EUROREGIO BNAM2022
Joint Acoustics Conference
9th-11th of May, Aalborg, Denmark

Equivalent Threshold Sound Pressure Levels (ETSPL) and Insertion Loss for the RadioEar DD65 v2 Circum-aural Audiometric Earphones

Rodrigo Ordoñez[1,*], Christian Sejer Pedersen[1] and Dorte Hammershøi[1]

[1]Department of Electronic Systems, Aalborg University, Aalborg Denmark.

[*]rop@es.aau.dk

Abstract

Assessment of hearing thresholds requires proper calibration of the audiometric equipment that considers the sensitivity of the earphones used. For this purpose, the ISO 389 series defines the Reference Equivalent Threshold Sound Pressure Level (RETSPL), as the sound pressure level produced by the earphone actuated by the voltage corresponding to the median auditory threshold of a young, healthy population, measured in a standardized acoustic coupler. As such RETSPL depend on the type and sensitivity of a given transducer. This paper describes the assessment of the Equivalent Threshold Sound Pressure Levels (ETSPL) and the measurement of insertion loss of the RadioEar DD65 v2 audiometric earphones. Hearing thresholds were determined for twenty-nine test subjects at eleven audiometric frequencies from 125 to 8000 Hz according to the specifications given in ISO 389-9 and ISO 8253-1. Insertion loss of two sets of earphones was measured in third-octave bands between 50 and 16000 Hz using an acoustic test-fixture in a reverberant sound field according to ISO 4869-3. The results are reported as ETSPL measured in an acoustic coupler conforming with the specifications given in IEC 60318-1 and compared to reference data used as a basis for the RETSPL for circum-aural audiometric earphones, ISO 389-8. Results show that the auditory thresholds obtained with the RadioEar DD65 v2 circum-aural audiometric earphones are in close agreement with reported values for the Sennheiser HDA200 circum-aural audiometric earphones and the reference values given in ISO 389-8. The insertion loss shows minimum values at the low frequency range (below 160 Hz) of 5 dB, then it gradually increases up to 45 dB at 2000 Hz and above.

Keywords: Audiometry - Earphones - Insertion Loss - Calibration

1 Introduction

Reliable audiometric assessment requires earphones to be calibrated according to a standardized reference, such as the reference equivalent threshold sound pressure levels (RETSPLs) of the ISO 389 series. The RETSPL for a given audiometric earphone type are derived from a number of independent studies of equivalent threshold sound pressure levels (ETSPLs) from normal hearing subjects at different laboratories.

ETSPLs express threshold values as sound pressure level (SPL), decibels (dB) with reference to 20μPa, or dB SPL. By relating the voltage applied to earphones at threshold to the SPL produced by the earphone measured in a standardized calibration fixture or artificial ear, as described in IEC 60318-1 [4], it is possible to compare hearing thresholds assessed with different equipment as calibrated hearing levels (HL). 0 dB HL represents the median hearing threshold of a normal hearing population.

ETSPLs are reported in literature for different earphones [for example, 6, 7, 8, 9, 10, 11, 12, 13], signal types [for example, 14, 15, 16, 17] and extended high-frequency ranges [for example, 18, 19]. Following the tradition in the field, this article describes the determination of pure-tone ETSPLs, and insertion loss for the RadioEar DD65 v2 circum-aural audiometric earphones in accordance with the guidelines of the ISO 389-9 [1] and ISO 4869-3 [3] standards. Results are presented in view of comparable data.

2 Materials and Methods

2.1. Electro-acoustic system

The system used for threshold measurements and for calibration consisted of: a computer running a MATLAB program, two programmable attenuators (PA5, Tucker Davis Technology), an external USB full duplex sound card (RME Fireface UFX 2), a power amplifier (ROTEL RB-976 MKII, modified to give a constant 0 dB gain and low noise), a custom-made earphone-measurement interface with constant attenuation (41.6 dB with output impedance of 1 Ohm), a response button, and the RadioEar DD65 v2 earphone (Part. 8510117 – WTG00009). Only one set of earphones (two transducers, left and right) were used in the threshold measurements, that is, all left ears were measured with the same left transducer (blue colour) and all right ears were measured with the same right transducer (red colour).

