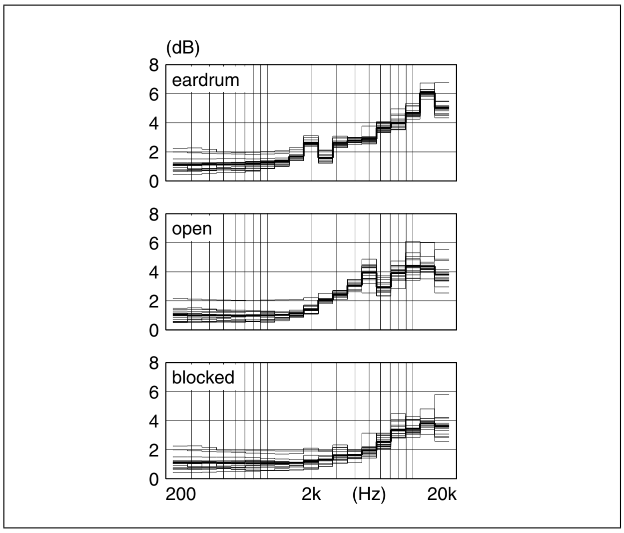

Figure 6. $\sigma(L_{FA})$ for 14 headphones (thin lines, mean in heavy line), when literature data are used for ΔL (equation (5)) and measurements carried out at eardrum (top), open entrance (middle) and blocked entrance (bottom).

raw measurements differ, yet the resulting sound pressure levels are quite similar.

Figure 4 shows individual and mean exposure measurements, HRTFs and resulting free-air related sound pressure levels for 40 human subjects for a single headphone. Data for measurements at blocked and open entrance are given in each their column. The variation between individuals is pronounced, and differences up to 10-30 dB depending on frequency exist. A statistical analysis is given in the following section.

3.2. Statistical variation with MIRE-technique

Figure 5 and Figure 6 show $\sigma(L_{FA})$ for 14 headphones, when individual respectively literature values are used for ΔL. When individual values are used (equation (4), Figure 5), $\sigma(L_{FA})$ is independent of ear canal measurement point but varies with sound field. When literature data are used (equation (5), Figure 6), $\sigma(L_{FA})$ varies with ear canal measurement point but not with sound field. In all cases, variations between subjects are small at low frequencies and somewhat higher at frequencies above a few kilohertz.

3.3. Literature data for ISO 11904-1

The collected free-field-front HRTFs are shown in Figure 7 and the collected diffuse-field HRTFs are presented in Figure 8.

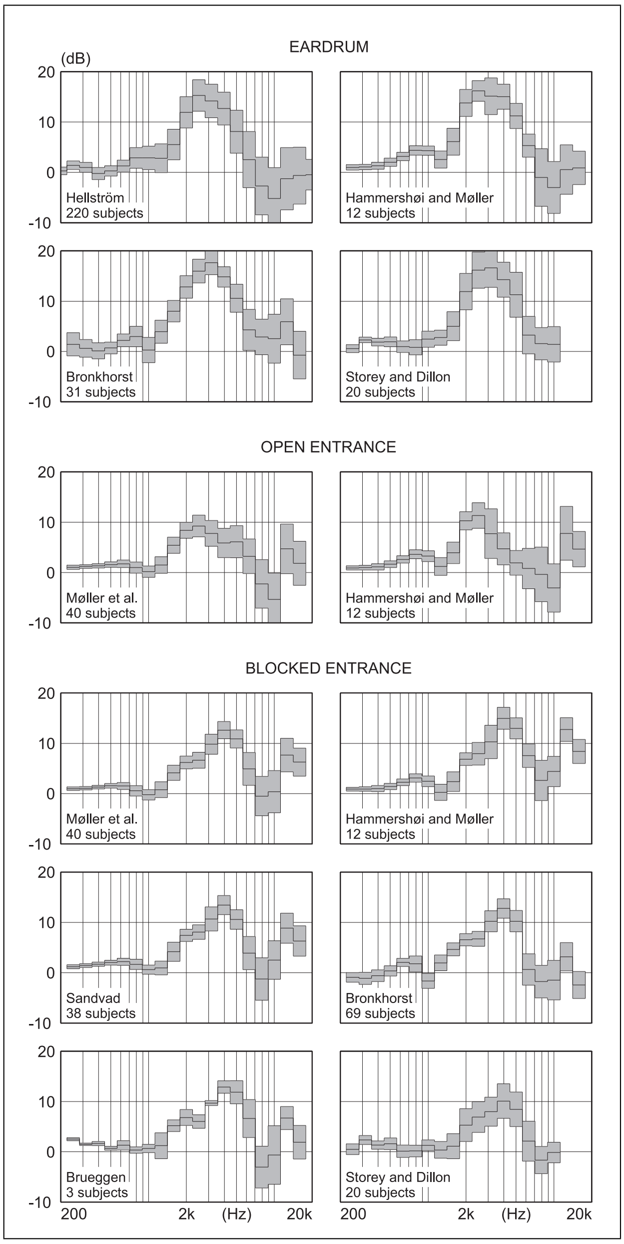

Figure 7. Free-field-front HRTFs from literature, mean (heavy line) and mean ± one standard deviation (grey area). Eardrum data from Hellström [10], Hammershøi and Møller [6], Bronkhorst [15], and Storey and Dillon [19], open entrance data from Møller *et al.* [7], and Hammershøi and Møller [6], blocked entrance data from Møller *et al.* [7], Hammershøi and Møller [6], Sandvad [11], Bronkhorst [15], Brüggen [17], and Storey and Dillon [19].

