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TELEPHONE HEADSET SOUND EXPOSURE ASSESSMENT BY THRESHOLD COMPARISON

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Abstract. There is concern about the occupational sound exposure of people working at call centers. There are two standard methods to measure sound immission from headsets. The first one, known as microphone in real ear (MIRE) uses a tiny microphone or probe inside the ear canal. The second uses an artificial ear or head with microphones at the bottom of the artificial canals. Both methods require expensive equipment, which is not easy to justify for an occupational health service. We propose a method using only readily available equipment. It consists in three steps. First, the headset is electrically calibrated by comparing the hearing threshold (which is assumed to be independent of the source) with the headset under test and with standard audiometric earphones. Second, the electric signal received by the telephone headset during normal use is digitally recorded. Finally, the recorded signal is converted into its acoustic equivalent taking into account any equalisation needed to compensate for the known response of the audiometric earphones and the already measured response of the headset. This method has been implemented by software running on a portable computer and HDA 200 audiometric earphones.

1 INTRODUCTION

Hearing conservation programs at the work place involve, as a first step, the assessment of workers noise exposure. In the case of call centers there are two main sources. The first one is the room noise due to dozens or even hundreds of telephone conversations taking place simultaneously. Considering the large room size and fairly long reverberation time, this noise may be troublesome. The second source is the sound immission from the headset. Due to room noise, operators usually set the level so that they can easily avoid intelligibility issues due to masking effects. This could be a rather high level, so it is very important to measure it as accurately as possible.

When a noise source is located at some distance from the worker, standard practice indicates that sound level should be measured at the worker's ear position with the worker absent. Here the sound field is assumed either free field or diffuse field. For noise sources such as a headset this method is inapplicable since the sound field is coupled to the eardrum in a very different way.

There are two standard methods to measure sound immission from headsets. The first one, known as *microphone in real ear* (MIRE) uses a tiny microphone or probe inside the ear canal of a subject. The second uses an artificial ear or a *head and torso simulator* (HATS) with microphones at the bottom of the artificial canals. These methods are not completely equivalent, if only because each subject has different personal pinna and ear canal shape and dimensions which can influence the results. However, both can be converted to free field or diffuse-field, as required, for an average subject, with certain degree of accuracy. The procedure and conversion tables are provided in ISO Standard 11904. Part 1 refers to the MIRE technique and part 2 to the manikin or HATS technique.

Both methods require expensive equipment, which is not easy to justify for an occupational health service and is usually found only in well-equipped, specialised acoustic laboratories. It will be very convenient to have an alternative method involving only readily available equipment such as audiometric earphones and a laptop. The purpose of this paper is to introduce a method involving hearing threshold comparisons between a calibrated audiometric earphone and the unknown telephone headset earphone.

2 METHOD

The method consists of three steps. First, the headset is electrically calibrated by comparing the hearing threshold (which is assumed to be independent of the source) with the headset under test and with standard audiometric earphones. Second, the electric signal received by the telephone headset during normal use is digitally recorded. Finally, the recorded signal is converted into its acoustic equivalent taking into account any equalisation needed to compensate for the known response of the audiometric earphones and the already measured response of the headset. The next sections describe each step in more detail.

2.1 Headset calibration

Let $S_{\mathrm{AE}}(f)$ be the eardrum sensitivity of the audiometric earphone, in pascals per volt, defined as the sound pressure at the eardrum, $p_{\mathrm{A,E}}$, over the voltage applied to the earphone, v_{A}. Similarly, $S_{\mathrm{T,E}}(f)$ is the eardrum sensitivity of the telephone headset. Thus,

$$p_{\mathrm{A,E}} = S_{\mathrm{A,E}}(f)\ v_{\mathrm{A}}, \tag{1}$$

$$p_{\mathrm{T,E}} = S_{\mathrm{T,E}}(f)\ v_{\mathrm{T}}, \tag{2}$$

where v_T is the voltage applied to the telephone headset or to the amplifier used with it (depending on normal use of each model). See Appendix 1 for symbols and notation.

In order to calibrate we first apply to the audiometric earphone a computer-generated tone of maximum amplitude and 400 Hz by means of the system shown in Figure 1. The volume control of the audio card digital mixer is adjusted to get a voltage close to 20 mV. This voltage is chosen to produce a nominal sound pressure level at the eardrum of 80 dB (this may depend on the specific earphone model). Since the digital tone has maximum amplitude, at 16 bit resolution digital noise is about 96 dB below, i.e., −16 dB, which is inaudible at all frequencies.

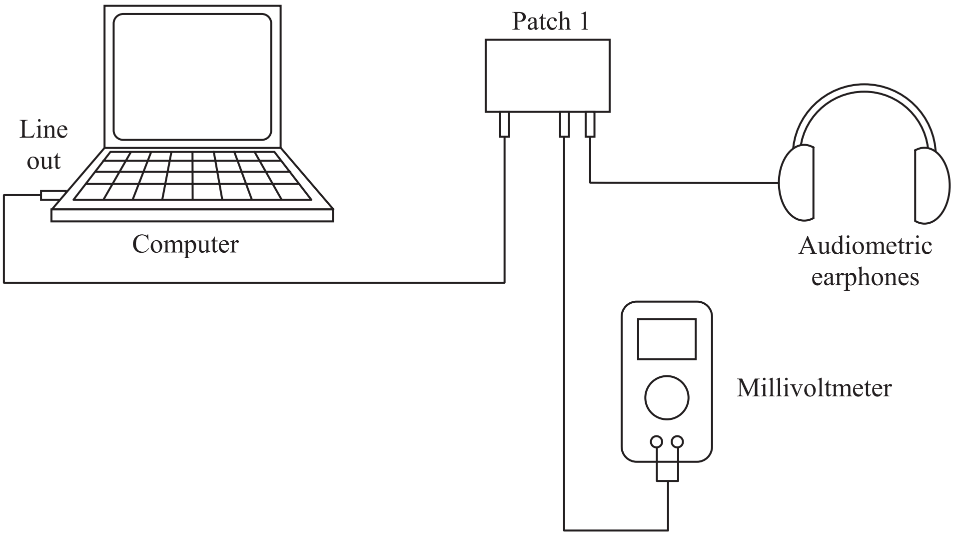

Figure 1: Block diagram of calibration setup. Patch 1 is just a connection box allowing to measure the voltage applied to the earphones. In some cases, since threshold levels are very weak, it may prove useful to insert a 100× voltage divider between the measurement point and the earphone, allowing higher voltage at the audio output of the computer.