During the threshold experiments, the signal level was controlled by the programmable attenuators, where each channel of the earphone was controlled by a different attenuator. Each attenuator covers a range from 0.0 to 120.0 dB and can be altered in 0.1 dB increments. The MATLAB program generates and presents the stimuli, collects user responses, controls the programmable attenuators and saves data to files. The stimuli, in the program, is generated as a full scale digital signal (48 kHz sampling frequency and 24 bits) and is sent through the sound card with 0 dB gain. The output of the sound card is fed through the programmable attenuators which in turn connect to the amplifier and attenuation box that powers the earphones.

1.1 Coupler measurements

The ETSPLs for the DD65 v2 were determined using an IEC 60318-1 [4] acoustic coupler (B&K type 4153), mounted on the side of a cube so that the distance between each earphone cushion was 135 mm with the measured side placed centred on the circum-aural earphone adapter plate of the coupler. The headband length was set to give 130 mm from the centre-line between cushion midpoints and the inside top of the headband, giving a coupling force of 10.3 $\pm$0.7 N. A pressure field microphone (B&K type 4134), microphone preamplifier (B&K type 2639) and measurement amplifier (B&K type 2636), were connected to one of the analog inputs of the sound card. The MATLAB program was used to reproduce the calibration stimuli and record the sound pressure level produced by the earphone in the acoustic coupler. Before the measurements, the entire electroacoustic chain (from microphone to digital value) was calibrated using a 1000 Hz calibrator, B&K type 4230. Measurements were made by setting the programmable attenuators to 0 dB and reproducing full scale tones from the MATLAB program. The recorded signals were compensated for the microphone sensitivity and measurement amplifier gain, obtaining amplitude values in Pascals.

In order to avoid high attenuation levels from the programmable attenuators, the maximum output level of the system was set below 80 dB SPL. The minimum RETSPL for this type of earphone is 2.5 dB at 3 kHz according to ISO 389-8 [5], thus the attenuation needed by the system would be in the order of 80 dB.

1.2 Earphone Insertion Loss

Measurements of insertion loss for the set of earphones used in the experiment were carried out according to the ISO 4869-3 [3] standard. The measurements were carried out in the reverberant room of the Acoustic Laboratory at Aalborg University, that complies with the diffuse field requirements stated in ISO 3741 [20]. The system used for the measurements consisted of: a computer running a MATLAB program, an external USB full duplex sound card (Roland Quad-Capture), a power amplifier (Pioner 616), an acoustic test fixture (GRAS type

Table 1: Test subjects age and gender distribution

Age	20	21	22	23	24	25	**Total**
Male	1	2	0	5	3	4	15
Female	3	3	3	3	2	0	14
Total	4	5	3	8	5	4	29

45CA) configured with two GRAS 40AD 1/2" pressure microphones mounted without an ear simulator, two loudspeakers (Electro-Voice S200) and a calibrated hand held sound level meter (Brüel & Kjær type 2270).

The sound field was produced by the two loudspeakers reproducing uncorrelated pink noise placed at different locations in the room. The sound pressure level at the location of the test fixture in the room with the sources active was measured with the sound level meter at 1 kHz to a level of 87.8 dB SPL.

Sound pressure level in dB at 1/3-octave bands from 50 Hz to 16 kHz were measured with the test fixture without the earphones and the sound sources on (Test Fixture), the sound sources off (Noise Floor), and with the earphones mounted on the test fixture and the sound sources on (Earphones). Measurements were repeated 6 times repositioning the earphones on the text fixture each time.