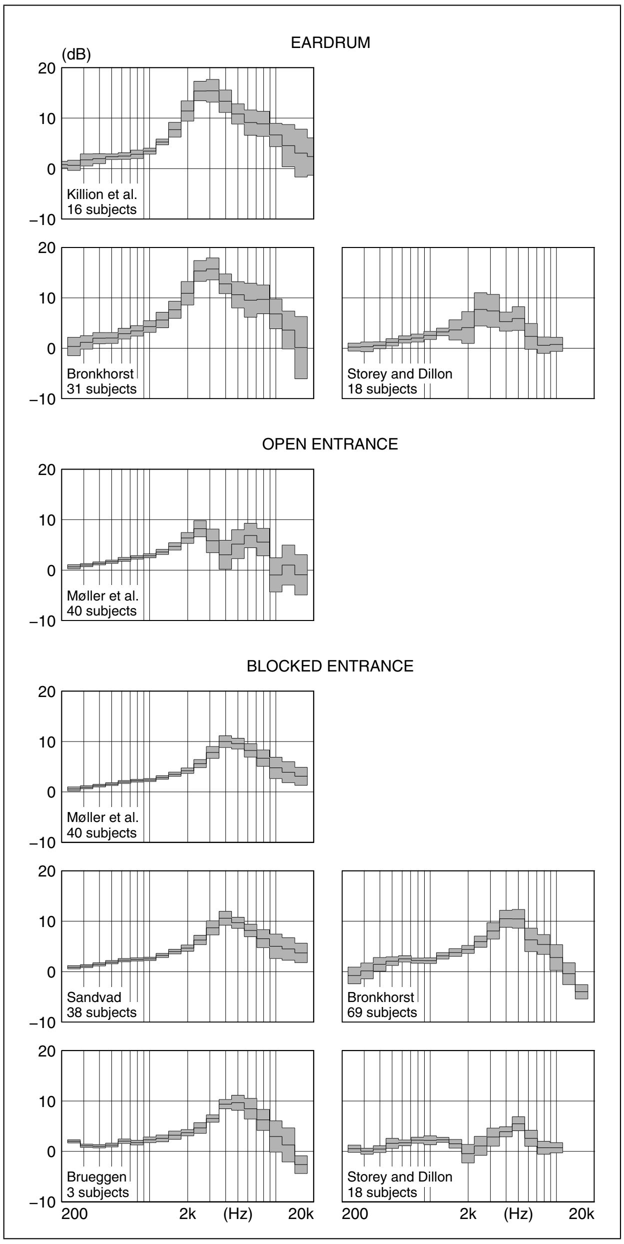

Figure 8. Diffuse-field HRTFs from literature, mean (heavy line) and mean ± one standard deviation (grey area). Eardrum data from Killion *et al.* [39, 40], Bronkhorst [15], and Storey and Dillon [18], open entrance data from Møller *et al.* [7, 8], and blocked entrance data from Møller *et al.* [7, 8], Sandvad [11], Bronkhorst [15], and Brüggen [17], Storey and Dillon [18].

A comparison of the aggregated data shows that there is fair agreement across investigations, which makes it reasonable to use them to derive a general set of data. One exception is the diffuse-field HRTF data from Storey and Dillon, which have clearly deviating characteristics. The reason for this deviation is not believed to relate to the characteristics of the human HRTFs, and these data were disregarded in the following.

It is reasonable to assume that the HRTFs depend slightly on gender and age. For several investigations, this information is not available, and for those investigations where the information exists, the measurements have been made on groups of adults that are not severely skew in age and gender. It should also be noted that some persons are represented with two ears, whereas others have only been measured at one ear. Despite of these circumstances, data were simply averaged (in decibels) across investigations with each investigation weighted by the number of ears.

An exception from the simple average is made for the lowest frequencies, where a high variation is seen for some investigations. This may be due to a number of reasons, but since HRTFs should approach 0 dB monotoni-

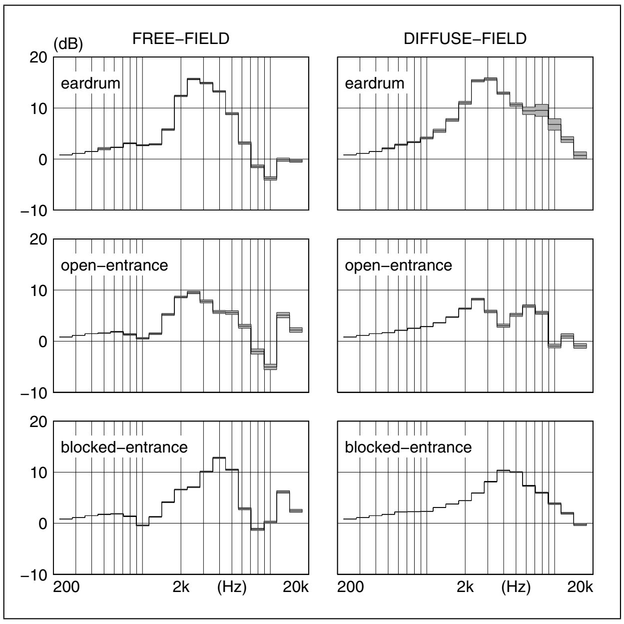

Figure 9. Free-field-front HRTFs (left) and diffuse-field HRTFs (right) for eardrum, open-entrance and blocked-entrance. Means (heavy lines) and means ± one standard error of mean (grey area) of literature data (using free-field-front eardrum HRTFs from [6, 10, 15, 19]; free-field-front open-entrance HRTFs from [6, 7]; free-field-front blocked-entrance HRTFs from [6, 7, 11, 15, 17, 19]; diffuse-field eardrum HRTFs from [15, 39, 40]; diffuse-field open-entrance HRTFs from [7, 8]; diffuse-field blocked-entrance HRTFs from [7, 8, 11, 15, 17]. The data are given in tabular form in Table II.

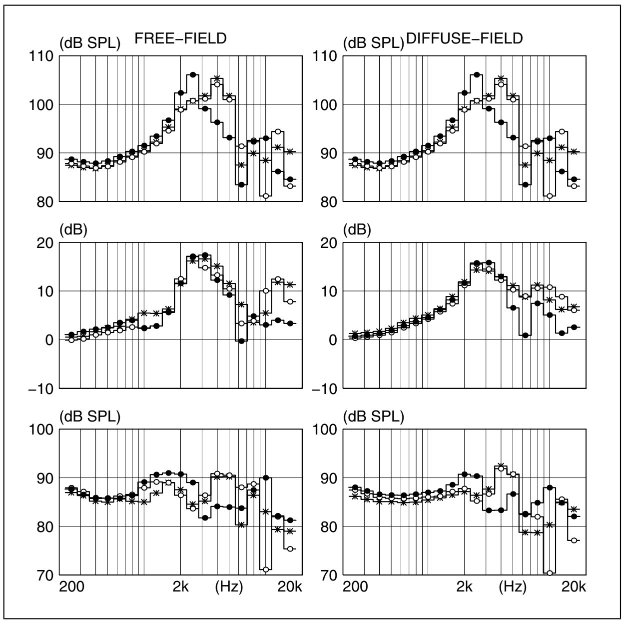

Figure 10. Top panels (identical) show exposure data for the Sony MDR 102 headphone, measurements with three manikins: KEMAR (stars), 4128 (circles), and HMS II (dots). Middle panels show the individual free-field (left) and diffuse-field manikin-HRTFs. Bottom panels show the resulting free-air related levels. A-weighting and summation give free-field related A-weighted levels of 97.2, 97.6 and 98.3 dB and diffuse-field related A-weighted levels of 97.1, 96.9 and 98.2 dB (for the three manikins, respectively).

cally at low frequencies, it was chosen to substitute manually with values that are more appropriate. The data from Møller *et al.* [7] has the expected characteristics and holds a very low variation, thus indicating a minimal experimental spread. Therefore, these data have gradually been given more weight from 630 Hz and down to 315 Hz, from which frequency only they have been used.

Mean literature data (± one standard error of the mean) for both free field and diffuse field and for the three measurement points (eardrum, open entrance, and blocked entrance) are given in graphical form in Figure 9 and in tabular form in Table II.

3.4. Manikin technique

An example of exposure data, HRTFs and resulting free- and diffuse-field related sound pressure levels for the three manikins is given in Figure 10. The exposure measurements and HRTFs differ considerably between manikins, and also the results differ considerably.

The difference between manikin-results and MIRE-results are shown in Figures 11, 12 and 13 for each of the three options of HRTF data. When the individual manikin HRTFs are used (Figure 11), the results obtained with manikins deviate systematically from those obtained with humans. The deviations are most distinct for the free-field related spectra, in particular in the frequency range between 800 Hz and 2 kHz, where a pattern of deviations in the order of ±1-5 dB is typical for all headphones. The deviations are smaller for a diffuse field than for a free field.