Then we apply computer-generated tones of audiometric frequencies f_k from 125 Hz to 8 kHz first to the audiometric earphones and then to the telephone headset (Figure 2), with several software-controlled amplitudes until the threshold of hearing at each frequency is located within ±2 dB. We get $v_{A,th}(f_k)$ and $v_{T,th}(f_k)$. Note that voltage has to be measured only once, i.e., at the condition of maximum amplitude. Other voltages can be found from the digital attenuation applied by software. These voltages are related to the eardrum pressure by Eqs. (1) and (2)

$$p_{A,E,th}(f_k) = S_{A,E}(f_k)\, v_{A,th}(f_k), \tag{3}$$

$$p_{T,E,th}(f_k) = S_{T,E}(f_k)\, v_{T,th}(f_k). \tag{4}$$

Our fundamental assumption is that the hearing threshold at a given frequency is reached at the same eardrum pressure independently of the transducer, i.e.,

$$p_{A,E,th}(f_k) = p_{T,E,th}(f_k). \tag{5}$$

Hence, we can compute the unknown eardrum sensitivity of the telephone headset, $S_{T,E}(f_k)$, as

$$S_{T,E}(f_k) = \frac{v_{A,th}(f_k)}{v_{T,th}(f_k)} S_{A,E}(f_k). \tag{6}$$

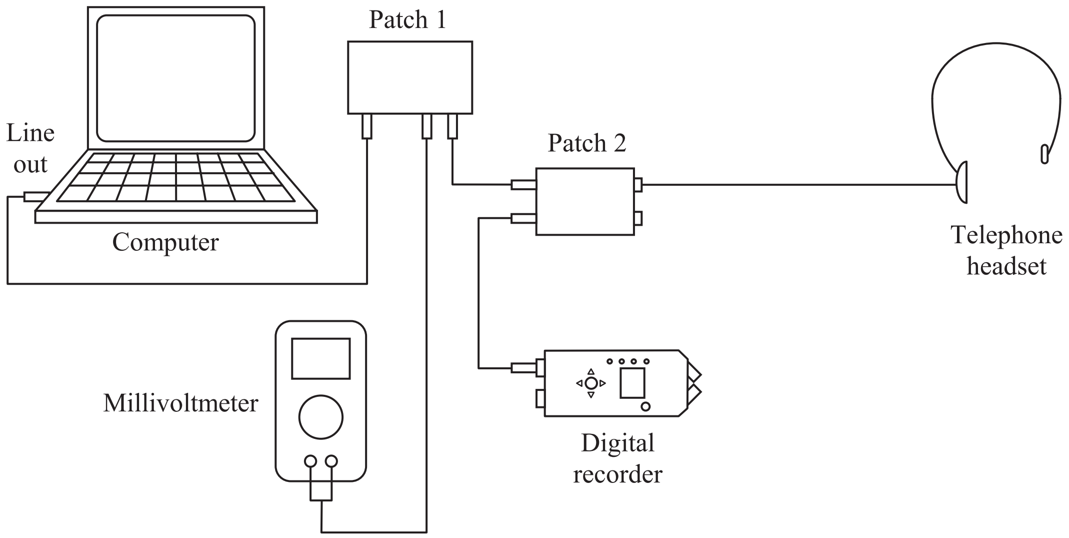

Figure 2: Block diagram of the telephone headset test setup. Patch 1 is a connection box allowing to measure the voltage applied to the earphones. Patch 2 is a connection box with in/out RJ-11 and two 1/4” mono jacks connectors in parallel with pertinent connections (earphone). The signal from the computer is fed into the headset amplifier and the digital recorder.

Health and safety regulations state that noise at the work place must be measured at the ear position in the absence of the worker. Assuming diffuse field (the most frequent case), we need an equation relating the sound pressure at the eardrum and the diffuse field sound pressure. It turns out to be a linear relationship with a frequency dependent constant:

$$p_{\mathrm{DF}}(f_{\mathrm{k}}) = K_{\mathrm{DF}}(f_{\mathrm{k}})\, p_{\mathrm{E}}(f_{\mathrm{k}}). \tag{7}$$

This constant is provided in Standard ISO 11904 Part 1 for an average subject, expressed in dB, as shown in Table 1 below. Then we can compute

$$L_{\mathrm{DF}}(f_{\mathrm{k}}) = L_{\mathrm{E}}(f_{\mathrm{k}}) - \Delta L_{\mathrm{DF}}(f_k). \tag{8}$$

Thus,

$$K_{\mathrm{DF}}(f_k) = 10^{-\frac{\Delta L_{\mathrm{DF}}(f_k)}{20}}. \tag{9}$$

Combining Eqs. (6), (7) and (9) we find the diffuse field sensitivity $S_{\mathrm{T,DF}}(f_k)$ of the telephone headset:

$$S_{\mathrm{T,DF}}(f_k) = 10^{-\frac{\Delta L_{\mathrm{DF}}(f_k)}{20}} \frac{v_{\mathrm{A,th}}(f_k)}{v_{\mathrm{T,th}}(f_k)} S_{\mathrm{A,E}}(f_k). \tag{10}$$

In order to render Eq. (10) useful we need to know $S_{\mathrm{A,E}}(f_k)$ for the particular model of audiometric earphones in use. While it would be logical to expect that the average eardrum sensitivity were readily available among the specifications of audiometric grade earphones, this is not the case. Manufacturers prefer to specify measurements made on a standard coupler because results are much more predictable and consistent. Table 2 gives the frequency response in dB when the HDA 200 audiometric earphones (used as an example in this paper) is tested on a B&K 4153 coupler. The third column gives the earphone coupler sensitivity, $S_{\mathrm{A,C}}(f_k)$, which has been computed with this formula:

f_k [Hz]	$\Delta L_{DF}(f_k)$ [dB]	$\Delta L_{FF}(f_k)$ [dB]
100	0,0	0,0
125	0,2	0,2
160	0,4	0,4
200	0,6	0,6
250	0,8	0,8
315	1,1	1,1
400	1,5	1,5
500	2,1	2,0
630	2,8	2,3
800	3,3	3,1
1 000	4,1	2,7
1 250	5,5	2,9
1 600	7,7	5,8
2 000	11,0	12,4
2 500	15,3	15,7
3 150	15,7	14,9
4 000	12,9	13,2
5 000	10,6	8,9
6 300	9,4	3,1
8 000	9,5	–1,4
10 000	6,8	–3,8
12 500	3,8	–0,1
16 000	0,7	–0,4

Table 1: Diffuse field and free field frequency response at the eardrum by the MIRE technique, according to International Standard ISO 11904-1 .