2.2. Threshold determination

2.1 Subjects

29 test subjects (15 male and 14 female) participated. Test subjects were between 20 and 25 years of age, see Table 1. All subjects were students at Aalborg University and received remuneration for their participation. Subject selection was made following the guidelines and questionnaire given in ISO 389-9 [1]. Subjects willing to participate in the experiment responded the questionnaire and were selected based on their previous hearing history. All subjects that indicated undue sound exposure (noisy working environment, loud music listening or playing, etc.) or previous hearing problems (drain operation, chronic middle ear infection, etc.) were not included in the test. Selected subjects were then screened with otoscopy and tympanometry. Only subjects that had an unobstructed ear canal (no excessive ear wax), a visible tympanic membrane, and middle ear pressure between $\pm$ 50 daPa, were included in the measurements. According to subject selection criteria from ISO 389-9 [1], no exclusion was made in terms of hearing levels and all results are reported here. From the 29 subjects that participated in the experiments results from one left ear were not registered, due to technical issues. Giving a total of 29 right ears and 28 left ears in the data set.

2.2 Procedure

For each subject ETSPLs were calculated by relating the programmable attenuator setting at threshold to the sound pressure levels measured in a earphone coupler at 0 dB attenuation.

The thresholds were determined using the ascending method complying with ISO 8253-1 [2] using a step size of 5 dB. The method was fully automated and controlled by a computer, supervised by the operator that monitored the progress of the test from the adjacent control room. The first stimuli was presented at 30 dB above the RETSPL for the Interacoustics DD45 earphones reported by [10]. The only exception was for the frequency of 125 Hz, where the maximum output level was below the desired start level. For that frequency the maximum output level of 68 dB was used as the starting level. The general principle of the ascending method is as follows: If a valid response is obtained, the level is reduced by 10 dB and a new presentation is made at that level. If no valid response is obtained, the level is increased by 5 dB and a new presentation is made at that level. This ascending series continues until a valid response is obtained. The threshold is defined as the level where valid responses were obtained three times out of a maximum of five ascents. If a threshold was not obtained within these five ascents a "second" try was performed. If a valid threshold was not obtained in the second try, threshold determination for that frequency was repeated at the end of the test.

Whether the left or the right ear was measured first was balanced across subjects. The sequence of frequencies followed the order stated in ISO 8253-1 [2] and the 1000 Hz tone was repeated at the end. The other ear was measured after a 5 minutes break following the first ear. The complete threshold determination (for all frequencies and for both ears) lasted between 20 and 30 minutes.

2.3 Signals

Pure tones needed for the hearing threshold measurements were created in MATLAB at the frequencies of interest complying with the requirements stated in ISO 8253-1 [2]. Each tone was 1.1 s in duration and the start and stop shaping was made with half a Blackman-Harris window of 100 ms in duration. Thus, each tone had onset and offset ramps of 50 ms, giving a 1 second section with constant amplitude. The inter-stimulus intervals were random in lengths varying from 1 to 3.3 s.

2.4 Test Site

All measurements were carried out in the audiometric room of the Acoustics Laboratory at Aalborg University. This room complies with the requirement of minimal background noise as stated in ISO 8253-1 [2]. An intercom system and a camera were used to communicate and monitor the subjects from the control room (adjacent to the audiometric room). Additionally the MATLAB program running the experiment displayed the presented levels and the subjects' responses, allowing the experimenter to follow the progress of the experiment. The earphones were fitted by the test subjects themselves under the supervision of the facilitator, all subjects were asked to remove glasses and earrings (if any) prior to fitting the earphones.

2.5 Response System

The audiometric room was equipped with a push button connected to the computer. In order to indicate that a tone was heard, the test subject pressed and released the push button immediately. Responses were only considered valid if the subject's response was registered while the test tone was playing or up to 0.5 s after the end of the tone. Otherwise the response was marked as not valid.

2.6 Instructions and familiarisation

All subjects were given verbal instructions on how to operate the response button and how to correctly fit the earphones. Following the instructions, a familiarisation trial with three frequencies (1000, 4000, and 500 Hz, presented in this order) was made, before data collection began.

3 Results

3.1. Equivalent Threshold Sound Pressure Level

Tables 2 show an overview of the audiometric data in dB ETSPL measured in the acoustic coupler that complies with IEC 60318-1 [4]. The table shows results for all ears, for left and right ears, for female and male subjects as well as for subjects between 20 and 22 yeas of age and subjects between 23 and 25 years of age.