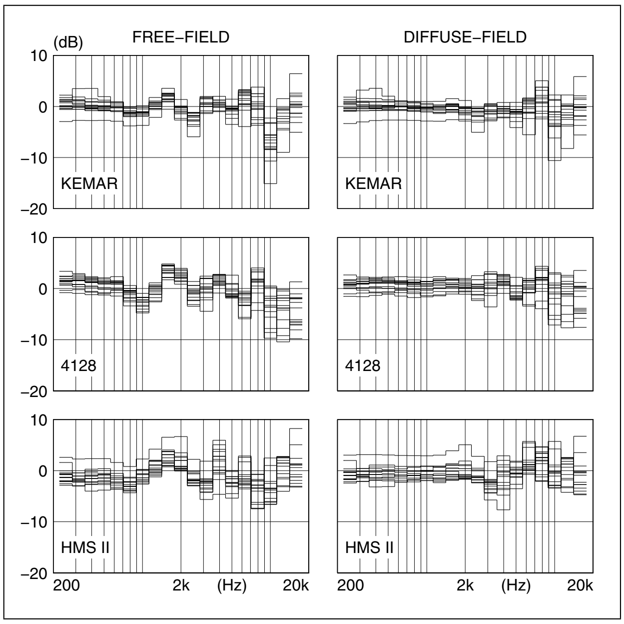

Figure 11. Difference between free-air related levels from measurements with manikins and with MIRE-technique (mean of 40 humans) for 14 headphones using individual manikin HRTFs.

Figure 12 shows the results if free-field and diffuse-field HRTFs are taken from the nominal values of IEC 60959 and ITU-T P.58, respectively. Problems are seen that are

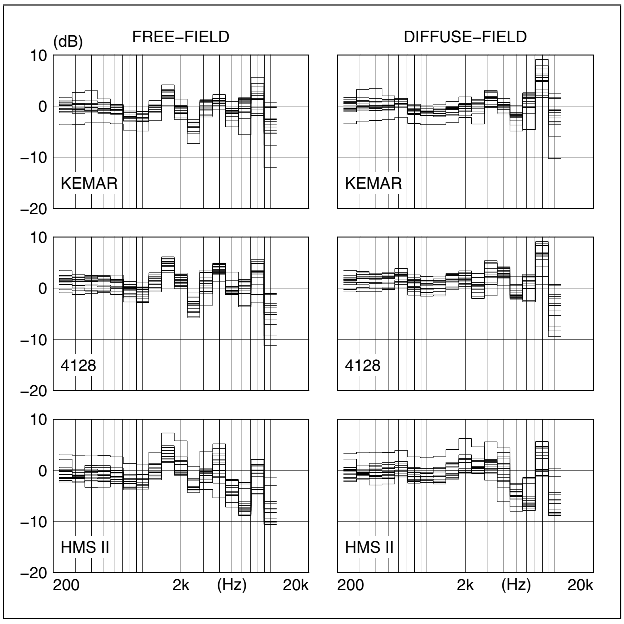

Figure 12. Difference between free-air related levels from measurements with manikins and with MIRE-technique (mean of 40 humans) for 14 headphones using nominal values for the HRTFs (free-field from IEC 60959/ITU-T P.58 and diffuse-field from ITU-T P.58).

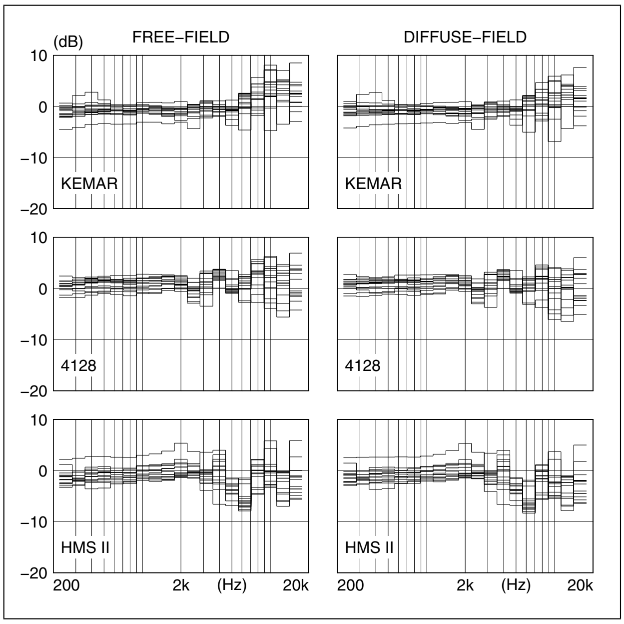

Figure 13. Difference between free-air related levels from measurements with manikins and with MIRE-technique (mean of 40 humans) for 14 headphones using mean human blocked-entrance HRTFs transferred to "manikin eardrum".

similar to those with data for the individual manikins. For the free-field-related values, there are in fact slightly larger deviations at 1.6 kHz and 2.5 kHz (typically ±2-6 dB). Also for diffuse field, the use of standardized values gives deviations, which for some frequencies are larger in amplitude than when individual manikin data are used. This can be seen for the KEMAR at 5 and 8 kHz (-1 to -5 dB, 2–9 dB), for the 4128 at 8 kHz (1–9 dB), and for the HMS II at 5 and 6.3 kHz (-3 to -8 dB, -2 to -8 dB).

Table II. Free-field-front HRTFs and diffuse-field HRTFs for eardrum (ED), open-entrance (OE) and blocked-entrance (BE) and for third-octave frequency bands. Means of literature data using free-field-front eardrum HRTFs from [6, 10, 15, 19]; free-field-front open-entrance HRTFs from [6, 7]; free-field-front blocked-entrance HRTFs from [6, 7, 11, 15, 17, 19]; diffuse-field eardrum HRTFs from [15, 39, 40]; diffuse-field open-entrance HRTFs from [8, 7]; diffuse-field blocked-entrance HRTFs from [7, 8, 11, 15, 17]. The data are given in graphical form in Figure 9.

Frequency	ΔL_{FF} [dB]			ΔL_{DF} [dB]		
[Hz]	ED	OE	BE	ED	OE	BE
≤ 100	0.0	0.0	0.0	0.0	0.0	0.0
125	0.2	0.2	0.2	0.2	0.2	0.2
160	0.4	0.4	0.4	0.4	0.4	0.4
200	0.6	0.6	0.6	0.6	0.6	0.6
250	0.8	0.8	0.8	0.8	0.8	0.8
315	1.1	1.1	1.1	1.1	1.1	1.1
400	1.5	1.5	1.5	1.5	1.5	1.5
500	2.0	1.6	1.7	2.1	1.7	1.7
630	2.3	1.8	1.8	2.8	2.1	2.2
800	3.1	1.3	1.4	3.3	2.5	2.3
1000	2.7	0.6	-0.4	4.1	2.9	2.3
1250	2.9	1.5	1.3	5.5	3.6	3.1
1600	5.8	5.2	4.1	7.7	4.7	3.8
2000	12.4	8.6	6.6	11.0	6.4	4.4
2500	15.7	9.5	7.1	15.3	8.2	5.9
3150	14.9	7.8	10.1	15.7	5.8	8.1
4000	13.2	5.7	12.8	12.9	3.0	10.3
5000	8.9	5.6	10.5	10.6	5.1	10.0
6300	3.1	2.9	2.8	9.4	6.9	7.3
8000	-1.4	-2.0	-1.2	9.5	5.6	6.0
10000	-3.8	-5.0	0.2	6.8	-0.9	3.8
12500	-0.1	5.1	6.1	3.8	1.0	2.0
16000	-0.4	2.2	2.4	0.7	-0.9	-0.2

When the human-like manikin HRTFs (section 2.7) are used, a nice improvement is seen (Figure 13). In particular, the large deviations for the free-field related levels at 1.6 and 2.5 kHz decrease significantly (reduced to typically within 2-3 dB). For the HMS II a systematic deviation of several dBs (at 4 and 5 kHz) remains.