Standard frequencies f_k (Hz)	$L_{A,C}$ [dB] @ V_{rms} = 0,5 V	$S_{A,C}(f_k)$ [Pa/V]
125	112,5	16,9
250	113,0	17,9
500	112,0	15,9
750	111,0	14,2
1 000	108,5	10,6
2 000	104,0	6,3
3 000	104,0	6,3
4 000	104,0	6,3
5 000	106,5	8,5
6 000	107,5	9,5
8 000	105,5	7,5
9 000	105,0	7,1
10 000	102,5	5,3
11 200	102,0	5,0
12 500	103,0	5,7
14 000	98,5	3,4
16 000	100,0	4,0

Table 2: Frequency response of HDA 200 according to the manufacturer (Sennheiser) and the corresponding sensitivity. Measurements reported here are performed on a calibrated coupler B&K 4153, which complies with Standard IEC 60318.

$$S_{\mathrm{A,C}}(f_k) = \frac{p_{\mathrm{A,C}}}{v_{\mathrm{A}}} = 10^{\frac{L_{\mathrm{A,C}}(f_k)}{20}} \frac{P_{\mathrm{ref}}}{0{,}5\ \mathrm{V}}, \tag{11}$$

where $L_{\mathrm{A,C}}(f_k)$ is the sound pressure level measured at frequency f_k inside the coupler when a 0,5 V voltage is applied to the earphones, and $P_{\mathrm{ref}} = 20\ \mu\mathrm{Pa}$.

Annex C of Standard ISO389-8 provides the correction necessary to convert from earphone coupler sensitivity $S_{\mathrm{A,C}}(f_k)$ to earphone free-field sensitivity $S_{\mathrm{A,FF}}(f_k)$ for the circumaural audiometric earphone HDA 200. It is presented in Table 3 as a difference of sensitivity levels:[1]

$$G_{\mathrm{F}}(f_k) - G_{\mathrm{C}}(f_k) = 20 \log \frac{S_{\mathrm{A,FF}}}{S_{\mathrm{o}}} - 20 \log \frac{S_{\mathrm{A,C}}}{S_{\mathrm{o}}} = 20 \log \frac{S_{\mathrm{A,FF}}}{S_{\mathrm{A,C}}}. \tag{12}$$

This correction between coupler and free-field sensitivities may be rearranged as

$$S_{\mathrm{A,FF}} = 10^{\frac{G_{\mathrm{F}}(f_k) - G_{\mathrm{C}}(f_k)}{20}} S_{\mathrm{A,C}}. \tag{13}$$

We can see from Table 1 that there is another known relationship between free-field and eardrum responses, i.e.,

$$L_{\mathrm{FF}}(f_k) = L_{\mathrm{E}}(f_\mathrm{k}) - \Delta L_{\mathrm{FF}}(f_k), \tag{14}$$

from which we can derive

$$S_{\mathrm{A,E}} = \frac{p_{\mathrm{A,E}}}{v_{\mathrm{A}}} = \frac{p_{\mathrm{A,FF}}\, 10^{\frac{\Delta L_{\mathrm{FF}}(f_k)}{20}}}{v_{\mathrm{A}}} = S_{\mathrm{A,FF}}\, 10^{\frac{\Delta L_{\mathrm{FF}}(f_k)}{20}}. \tag{15}$$

f_k [Hz]	$G_{\mathrm{F}}(f_k) - G_{\mathrm{C}}(f_k)$ [dB]
125	–5,0
160	–4,5
200	–4,5
250	–4,5
315	–5,0
400	–5,5
500	–2,5
630	–2,5
800	–3,0
1000	–3,5
1250	–2,0
1600	–5,5
2000	–5,0
2500	–6,0
3150	–7,0
4000	–13,0
5000	–14,5
6300	–11,0
8000	–8,5

Table 3: Correction between earphone coupler and free-field sensitivities (ISO 389-8 Ann. C; Richter, 1992).

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[1] Sensitivity level is defined as 20 log(S/S_{o}), where S is a sensitivity and S_{o} an arbitrary reference sensitivity such as 1 Pa/V

Now we can combine Eqs. (11), (13) and (15) to get the eardrum sensitivity of the audiometric earphone, i.e., the last item we needed in order to apply Eq. (10):

$$\begin{aligned} S_{\mathrm{A,E}}(f_k) &= 10^{\frac{\Delta L_{\mathrm{FF}}(f_k)}{20}}\, S_{\mathrm{A,FF}}(f_k) = \\ &= 10^{\frac{\Delta L_{\mathrm{FF}}(f_k)}{20}}\, 10^{\frac{G_{\mathrm{F}}(f_k)\, -\, G_{\mathrm{C}}(f_k)}{20}}\, S_{\mathrm{A,C}}(f_k) = \\ &= 10^{\frac{\Delta L_{\mathrm{FF}}(f_k)}{20}}\, 10^{\frac{G_{\mathrm{F}}(f_k)\, -\, G_{\mathrm{C}}(f_k)}{20}}\, 10^{\frac{L_{\mathrm{A,C}}(f_k)}{20}}\, \frac{P_{\mathrm{ref}}}{0{,}5\ \mathrm{V}} = \\ &= \frac{P_{\mathrm{ref}}}{0{,}5\ \mathrm{V}}\, 10^{\frac{G_{\mathrm{F}}(f_k)\, -\, G_{\mathrm{C}}(f_k)\, +\, \Delta L_{\mathrm{FF}}(f_k)\, +\, L_{\mathrm{A,C}}(f_k)}{20}} \end{aligned} \quad . \tag{16}$$