The final ETSPL values are given rounded to the nearest half decibel and are shown in Table 3.

According to the general guidelines for expression of measurement uncertainty, and using the recommended model outlined in Annex A from ISO 8253-1 [2], the expanded measurement uncertainty is calculated to be

Table 2: Equivalent threshold sound pressure level (ETSPL) for RadioEar DD65 v2 earphone and an acoustic coupler that complies with IEC 60318-1 [4]. Data is shown as the median, average and standard deviation for all ears, each side, gender and age groups.

Frequency [Hz]	125	250	500	750	1000	1500	2000	3000	4000	6000	8000	N
All median [dB]	28.5	15.5	6.8	4.9	4.3	2.1	1.9	2.5	9.6	19.1	21.4	57
All mean [dB]	30.8	17.4	8.8	4.5	5.0	3.6	2.4	2.7	9.0	19.0	22.4	57
All Std. Dev. [dB]	5.6	5.1	6.9	6.4	5.5	6.6	5.9	6.4	6.0	6.8	8.2	57
Left median [dB]	28.5	15.5	6.8	5.0	4.3	1.5	1.9	1.9	9.6	19.1	21.4	28
Left mean [dB]	31.5	18.0	9.5	4.5	4.0	2.3	2.3	2.6	8.7	18.4	21.6	28
Left Std. Dev. [dB]	5.3	5.9	7.5	7.1	5.4	6.1	6.5	7.4	5.9	6.6	9.2	28
Right median [dB]	27.7	14.7	6.3	4.9	5.1	2.1	3.1	2.5	9.6	20.2	26.1	29
Right mean [dB]	30.1	16.9	8.2	4.6	6.0	4.7	2.5	2.7	9.4	19.7	23.1	29
Right Std. Dev. [dB]	5.8	4.3	6.3	5.7	5.5	6.9	5.4	5.3	6.0	7.1	7.3	29
Female median [dB]	28.5	15.5	6.3	4.9	4.3	2.1	1.9	1.9	4.6	19.1	21.1	27
Female mean [dB]	31.4	16.9	7.1	2.6	3.6	2.7	1.8	1.3	7.5	17.4	21.6	27
Female Std. Dev. [dB]	5.2	4.6	4.9	3.8	4.2	5.8	5.1	4.9	5.4	5.4	6.7	27
Male median [dB]	28.5	15.5	9.1	5.0	5.1	2.1	1.9	2.5	9.6	19.1	21.4	30
Male mean [dB]	30.2	17.9	10.4	6.3	6.3	4.3	3.0	3.9	10.4	20.5	23.1	30
Male Std. Dev. [dB]	5.9	5.6	8.1	7.6	6.2	7.2	6.6	7.3	6.2	7.7	9.4	30
20-22 years median [dB]	32.7	15.5	6.8	4.9	4.3	1.8	3.1	2.5	9.6	19.6	23.6	26
20-22 years mean [dB]	31.7	16.6	7.3	4.2	4.5	3.5	2.7	3.4	9.6	19.1	22.6	26
20-22 years Std. Dev. [dB]	5.6	4.9	4.7	3.7	3.3	7.4	5.6	6.4	5.7	5.1	9.3	26
23-25 years median [dB]	28.5	15.5	11.3	0.0	5.1	2.1	1.9	2.5	9.6	19.1	21.4	31
23-25 years mean [dB]	30.0	18.1	10.1	4.8	5.4	3.6	2.2	2.1	8.6	19.0	22.2	31
23-25 years Std. Dev. [dB]	5.4	5.3	8.2	8.0	6.8	5.9	6.3	6.3	6.2	8.1	7.4	31

Table 3: Equivalent threshold sound pressure level (ETSPL) for RealEar DD65v2 earphone and an acoustic coupler that complies with IEC 60318-1 [4], rounded to the nearest 0.5 dB.