4. Discussion

4.1. Measurements at blocked ear canal

It has generally been assumed that the correct free-air level can be found from exposure measurements at the eardrum, at the open entrance, or at the blocked ear canal, if only the corresponding ΔL is used. This is not entirely correct. When measurements are made at the blocked entrance, the impedance relations at the entrance may be of importance as shown in the following.

Figure 14 shows an anatomical sketch and an analog model of the external ear (from [44]). The sound pressure at the entrance to the ear canal is denoted P_{OE}, and the

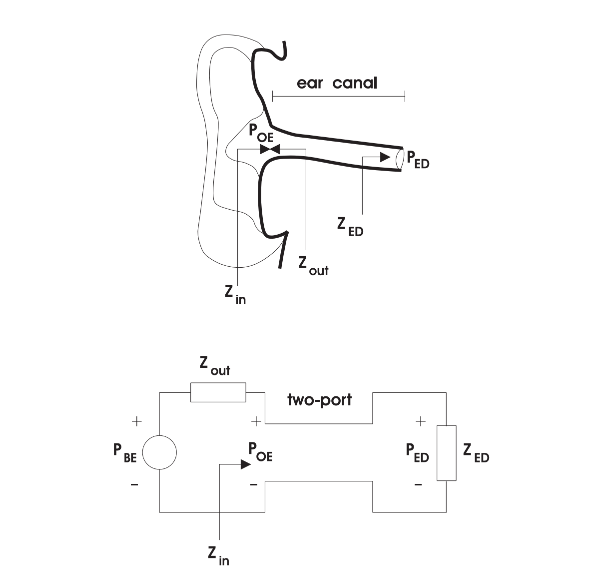

Figure 14. Sound transmission through external ear. Sketch of anatomy and analog model (from [44]).

pressure at the eardrum is P_{ED}. The acoustic impedance of the eardrum is Z_{ED}, the input impedance to the ear canal is Z_{in}, and the impedance seen outward from the ear canal entrance is Z_{out}.

The ear canal is modelled by a passive two-port which is loaded by Z_{ED}, has the input impedance Z_{in}, and has the input and output pressures P_{OE} and P_{ED}, respectively. The "outside world" is modelled by its Thevenin equivalent with the "open-circuit" pressure P_{BE} and the impedance Z_{out}. The open-circuit pressure is the pressure that would exist at the same position, when no volume velocity ("current") runs through Z_{out}.

P_{BE} does not exist physically in daily life, but in measurements it can be found as the sound pressure at the entrance to the ear canal, when the ear canal is physically blocked, for instance with an earplug. Naturally, P_{OE} and P_{ED} do not exist at the same time.

It is possible to find P_{OE} from a pressure division of P_{BE} between Z_{out} and Z_{in}. Thus

$$\frac{P_{OE}}{P_{BE}} = \frac{Z_{in}}{Z_{in} + Z_{out}}. \tag{6}$$

This pressure division depends on the situation, and is different during measurement of the noise (situation I), and during measurement of the HRTF (situation II). When P_{FA} is determined from blocked ear canal measurements, the result is

$$P_{FA,BE} = \frac{[P_{BE}]_I}{[P_{BE}/P_{ref}]_{II}}, \tag{7}$$

where P_{BE}/P_{ref} is–by definition–the blocked entrance HRTF (see e.g., [45], P_{ref} is the free-field sound pressure at the position of the subject, but with the subject absent).

P_{FA} should ideally have been determined from eardrum measurements,

$$P_{FA,ED} = \frac{[P_{ED}]_I}{[P_{ED}/P_{ref}]_{II}}. \tag{8}$$

The error is given by the ratio between $P_{FA,BE}$ and $P_{FA,ED}$ (equations (7) and (8)):

$$\frac{P_{FA,BE}}{P_{FA,ED}} = \tag{9}$$

$$\frac{[P_{BE}]_I}{[P_{BE}/P_{ref}]_{II}} \cdot \frac{[P_{ED}/P_{ref}]_{II}}{[P_{ED}]_I} =$$

$$\frac{[P_{BE}]_I \cdot [\frac{P_{ED}}{P_{OE}}]_{II} \cdot [\frac{P_{OE}}{P_{BE}}]_{II} \cdot [\frac{P_{BE}}{P_{ref}}]_{II}}{[\frac{P_{BE}}{P_{ref}}]_{II} \cdot [\frac{P_{ED}}{P_{OE}}]_I \cdot [\frac{P_{OE}}{P_{BE}}]_I \cdot [P_{BE}]_I}.$$

Further reduction, while inserting equation (6) and using that P_{ED}/P_{OE} as well as Z_{in} are the same in the two situations I and II, leads to an error of:

$$\frac{[P_{OE}/P_{BE}]_{II}}{[P_{OE}/P_{BE}]_I} = \tag{10}$$

$$\frac{[\frac{Z_{in}}{Z_{in}+Z_{out}}]_{II}}{[\frac{Z_{in}}{Z_{in}+Z_{out}}]_I} = \frac{\frac{Z_{in}}{Z_{in}+[Z_{out}]_{II}}}{\frac{Z_{in}}{Z_{in}+[Z_{out}]_I}} =$$

$$\frac{Z_{in} + [Z_{out}]_I}{Z_{in} + [Z_{out}]_{II}} = PDR.$$

The term is denoted pressure division ratio, PDR. The PDR is unity, if Z_{out} is the same in the two situations, or if $Z_{in} \gg Z_{out}$. Physically this means that the impedance seen outwards from the ear canal should be either undisturbed by the presence of the sound source or it should–with and without the sound source–be low compared with the impedance of the ear canal as seen from the outside.

Previous investigations showed that, for a range of headphones, deviations from unity in PDR were moderate (up to a few decibels) and only occurred in narrow frequency bands above 2 kHz [5, 46]. Circum-aural, supra-aural and supra-concha headphones were tested as well as headphones that completely lacked contact to the ear. Numerous other sources close to the ear will not be in direct contact to the ear, and thus have a PDR equal to unity.

Deviations from unity that are more severe are only expected if Z_{out} is more severely affected by the presence of the noise source, i.e. with noise sources which are coupled even closer to the ears, such as insert earphones and possibly some intra-concha earphones.