This result is of interest by itself, since we can estimate the eardrum pressure (and hence, the sound pressure level), from the voltage applied to the earphones, as a function of frequency:

$$p_{\mathrm{A,E}}(f_k) = S_{\mathrm{A,E}}(f_k)\, v_{\mathrm{A}}(f_k)\,. \tag{17}$$

Table 4 includes a comparison of the sound pressure level of the HDA 200 audiometric earphones inside a coupler and at the eardrum for the same voltage (0,5 V).

f_k (Hz)	$L_{\mathrm{A,C}}(f_k)$ [dB]	$L_{\mathrm{A,E}}(f_k)$ [dB]	$L_{\mathrm{A,E}}(f_k) - L_{\mathrm{A,C}}(f_k)$ [dB]
125	112,5	107,7	–4,8
160	112,6	108,5	–4,1
200	112,8	108,9	–3,9
250	113,0	109,3	–3,7
315	112,7	108,8	–3,9
400	112,4	108,4	–4,0
500	112,0	111,5	–0,5
630	111,5	111,3	–0,2
800	110,5	110,6	0,1
1000	108,5	107,7	–0,8
1250	107,4	108,3	0,9
1600	105,8	106,1	0,3
2000	104,0	111,4	7,4
2500	104,0	113,7	9,7
3150	104,0	111,9	7,9
4000	104,0	104,2	0,2
5000	106,5	100,9	–5,6
6300	107,2	99,3	–7,9
8000	105,5	95,6	–9,9

Table 4: Frequency response of HDA 200 on a coupler and at the eardrum as calculated in the text, both for $V_{\mathrm{rms}} = 0{,}5$ V. Last column includes correction term from coupler to eardrum sound pressure level.

Figure 3 summarises graphically the preceding results for the audiometric earphone HDA 200. Sensitivities are presented logarithmically, since this makes comparisons easier. As can be seen, while coupler sensitivity is the easiest to measure directly, it is quite unrealistic. In audiology this is of no concern, since each earphone model has well-defined standardised reference equivalent threshold sound pressure level (RETSPL) that can be used as an audiometric zero. In applications where one is interested in the real sound pressure level under a given condition, other than coupler sensitivities are necessary. Eardrum sensitivity, as expected, presents a large peak at about 2,5 kHz due to ear canal resonance. Free-field and diffuse-field sensitivities are very similar, except at the high frequency end.

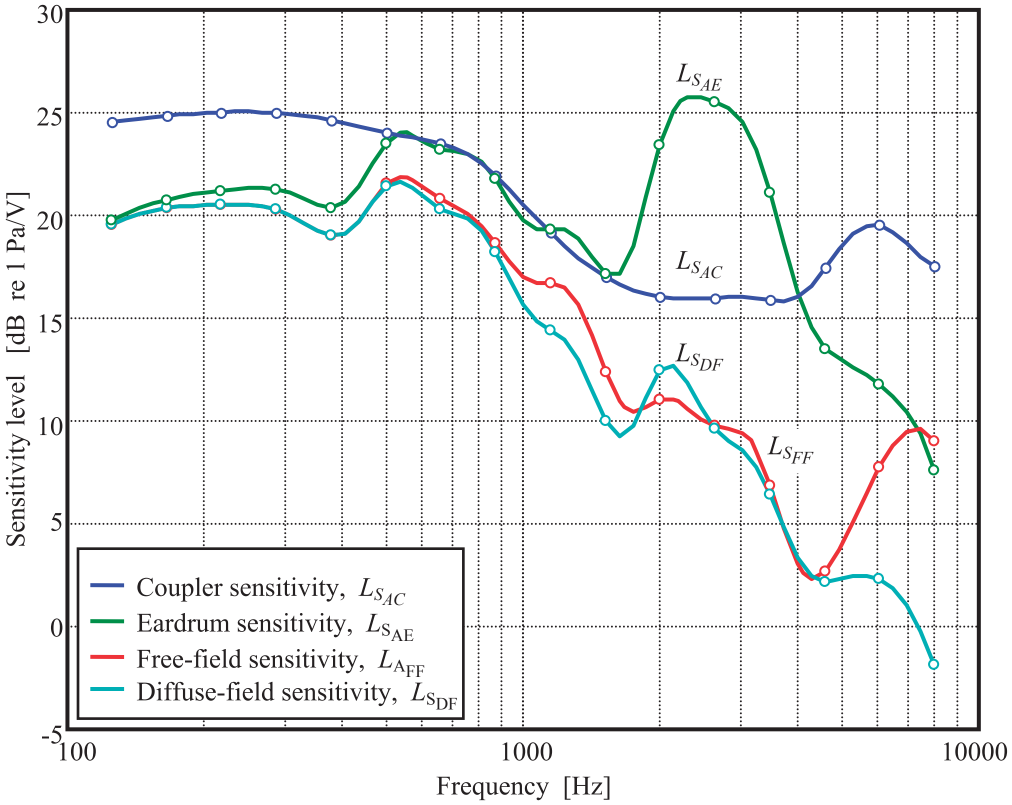

Figure 3: Sensitivity level (defined as 20 log($p/v/S_{\mathrm{ref}}$)) of the audiometric earphones HDA200 in different situations: inside a coupler (artificial ear), at the eardrum with a probe microphone, free-field that would cause the same sensation, and diffuse field that would cause the same sensation. Small circles show original data, thick lines are interpolated data.

Next, we apply Eq. (10):

$$S_{\mathrm{T,DF}}(f_k) = \frac{P_{\mathrm{ref}}}{0{,}5\ \mathrm{V}} 10^{\frac{G_{\mathrm{F}}(f_k) - G_{\mathrm{C}}(f_k) + \Delta L_{\mathrm{FF}}(f_k) - \Delta L_{\mathrm{DF}}(f_k) + L_{\mathrm{A,C}}(f_k)}{20}} \frac{v_{\mathrm{A,th}}(f_k)}{v_{\mathrm{T,th}}(f_k)}. \qquad (18)$$

This formula allows computation of diffuse field sound pressure in terms of the voltage at the telephone headset:

$$p_{\mathrm{T,DF}}(f_k) = S_{\mathrm{T,DF}}(f_k)\, v_{\mathrm{T}}(f_k). \qquad (19)$$

Finally, we compute the diffuse-equivalent sound pressure level due to a voltage v_{T} applied to the telephone headset

$$\begin{aligned} L_{p\mathrm{T,DF}}(f_k) &= G_{\mathrm{F}}(f_k) - G_{\mathrm{C}}(f_k) + \Delta L_{\mathrm{FF}}(f_k) - \Delta L_{\mathrm{DF}}(f_k) + L_{\mathrm{A,C}}(f_k)\ + \\ &\quad + 20 \log \frac{v_{\mathrm{A,th}}(f_k)}{v_{\mathrm{T,th}}(f_k)} + 20 \log \frac{v_{\mathrm{T}}(f_k)}{0{,}5\ \mathrm{V}}. \end{aligned} \qquad (20)$$

If this equation is applied to the audiometric earphone instead of a telephone headset, we get the conversion between coupler and diffuse field. At $v_A = 0{,}5$ V the last term vanishes.