Frequency [Hz]	125	250	500	750	1000	1500	2000	3000	4000	6000	8000
All Median [dB]	28.5	15.5	7.0	5.0	4.5	2.0	2.0	2.5	9.5	19.0	21.5

7.2 dB for frequencies below and up to 4 kHz and 10.4 dB for frequencies above 4 kHz. This measurement uncertainty takes into account standardised uncertainty values given in ISO 8253-1 [2] for: 1) variations observed in repeated threshold determinations due to the subjects' criteria; 2) variations to calculated threshold level due to equipment calibration and methodological parameters; and 3) variations in presented sound pressure level due to differences in fitting of the earphones.

3.2. Insertion loss

Figure 1 shows the average SPL measured with the acoustic test fixture in the reverberant sound field with and without the earphones mounted on the test fixture and the sound sources active, and the background noise in the room. Table 4 shows the calculated insertion loss for each cup of the earphone used in the experiment. The measurement uncertainty was calculated using the standard deviation for the repeated measurement of the open and occluded test fixture, and tabulated values (Appendix B in ISO 4869-3 [3]) for: uncertainties associated to the sound field, equipment and acoustic test fixture. The expanded uncertainty of the insertion loss measurements reported here is calculated to be 1.9 dB.

Table 4: Average insertion loss [dB] in 1/3-octave bands calculated as the level difference between the SPL at the test fixture microphones without and with the earphones mounted on the test fixture, and the sound sources active (Columns 2 and 3). Standard deviation over 6 repetitions of the measurements (Columns 4 and 5).

	Insertion Loss		Standard Deviation	
Freq. [kHz]	L [dB]	R [dB]	L [dB]	R [dB]
0.05	6.8	5.8	1.8	1.7
0.063	5.4	4.4	1.5	1.3
0.08	5.5	4.7	2.5	2.3
0.1	8.5	6.7	0.9	1.2
0.125	9.6	8.2	0.9	1.1
0.16	9.0	9.5	0.7	0.6
0.2	11.3	12.0	0.5	0.4
0.25	15.4	15.7	0.4	0.2
0.315	19.1	19.3	0.6	0.6
0.4	23.2	23.4	0.3	0.4
0.5	26.2	25.8	0.3	0.3
0.63	28.4	27.6	0.2	0.3
0.8	29.2	26.2	0.4	0.2
1	32.1	31.8	0.3	0.2
1.25	29.7	30.6	0.1	0.2
1.6	34.5	35.1	0.5	0.2
2	42.8	46.8	0.5	0.6
2.5	44.4	48.9	0.9	0.6
3.15	41.0	42.7	0.3	0.4
4	43.5	44.3	0.6	0.4
5	46.1	46.1	1.1	0.9
6.3	45.0	46.6	1.1	0.7
8	45.4	45.8	1.2	0.7
10	42.9	43.2	1.0	0.4
12.5	44.0	44.5	0.5	0.4
16	43.9	46.0	1.5	1.1