4.2. Correlation between L and ΔL

If it is assumed that the two terms in equation (4) are uncorrelated, the equation simplifies to:

$$\sigma^2(L_{FA}) = \sigma^2(L_{BE}) + \sigma^2(\Delta L_{BE}) \tag{11}$$

The assumption of the terms being uncorrelated can be evaluated from Figure 15 and Figure 16 for free and diffuse fields, respectively. The figures show $\sigma(L)$ calculated

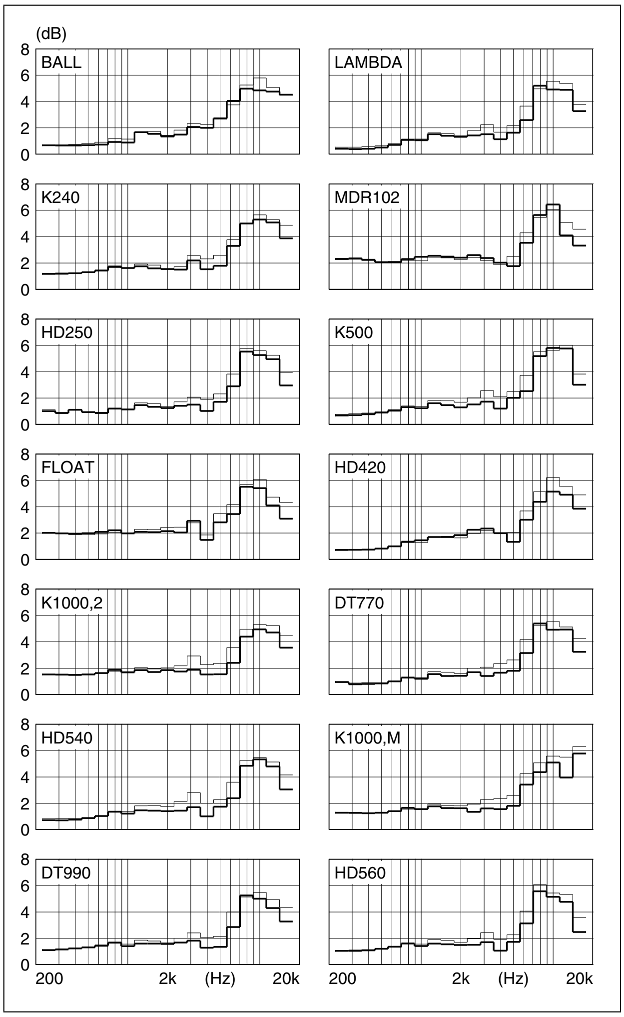

Figure 15. $\sigma(L_{FF})$ for 14 headphones. Derived from complete calculation of $L_{BE} - \Delta L_{BE}$ (heavy line) or from the combined variances of L_{BE} and ΔL_{BE} (thin line) (respectively left and right side of equation 11).

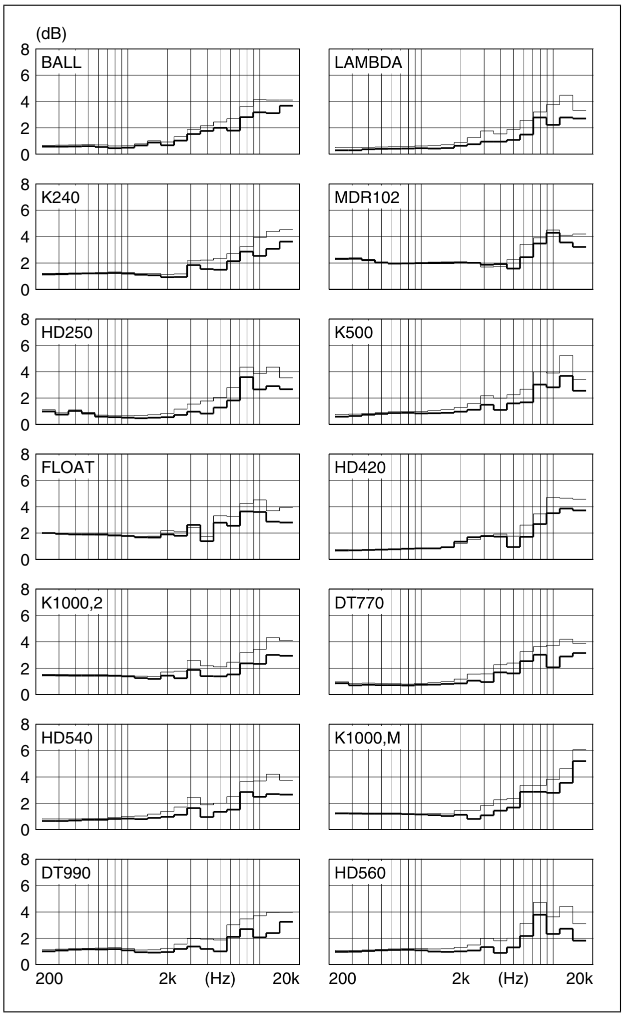

Figure 16. $\sigma(L_{DF})$ for 14 headphones. Derived from complete calculation of $L_{BE} - \Delta L_{BE}$ (heavy line) or from the combined variances of L_{BE} and ΔL_{BE} (thin line) (respectively left and right side of equation (11)).

either from individual values of the final result (left side of equation (11)), or as the square root of the combined variances (right side of equation (11)). As seen, the combined variances provide a fair approximation to the true variance for all headphones and for both fields, although there is a tendency to overestimation. This is taken as evidence of a slight positive correlation between exposure measurements and HRTFs. Equation (11) thus provides a conservative estimate of the uncertainty.

4.3. Statistical uncertainty with MIRE-technique

When using measurements on n subjects, the variance of the mean $\overline{L_{FA}}$ can be estimated as follows:

$$\sigma^2(\overline{L_{FA}}) = \frac{\sigma^2(L_{FA})}{n}. \qquad (12)$$

Values from Figure 5 and Figure 6 may be used for insertion in equation (12) in order to estimate the needed number of subjects, when a given uncertainty is required.

Usually the type of free-air sound field is decided beforehand. Then it is worth noting that with individual determination of ΔL the measurement point does not affect the uncertainty, and with literature data the lowest uncertainty is found, when a blocked ear canal is used. Then (also) from an uncertainty point of view, a blocked ear canal can be recommended whenever permitted (i.e. unless the noise has significant narrow-band components at high frequencies and unless the noise source is coupled very closely to the ear, see section 4.1).

It is also worth noting that the statistical uncertainty is not in general lower, when individual rather than literature data are used for ΔL. When reference is to be made to a free sound field the lowest statistical uncertainty is obtained with literature data and with a blocked ear canal. When reference is to be made to a diffuse sound field the lowest statistical uncertainty is obtained with individual data, but nearly as low values are found with literature data and blocked ear canal. (This is assuming that the literature data do not contribute to uncertainty, since these are in principle invariant (fixed), but, of course, some uncertainty does exist for the specific literature data derived, see Figure 9, and section 3.3.)

4.4. Other sources of uncertainty, MIRE-Technique

In addition to the finite sample size already mentioned, other sources of uncertainty should be pointed out. A particularly critical point in the method is the calibration of the miniature or the probe tube microphone. If literature data are used for ΔL, this calibration (including determination of the microphone's frequency response) is critical, since it will affect the measured level and thus the result directly. If individual measurements of HRTFs are made with the same miniature or probe microphone, its calibration cancels (provided that it is stable between measurements), and the critical calibration becomes that of the microphone used to measure the free-air sound field when measuring the HRTF.

Similarly, inaccurate positioning of the microphone in the ear canal is critical when literature data are used, whereas it cancels when individual measurements are made of ΔL (provided that the positioning is stable between measurements). Examples of the effect of inaccurate positioning of the microphone are given in Figure 17.