Equation (20) has been applied to a telephone headset Plantronics Hw 251 as reported later. The resulting average difuse-field sensitivity of both the HDA 200 and the Hw 251 are shown in Figure 4. As it can be seen, the telephone headset is about 12 dB less sensitive at low frequencies but it presents a much faster decay at high frequency. This may be no surprise, since the useful spectral range of the telephone line is limited above 4 000 Hz, so the designer may have made a trade-off between high frequency fidelity and ruggedness .

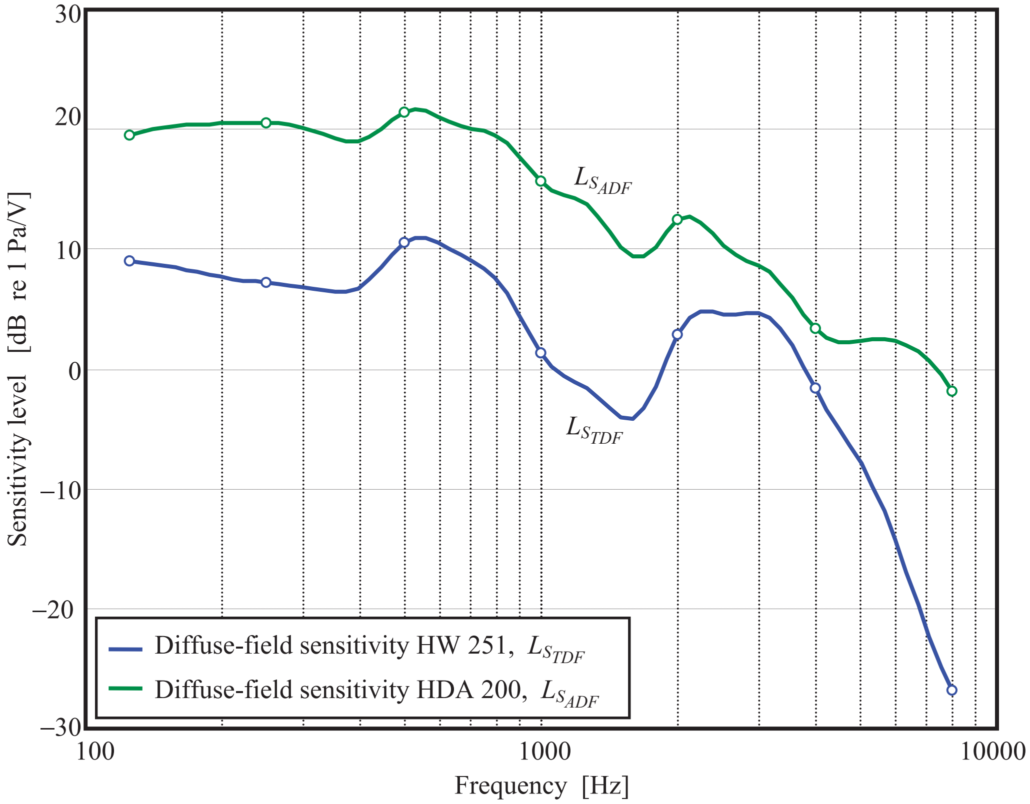

Figure 4: Average difuse-field sensitivity level (defined as 20 log($p/v/S_{\mathrm{ref}}$)) of both the audiometric earphones HDA200 and the telephone headset Hw251. Small circles show audiometric frequencies data, thick lines are interpolated data.

2.2 Digital recording of telephone signal

Once the relationship between the voltage applied to the telephone headset and the diffuse-equivalent sound pressure level is ascertained, we are in a position to record the electric signal during use of the headset in a real situation. A Zoom H4 digital recorder has been used for this purpose. Its suitability as a component of an acoustical measurement system has been discussed and validated in Miyara et al., 2010. Since the signal is saved to a SD flash memory card, it is readily transferred to a computer for subsequent processing. The recording setup is shown in Figure 5.

Besides the telephone signal, the calibrated audio output of a precision sound level meter collecting unweighted acoustic noise inside the call center is recorded simultaneously to another channel of the recorder. However, no attempt has been made to correct this signal for the attenuation caused by the use of the headset since it is of supraaural type, with a relatively low external noise attenuation,[2] and it is worn on only one ear.

Recording is done with no compression, at a resolution of 16 bit and a standard sampling rate of 44 100 Hz, allowing to capture the entire audio spectrum, even if the spectral content above 8 kHz is of little importance.

Care has to be taken to record a calibration signal, i.e, a sine wave whose root mean square value has been measured and is known. Otherwise the whole procedure is worthless since there is no way to convert digital samples back into voltage.