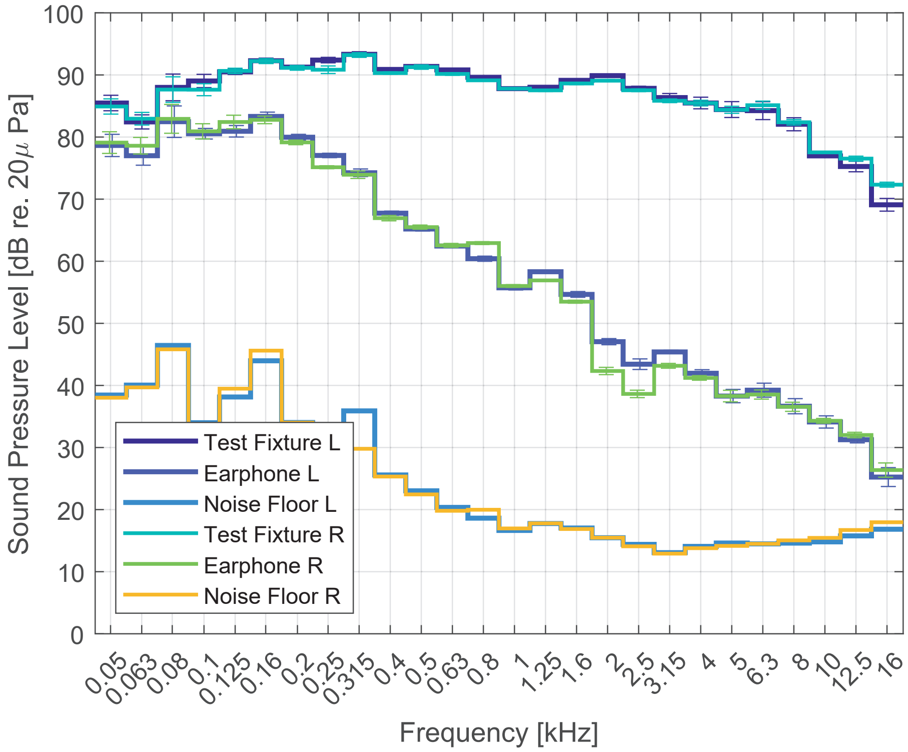

Figure 1: Average sound pressure level (SPL) [dB re. 20μPa] in 1/3-octave bands measured in the reverberant room with the text fixture microphones, with the sound sources active and no earphones (Test Fixture); with the sound sources active and the earphones mounted on the test fixture (Earphone); and with the sound sources disabled and no earphones (Noise Floor). Errorbars show ± standard deviation between repeated measurements.

4 Discussion

4.1. Threshold determination method

Thresholds were determined using the ascending method, defining the threshold as the level heard by the subject in three out of a maximum of five ascending tracks according to ISO 8253-1 [2]. This method has the inherent bias of approaching the threshold from below, leading to an overestimation of the threshold compared to the classical definition: the 50% detection of the psychometric function. This is because the threshold is estimated using only the last level the subject hears. This method has the advantage that it does not require complex calculations, and it is easily implemented with manual audiometers readily available in clinics. The problem is that it makes comparison with thresholds obtained with other methods that aim at a threshold around the 50% detection problematic [21, p. 24–25]. In order to illustrate this, maximum likelihood estimates (MLE) of the thresholds for each ear were calculated using all levels and answers given by the subjects after the initial familiarisation descend of each trial. This includes all levels presented to the subjects after the first ”not heard” answer. The thresholds estimated with the MLE method represent the 50% detection probability of the estimated psychometric function modelled as a cumulative normal distribution. The MLE threshold estimates are significantly lower than the ones obtained using three ascents at the same level, for all frequencies tested ($t_{df=56} > 8, p < 0.8 \times 10^{-11}$). The average difference between the methods is of 3.7 dB with a minimum of 1.8 dB and a maximum of 5.6 dB. A comparison of the average estimate across subjects for both methods is shown in Figure 2.

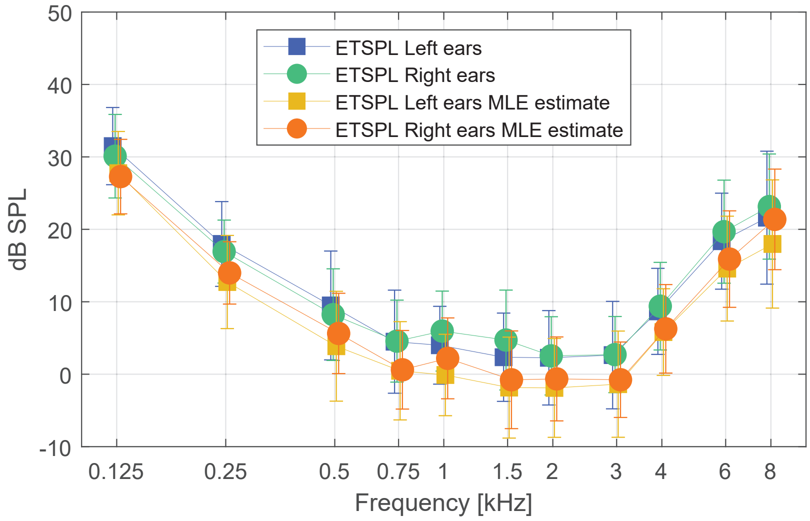

Figure 2: Average Equivalent Threshold Sound Pressure Levels (ETSPL) for DD65v2 earphones for left and right ears. Determined using the ascending method's stop criteria (light grey symbols); and using a Maximum Likelihood Estimate (MLE) procedure (dark grey and black symbols). Error-bars represent ± standard deviation. Symbols have been shifted in frequency for clarity.