4.5. Difference between MIRE and manikin results

A difference between results obtained with humans and with manikins has also been observed in a previous study by Richter and Fedtke [47]. It would be interesting to see, if the improvement obtained in the present study by using human-like manikin HRTFs could be applied also to their data. Figure 18 upper and middle row show original data using individual and standardized HRTFs respectively (average of 9 headphone-manikin combinations). Disagreements comparable to those of the present investigation are clearly seen at 1.6, 2, and 2.5 kHz. The lower row of Figure 18 shows results, if the human-like manikin HRTFs of the present study are used. It is seen that by using these data the magnitude of the deviations for Richter and Fedtke's data is reduced.

This result further supports that the impact of possible shortcomings with the manikin-technique is reduced when using the human-like manikin HRTFs. Table I is therefore included in the ISO 11904-2. The results also suggest that the manikins are more satisfactory for the exposure measurements, than they are for applying proper HRTFs in a sound field. This is a little surprising, since the free-field and diffuse-field performance has been the focus of the standards for the manikins.

4.6. Comparison of manikin standards with humans

The poor results obtained with HRTFs from the standards (and from actual manikins) make it relevant to evaluate the requirements of the standards by comparisons with human data. Figure 19 shows the free-field-front HRTF requirements of IEC 60959 and ITU-T P.58 together with free-field-front eardrum HRTFs for a group of humans.

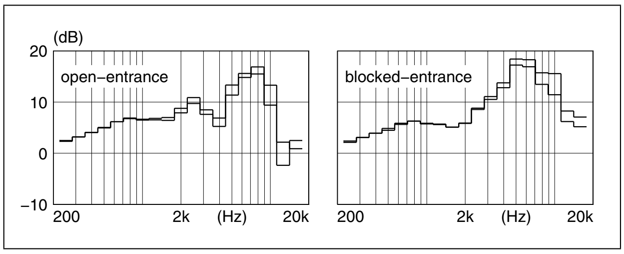

Figure 17. Measurements with 3-mm microphone displacement between (both microphone and blockage are displaced). Brüel and Kjær 4128, HRTF at approximately 90° azimuth measured with probe microphone.

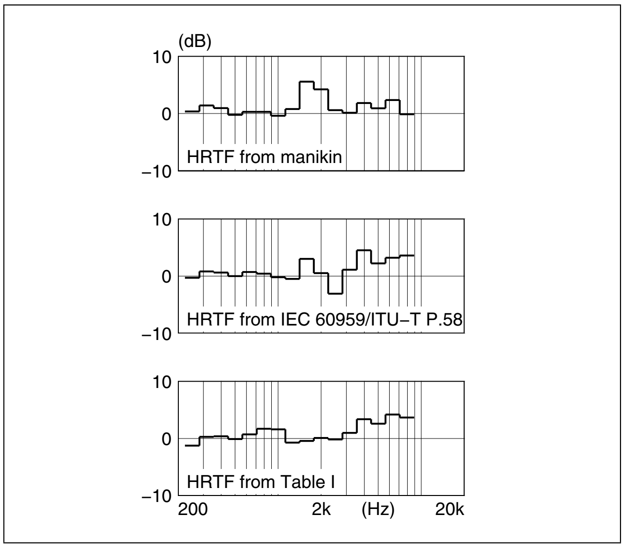

Figure 18. Difference between free-field related levels measured with manikins and with a group of humans as reported by Richter and Fedtke [47]. Mean of 9 combinations of headphone and manikin, calculated using individual manikin HRTFs (top), using nominal values from IEC 60959/ITU-T P.58 (center), and using alternative data (section 2.7, data in Table I).

A fair agreement is seen between requirements and humans, except at high frequencies. However, due to a large spread between humans it is difficult to see whether the two documents really specify an average human. Since a large degree of variation in the human HRTF data comes from the blocked-entrance to eardrum transmission, it would be better to compare with human blocked-entrance data. The requirements of IEC 60959 and ITU-T P.58 are therefore transferred to corresponding blocked-entrance requirements by subtracting the transmission for the ear canal simulator (similarly to the addition of this transmission in section 2.7). Figures 20 and 21 show the transferred requirements together with human blocked-entrance data. It is seen that the human data show considerably less variation than for the eardrum data in Figure 19, and it is easier to evaluate the agreement. The coarse structures of the requirements are similar to those of the human data, but there are notable differences, which will be reported in the following.

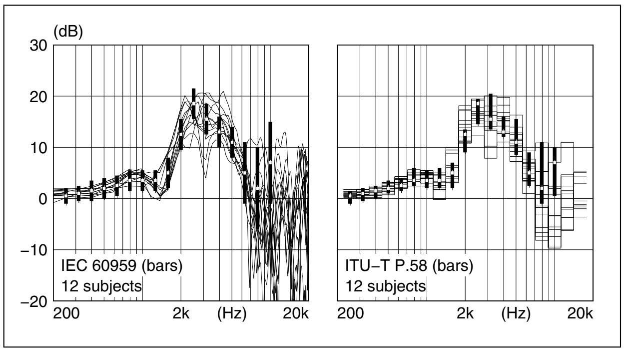

Figure 19. Left: Free-field-front HRTF requirements of IEC 60959 (vertical bars, nominal value at white dot) and human eardrum data (12 subjects, thin lines). Right: Free-field front third-octave noise-band HRTF requirements of ITU-T P.58 (vertical bars, nominal value at white dot) and human eardrum data (12 subjects, thin lines). Human data from [6].

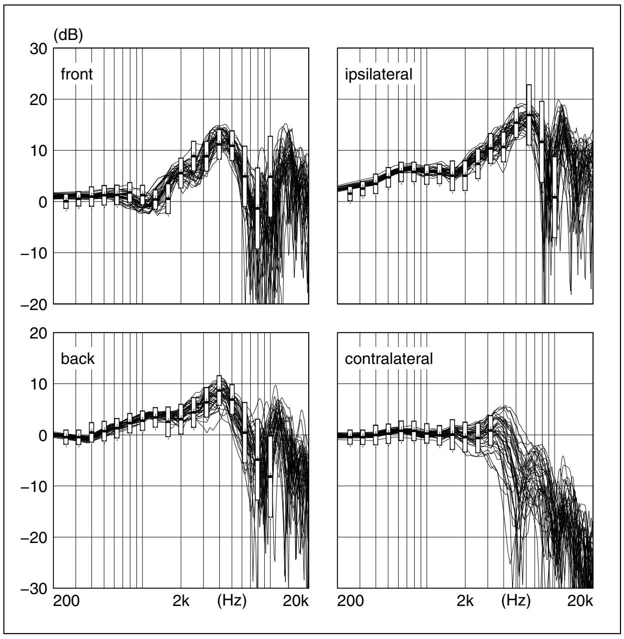

Figure 20. Pure-tone requirements of IEC 60959 (vertical bars, nominal value at black dot) transferred to blocked entrance (using mean values of Figure 2) compared with 40 individual human blocked-entrance HRTFs. Human data from [7].

For the front direction the requirements of IEC 60959 are slightly too high at 800 Hz and 1 kHz, too low at 1.6 kHz, too high at 2.5 kHz, and slightly too high at 10 kHz (Figure 20). Basically, the structures displayed in the requirements do not well replicate those of humans for the front direction. The agreement is better for the other three directions.