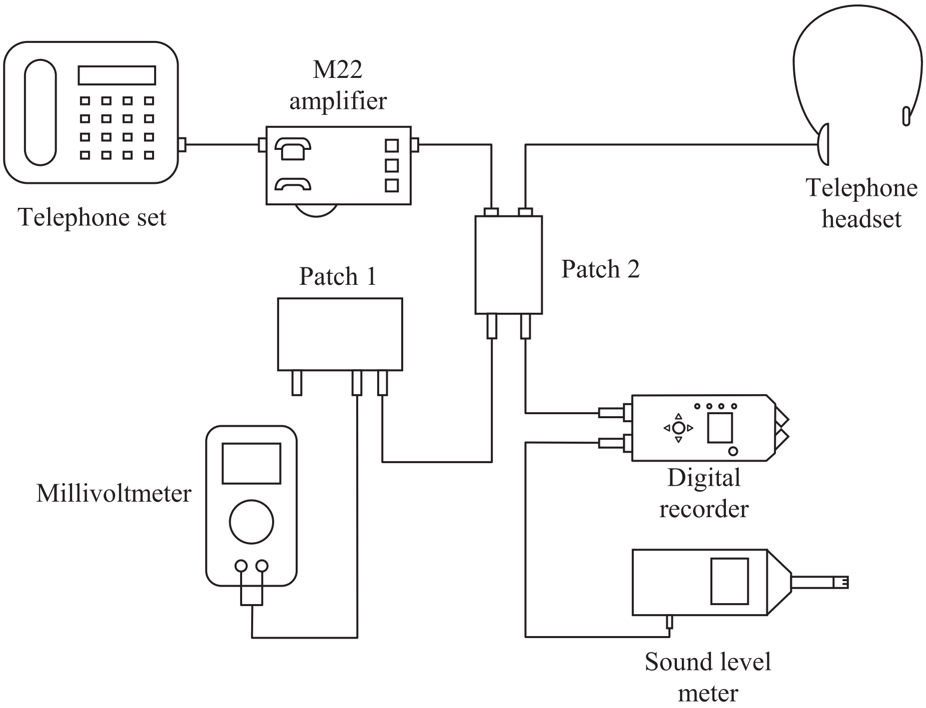

Figure 5: Block diagram of the recording setup. Patch 2 is a connection box with in/out RJ-11 connectors and two 1/4” mono jacks in parallel with pertinent connections (earphone). The signal from the telephone set is fed through the amplifier into headset and the digital recorder

2.3 Conversion into acoustic equivalent

Once loaded into the computer memory, the signal is filtered by an FFT overlap-add filter[3] with window length $N = 4096$ in which the filtering window has the shape of Figure 4, computed with Eq. (18) and. The frequency response is interpolated between 0 Hz and 8 000 Hz and set to zero beyond 8 000 Hz, in order to complete $N/2 =$ 2048 frequency samples from 0 Hz to 22 050 Hz.

The filtered signal represents the diffuse-field equivalent of the sound presented at the ear by the telephone headset, i.e., an hypotetical diffuse-field sound causing the same sensation. This signal is further filtered to apply an A-weighting (since this is required by regulations on health an safety at the workplace) and finally averaged on an energy basis. In a practical implementation a single filtering window is obtained multiplying $S_{\mathrm{TDF}}(f)$ by $A(f)$ in order to increase processing speed.

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[2] Attenuation is concentrated mainly in the high frequency region. At low frequency it is about 5 dB, and at high frequency, 25 dB. (See ANSI S3.1-1999; Michael et al., 1981).

[3] The overlap-add technique is explained in Miyara et al, 2009.

3 EXPERIMENTAL SETUP

3.1 Audiometric earphones calibration

The published specifications of the HDA 200 do not include any tolerance, except for the absolute maximum at 5 V. This does not mean, of course, that the actual performance sticks tightly to the specified typical response. Instead of having the earphones calibrated in a specialised laboratory, which usaually calibrates a complete audiometer, we calibrated them using a Head and Torso Simulator Kemar GRAS type 45 DA. This piece of equipment resembles the external anatomy of the pinna and has a sort of artificial ear canal simulating the real one. At the bottom of each artificial canal there is a microphone.

Measurements provide, in this case an approximation to the eardrum sensitivity $S_{\mathrm{A,E}}$. Standard ISO 11904 Part 2 does not give a table with free-field and diffuse-field response as Part 1, but refers to IEC 60959:1990 and ITU-T P.58 for free-field and diffuse-field responses respectively. Comparing, for instance, table 3 of ITU-T P.58 with table 1 of ISO 11904 Part 1 and assuming equal diffuse field, we find that the difference between the real eardrum and the microphone of the HATS lies in general within ± 2 dB except for 8 kHz, but in any case it is below the specified tolerance.

Using the setup shown in Figure 6, the $S_{\mathrm{A,E}}$ was measured indirectly by relating the recorded signals from the input to the earphones $x(t)$ and the output of the microphone $y(t)$ of the manikin.

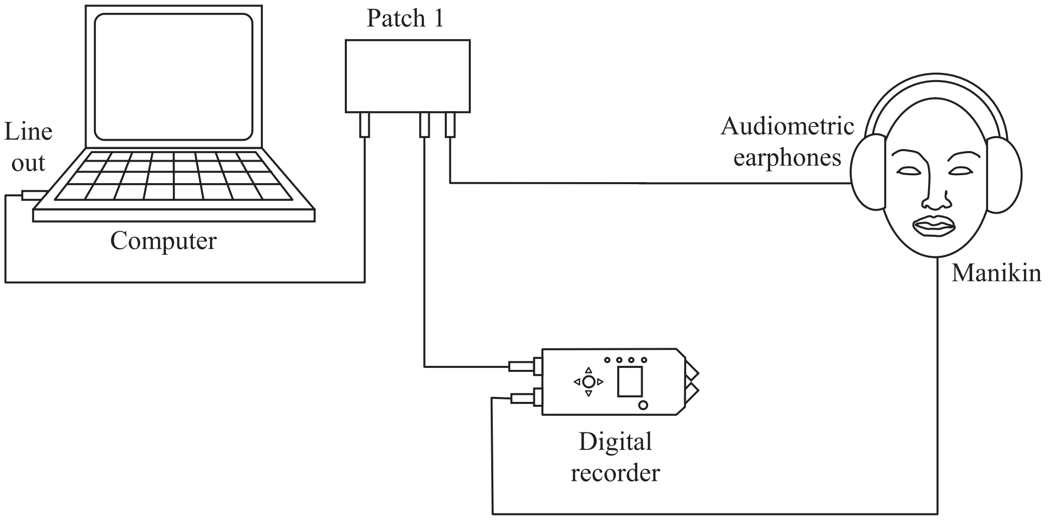

Figure 6: Block diagram of the telephone headset test setup. Patch 1 is a connection box allowing to measure the voltage applied to the auricular. The signal from the computer is fed into the auricular and the digital recorder. The left output of the Kemar GRAS type 45 DA manikin microphones is fed to the digital recorder.