The nominal values of the requirements of ITU-T P.58 are identical to those given for pure tones in IEC 60959. Asymmetrical tolerances have, for some frequencies, repaired the deviation of nominal values from human values (2.5, 3.15, 4 and 10 kHz). However, at other frequencies the asymmetry increases the disagreement (0.8, 1 and 1.6 kHz).

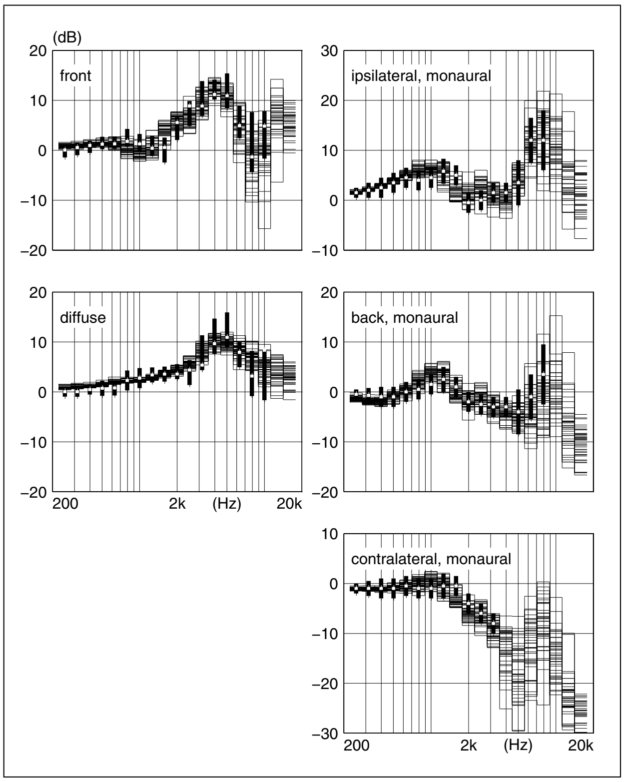

Figure 21. Third-octave noise-band requirements of ITU-T P.58 (vertical bars, nominal value at white dot) transferred to blocked entrance (using mean values of Figure 2) compared with 40 individual human blocked-entrance HRTFs. Human data from [7].

For the diffuse-field HRTF the nominal values of ITU-T P.58 are slightly too low at quite many frequencies (630 Hz and below, 2, 2.5, 3.15 and 8 kHz) and too high at 10 kHz. The asymmetrical tolerances repair the deviations at 2, 3.15 and 10 kHz, though.

Deviations of requirements of ITU-T P.58 from human values are also seen for the monaural transfer functions. Some of these deviations can be explained by the disagreement for the front direction, since the monaural transfer functions result from subtraction of the front HRTFs (e.g. the high front values at 0.8, 1 and 2.5 kHz result in low values for the ipsilateral monaural transfer function, and the low front value at 1.6 kHz results in a high value for the ipsilateral monaural transfer function).

Generally, the requirements of the standards do not accurately represent the average or typical characteristics of humans well, and improvements are needed.[3] Provided that the IEC 60711 coupler is maintained, revised standards should be based on human blocked-entrance HRTFs multiplied by the coupler transfer function (for the front direction and the diffuse field equal to human-like manikin HRTFs described in section 2.7).

[3] Also localization studies show imperfections in manikins. Møller *et al.* [48] and Minnaar *et al.* [49] have shown that the localization performance using manikin recordings is significantly poorer than when using human recording heads.

4.7. Other sources of uncertainty, manikins

An uncertainty in the computed free-air related levels may arise, if the sound source is in physical contact with the manikin pinnae, as e.g. supraaural headphones. If the stiffness of the manikin's pinnae deviates from that of typical humans, the sound source will couple to the ear in a wrong way. This may lead to a wrong load of the sound source, and it may introduce leakage that does not exist, when humans are exposed to the same sound. It may of course also–depending of the specific properties of the pinna and the sound source–hinder leakage that exists for humans. It will however, in any case lead to an exposure measurement that does not well represent, what humans may be exposed to from the same sound source.

5. Conclusions

The results from the MIRE-method are the same, wherever in the ear canal the measurements are made, e.g. at the eardrum, the open entrance or the blocked entrance. There is good agreement between human HRTFs measured at different laboratories, and for eardrum, open-entrance and blocked entrance, standard HRTF data have been derived, which may be used instead of HRTFs measured for each subject. The resulting statistical uncertainty depends on the choice of measurement point, and whether individual or standard HRTF data are used. Generally, measurements at the blocked entrance are practical and produce results with low statistical uncertainty.

The results from manikin-measurements do not agree well with results from humans (MIRE), when HRTFs from the actual manikin or from the standards are used for the transfer to free-air related levels. A better agreement is obtained with HRTFs constructed by multiplying human blocked-entrance data with the transfer function of the standardized coupler for manikins. This method is therefore described (and data tabled) in ISO 11904-2.

A comparison between humans, manikins, and the manikin standards (IEC 60959 and ITU-T P.58) suggest, that standards do not specify an average human and should be revised.

Acknowledgement

The authors would like to thank the ISO/TC 43/WG 6 and occasional observers for fruitful discussions and suggestions. We would also like to thank Prof. emeritus Edgar A. G. Shaw from Canada, Per-Anders Hellström from Lindholmen Utveckling AB, Adelbert Bronkhorst from TNO-HRFI in The Netherlands, Marc Brüeggen from Ruhr-University Bochum in Germany, Lydia Storey from National Acoustic Laboratories in Australia and any others involved, but not here quoted, for their kind collaboration in the collection of HRTFs for the literature data reference. The investigation has been carried out with financial support from the Danish Research Council for Technology and Production.

References

[1] ISO 11904-1: Acoustics – determination of sound immissions from sound sources placed close to the ears – Part 1: Technique using microphones in real ears (MIRE-technique). International Standardization Organization, Geneva, Switzerland, 2002.

[2] ISO 11904-2: Acoustics – determination of sound immissions from sound sources placed close to the ears – Part 1: Technique using a manikin. International Standardization Organization, Geneva, Switzerland, 2004.

[3] C. G. Rice, M. Breslin, M. Roper: Sound levels from personal cassette players. British Journal of Audiology **21** (1987) 273–278.

[4] C. G. Rice, G. Rossi, M. Olina: Damage risk from personal cassette players. British Journal of Audiology **21** (1987) 279–288.

[5] H. Møller, D. Hammershøi, C. B. Jensen, M. F. Sørensen: Transfer characteristics of headphones measured on human ears. J. Audio Eng. Soc. **43** (1995) 203–217.

[6] D. Hammershøi, H. Møller: Sound transmission to and within the ear canal. J. Acoust. Soc. Am. **100** (1996) 408–427.

[7] H. Møller, M. F. Sørensen, D. Hammershøi, C. B. Jensen: Head-related transfer functions of human subjects. J. Audio Eng. Soc. **43** (1995) 300–321.

[8] H. Møller, C. B. Jensen, D. Hammershøi, M. F. Sørensen: Design criteria for headphones. J. Audio Eng. Soc. **43** (1995) 219–232.

[9] P.-A. Hellström, A. Axelsson: Miniature microphones probe tube measurements in the external auditory canal. J. Acoust. Soc. Am. **93** (1993) 907–919.

[10] P.-A. Hellström: Free-field-front eardrum HRTFs for 220 subjects (384 ears), measured as described in [9]. Personal communication, 1999.