The calibration constant C of the manikin microphones and associated signal conditioners was estimated by recording a reference pure tone of 94 dB and 1 kHz from an acoustic calibrator connected directly to the manikin microphone (without the ear canal simulator). If $Y_{\mathrm{cal,rms}}$ is the root mean square of the recorded signal in arbitrary units, then C is estimated as

$$C = \frac{P_{\mathrm{ref}}}{Y_{\mathrm{cal,rms}}} \tag{21}$$

A chirp signal of constant amplitude V_{rms} = 0,5 V and frequency varying exponentially between the limits of each 1/3 octave band centered at f_{k} was fed into the earphone and simultaneously recorded on one channel of a Zoom H4 recorder, while the other channel recorded the output of the microphone, as shown in Figure 6. Finally the $S_{\mathrm{A,E}}$ is estimated as:

$$S_{\mathrm{A,E}}(f_k) \cong \frac{C}{0{,}5}\frac{y_{\mathrm{rms}}(f_k)}{x_{\mathrm{rms}}(f_k)}\,, \tag{22}$$

Table 5 colects the results of applying a voltage of 0,5 V to the earphones HDA 200 and Figure 7 ilustrates the difference which may be due to manufacturer unspecified tolerances.

f_k [Hz]	$L_{\mathrm{pE}}(f_k)$ [dB] @ v_{rms} = 0,5 V
100	100,9
125	105,5
160	109,5
200	112,1
250	113,2
315	113,6
400	113,5
500	113,4
630	112,6
750	112,0
800	112,4
1000	112,2
1250	111,6
1500	111,7
1600	112,8
2000	115,5
2500	119,0
3000	117,7
3150	114,7
4000	113,0
5000	108,6
6000	107,6
6300	109,3
8000	108,4

Table 5: Frequency response of HDA 200 at the eardrum as calculated in the text for V_{rms} = 0,5 V.

3.2 Audiometric tests on subjects

The audiometric tests were carried out running a dedicated sofware that prompts for frequency and level referred to a 1 kHz tone. Since we are not specifically interested in measuring hearing ability but in the detection of threshold for comparing two transducers, there was no correction for RETSPL, nor for differences in the response of the HDA 200. Indpendently of frequency, whenever a tone was delivered with a given voltage, it was labelled as if it had the same sound pressure level as it would at 1 kHz. Let us call it pseudo-level.

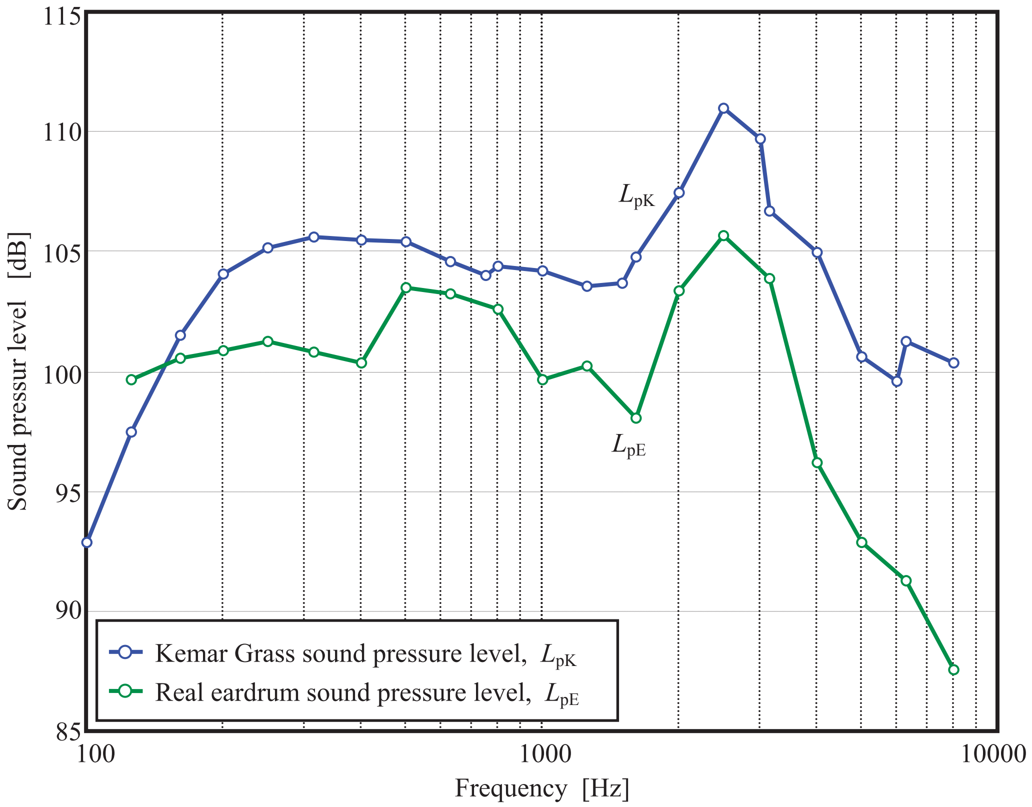

Figure 7: Comparison between the specified real eardrum response of the HDA 200 and the response as measured with a Head and Torso Simulator

Once a frequency has been presented, it is kept constant until two pseudo-levels are located such that they differ by 2 dB and one is audible and the other is not. The threshold is then considered equal to average of these pseudo-levels.

This procedure is repeated with the telephone headset. Some care is necessary here because as the headset is of the supraaural type, ambient noise is not atenuated as it is in the case of the HDA 200, and could easily mask weak sounds close to the threshold. This could raise the threshold considerably turning false the assumption of constancy of the eardrum pressure at threshold.regardless of the transducer. This is particularly the case when the audiometry is performed with the aid of a laptop, due to fan noise. Traffic noise is also a factor that could render inaudible a sound that in silence is audible. If a sound-proof audiometry cabinet is not available, one solution is to carry out the tests at a location as quiet as possible and to place the computer in a neighbouring room

Besides external noise, internal, biological noise may differ between a circumaural earphone and a supraaural one. Rudmose has observed and explained in terms of physiological noise a paradoxical phenomenon by which, at low frequencies, the threshold for circumaural earphones required is about 6 dB louder than in free-field exposure (Rudmose, 1982).