[11] J. Sandvad: Dynamic aspects for auditory virtual environments. Proc. 100th Audio Eng. Soc. Conv., preprint 4226, Copenhagen, 1995, 1–14.

[12] A. Bronkhorst: Localization of real and virtual sound sources. J. Acoust. Soc. Am. **98** (1995) 2542–2553.

[13] E. H. A. Langendijk, A. Bronkhorst: Fidelity of 3D sound reproduction using a virtual auditory display. J. Acoust. Soc. Am. **107** (2000) 528–537.

[14] R. Drullman, A. Bronkhorst: Multichannel speech intelligibility and speaker reckognition using monaural, binaural, and 3D auditory presentation. J. Acoust. Soc. Am. **107** (2000) 2224–2235.

[15] A. Bronkhorst: Free-field-front and diffuse-field eardrum HRTFs for 31 subjects (62 ears) and free-field-front and diffuse-field blocked-entrance HRTFs for 69 subjects (138 ears). Data from [13] and [14] using largely the methods described in [12]. Personal communication, 1999.

[16] K. Hartung: Messung, Verifikation und Analyse von Aussenohrübertragungsfunktionen. Fortschritte der Akustik, DAGA '95, 1995, 755–758.

[17] M. Brüggen: Free-field-front and diffuse-field blocked-entrance HRTFs for 3 subjects (6 ears), measurede largely as the methods described in [16]. Personal communication, 1999.

[18] L. Storey, H. Dillon: Self-consistent correction figures for hearing aids. In preparation, 1999.

[19] L. Storey: Free-field-front blocked-entrance and eardrum HRTFs for 20 subjects (20 ears), and diffuse-field blocked-entrance and eardrum HRTFs for 18 subjects (18 ears) measured as described in [18]. Personal communication, 1999.

[20] F. M. Wiener, D. A. Ross: The pressure distribution in the auditory canal in a progressive sound field. J. Acoust. Soc. Am. **18** (1946) 401–408.

[21] F. M. Wiener: On the diffraction of a progressive sound wave by the human head. J. Acoust. Soc. Am. **19** (1947) 143–146.

[22] Z. Yamaguchi, N. Sushi: Real ear response of receivers. J. Acoust. Soc. Jpn. **12** (1956) 8–13.

[23] D. W. Robinson, L. S. Whittle: The loudness of directional sound fields. Acustica **10** (1960) 74–80.

[24] G. Jahn: Über den Unterschied zwischen den Kurven gleicher Lautstärke der ebenen Welle und im diffusen Schallfeld. Hochfrequenztech. Elektroakust. **69** (1960) 75–81.

[25] E. A. G. Shaw: Ear canal pressure generated by a free sound field. J. Acoust. Soc. Am. **39** (1966) 465–470.

[26] J. Blauert: Räumliches Hören. S. Hirzel Verlag, Stuttgart, Germany, 1974.

[27] J. Blauert: Spatial hearing. The psychophysics of human sound localization. The MIT Press, Cambridge, Massachusetts, London, England., 1983.

[28] S. Mehrgardt, V. Mellert: Transformation characteristics of the external human ear. J. Acoust. Soc. Am. **61** (1977) 1567–1576.

[29] M. Morimoto, Y. Ando: On the simulation of sound localization. J. Acoust. Soc. Jpn. (E) **1** (1980) 167–174.

[30] C. Pösselt, J. Schröter, M. Opitz, P. L. Divenyi, J. Blauert: Generation of binaural signals for research and home entertainment. Proc. 12th Int. Congr. Acoust. Vol. 1, B, Toronto, Ont. Canada, 1986, 1–6.

[31] A. Schmitz, M. Vorländer: Messungen von Aussenohrstoßantworten mit Maximalfolgen-Hadamard-Transformation und deren Anwendungen bei Inversionsversuchen. Acustica **71** (1990) 257–268.

[32] K. Okabe, T. Miura: Construction of a head and torso simulator for orthostereophonic system (~~oss~~). J. Acoust. Soc. Jpn. **46** (1990) 885–892.

[33] E. A. G. Shaw: Transformation of sound pressure level from the free field to the eardrum in the horizontal plane. J. Acoust. Soc. Am. **56** (1974) 1848–1861.

[34] E. A. G. Shaw, M. M. Vaillancourt: Transformation of sound-pressure level from the free field to the eardrum presented in numerical form. J. Acoust. Soc. Am. **78** (1985) 1120–1123.

[35] M. D. Burkhard, R. M. Sachs: Anthropometric manikin for acoustic research. J. Acoust. Soc. Am. **58** (1975) 214–220.

[36] H.-J. Platte: Zur Bedeutung der Aussenohrübertragungseigenschaften für den Nachrichtenempfänger 'Menschliches Gehör'. Dissertation. Rheinisch-Westfälischen Technischen Hochschule, Aachen, Germany, 1979.

[37] K. Genuit: Ein Modell zur Beschreibung von Aussenohrübertragungseigenschaften. Dissertation. Rheinisch-Westfälischen Technischen Hochschule, Aachen, Germany, 1984.

[38] E. M. Wenzel, F. L. Wightman, S. H. Foster: A virtual display system for conveying three-dimensional acoustic information. Proc. Human Factors Soc., 32nd Ann. Meet., 1988, 86–90.

[39] M. Killion, E. H. Berger, R. A. Nuss: Diffuse field response of the ear. J. Acoust. Soc. Am. **81** (1987) S75.

[40] E. H. Berger: Diffuse-field eardrum HRTFs for 16 subjects (one ear or subject mean). Originally presented in [39]. Personal communication, 1999.

[41] IEC 60959: Provisional head and torso simulator for acoustic measurements on air conduction hearing aids (Technical Report). International Electrotechnical Commission, Geneva, Switzerland, 1990.

[42] ITU-T Recommendation P.58: Series P: Telephone transmission quality. Objective measuring apparatus. Head and torso simulator for telephonometry. International Telecommunication Union (previously CCITT Recommendation, 1996.

[43] D. Hammershøi, H. Møller: Artificial heads for free field recording: How well do they simulate real heads? Proc. 14th Int. Congr. Acoust., Beijing, 1992, Paper H6–7.

[44] H. Møller: Fundamentals of binaural technology. Applied Acoustics **36** (1992) 171–218.

[45] D. Hammershøi, H. Møller: Binaural technique: Basic methods for recording, synthesis, and reproduction. – In: Communication Acoustics. J. Blauert (ed.). Springer Verlag, Berlin Heidelberg, 2005, 223–254.

[46] D. Ćirić, D. Hammershøi: Coupling of earphones to human ears and to standard coupler. J. Acoust. Soc. Am. **120** (2006) 2096–2107.

[47] U. Richter, T. Fedtke: Determination of sound immissions from headphones and earphones. Suitability of ~~hats~~ for the measurement of earphones. Proc. 6th Int. Congr. Sound and Vibr., Copenhagen, 1999.

[48] H. Møller, D. Hammershøi, C. B. Jensen, M. F. Sørensen: Evaluation of artificial heads in listening tests. J. Audio Eng. Soc. **47** (1999) 83–100.

[49] P. Minnaar, S. K. Olesen, F. Christensen, H. Møller: Localization with binaural recordings from artificial and human heads. J. Audio Eng. Soc. **49** (2001) 323–336.