These factors lead to large spread in the results. For instance, see Figure 8, where the results for six subjects is compared with the average interpolated curve. The standard deviation is very large (about 6 dB)

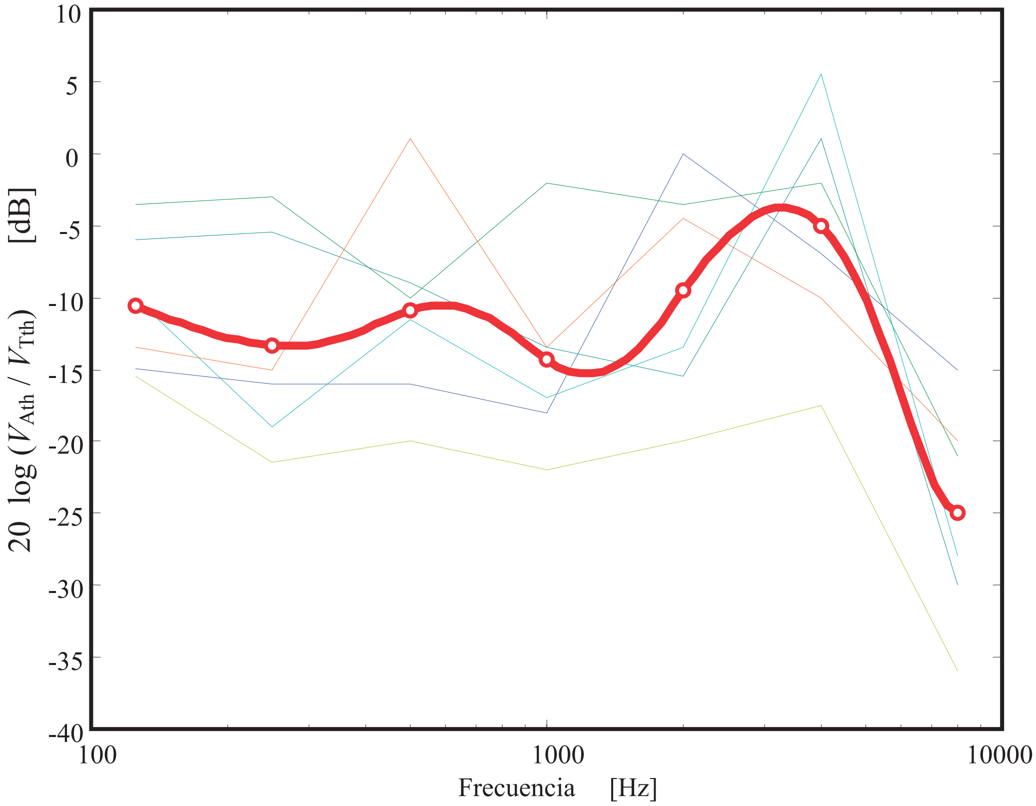

Figure 8: Six curves of 20 log (V_{Ath} / $\mathrm{V}_{\mathrm{Tth}}$), and the average (thick cuve in red).

4 CONCLUSIONS

A method has been proposed to assess the hearing risk at call centers by calibration of a telephone headset against standard audiometric earphones by threshold comparison. The method has the advantage of being quite inexpensive, since once the audiometric earphones are calibrated, there is no need to use expensive equipment that cannot be justified in an ocupational health care service. However, it is not very robust since the dertermination of the hearing threshold for a supraural, open headset may be contaminated by several effects such as ambient noise, fan nioise from the computer, etc. However, if the exposure value obtained by this method plus the estimated uncertainty to happen to be under the regulatory limits, the method would be quite useful. Even if it not the case, it is possible to take some measures to minimise these undesirable effects, such as isolating the subjects from noisy areas for the test, providing the with a sort of helmet acting as an acoustic screen.

Appendix 1 - Symbols and notation

As the text includes a large number of symbols including multiple subscripts, here is a list for quick reference. When possible, underscore fonts give a hint about the meaning of subscripts.

Symbol	Unit	Description
K_{DF}		Conversion constant from eardrum pressure to diffuse field pressure
$p_{A,C}$	Pa	Coupler sound pressure of the audiometric earphones
$p_{A,DF}$	Pa	Equivalent diffuse-field sound pressure of the audiometric earphones
$p_{A,E}$	Pa	Eardrum sound pressure of the audiometric earphones
$p_{A,E,th}$	Pa	Eardrum threshold sound pressure of the audiometric earphones
$p_{A,FF}$	Pa	Equivalent free-field sound pressure of the audiometric earphones
p_{DF}	Pa	Generic diffuse field sound pressure
p_{E}	Pa	Generic eardrum pressure
p_{FF}	Pa	Generic free field sound pressure
P_{ref}	Pa	Reference sound pressure (20 μPa)
$p_{T,DF}$	Pa	Equivalent diffuse-field sound pressure of the telephone headset
$p_{T,E}$	Pa	Eardrum sound pressure of the telephone headset
$p_{T,E,th}$	Pa	Eardrum threshold sound pressure of the telephone headset
$p_{T,FF}$	Pa	Equivalent free-field sound pressure of the telephone headset
G_{C}	dB	Coupler sensitivity level
G_{F}	dB	Free field sensitivity level
$G_{F} - G_{C}$	dB	Correction from coupler sensitivity level to free-field sensitivity level
L_{DF}	dB	Diffuse field sound pressure level
L_{FF}	dB	Free field sound pressure level
L_{E}	dB	Generic eardrum sound pressure level
$S_{A,C}$	Pa/V	Coupler sensitivity of audiometric earphone
$S_{A,DF}$	Pa/V	Diffuse-field sensitivity of audiometric earphone
$S_{A,E}$	Pa/V	Eardrum sensitivity of audiometric earphone
$S_{A,FF}$	Pa/V	Free-field sensitivity of audiometric earphone
$S_{T,DF}$	Pa/V	Diffuse-field sensitivity of telephone headset
$S_{T,E}$	Pa/V	Eardrum sensitivity of telephone headset
v_{A}	V	Voltage applied to audiometric earphone
v_{T}	V	Voltage applied to telephone headphones
$v_{A,th}$	V	Voltage applied to audiometric earphone at hearing threshold
$v_{T,th}$	V	Voltage applied to telephone headphones at hearing threshold
ΔL_{FF}	dB	Correction from eardrum to free field sound pressure level
ΔL_{DF}	dB	Correction from eardrum to diffuse field sound pressure level
f_{k}	Hz	k-th standard audiometric frequency

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