4.2. Reference data

Figure 3 shows the present data with the data of five other studies reporting ETSPLs for circum-aural earphones. The first four studies serve as part of the reference material for ISO 389-8 [5] reporting ETSPL values for the Sennheiser HDA 200 earphones [6, 22, 23, 8]. The last study reports ETSPL values for RadioEar DD65 v2 earphones [24], the same type used here. These results confirm that the populations of subjects used in this

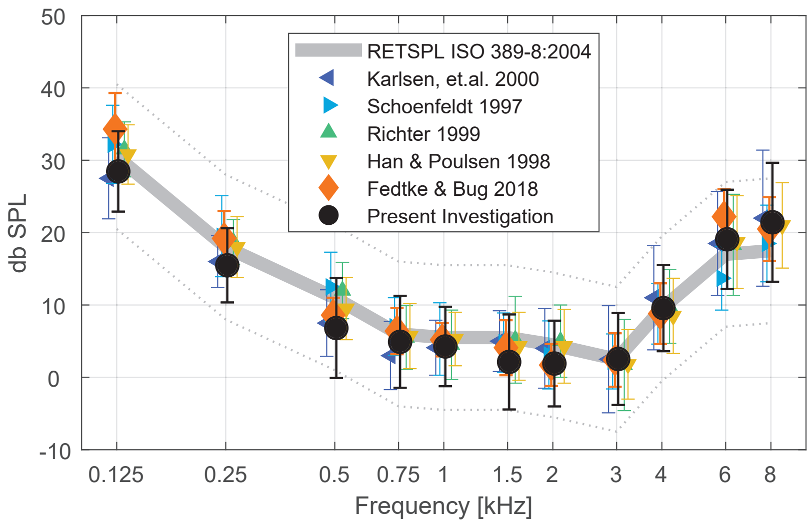

Figure 3: Median Equivalent Threshold Sound Pressure Levels (ETSPL) reported as reference data for ISO 389-8 [5], using Sennheiser HDA 200 earphones (grey symbols); and using RadioEar DD65 v2 earphones (dark grey and black symbols). Error-bars represent ± standard deviation. Symbols have been shifted in frequency for clarity. Also shown in the figure is the RETSPL from ISO 389-8 [5] (thich line) and ±10 dB (dotted lines).

experiment can be considered of normal hearing, and the equivalent threshold sound pressure levels presented here are in good agreement with reference data given in ISO 389-8 [5].

Equivalent threshold sound pressure levels, ETSPLs, for the RadioEar DD65 v2 circum-aural audiometric earphones are similar to the ETSPLs for Sennheiser HDA200 circum-aural audiometric earphones, and should be considered as having the same RETSPL for the calibration of audiometric equipment.

Acknowledgements

The authors would like to thank Claus Vestergaard Skipper for his technical assistance with equipment and laboratory facilities, as well as Oliver Erik Palmhøj Jokumsen for his assistance with data collection. Finally, thanks to all the subjects that participated in this experiment.

References

[1] ISO 389-9. Acoustics – Reference zero for the calibration of audiometric equipment – Part 9: Preferred test conditions for the determination of reference hearing threshold levels. Technical report, International Organization for Standardization, Geneva, 2009.

[2] ISO 8253-1. Acoustics – audiometric test methods – part 1: Pure-tone air and bone conduction audiometry. Technical report, International Organization for Standardization, Geneva, 2010.

[3] ISO 4869-3. Acoustics – Hearing Protectors – Measurement of insertion loss of ear-muff type protectors using an acoustic test fixture. Technical report, International Organization for Standardiazation, Geneva, 2006.

[4] IEC 60318-1. Electroacoustics – Simulators of human head and ear – Part 1: Ear simulator for the measurement of supra-aural and circumaural earphones. Technical report, International Electrotechnical Commission, Geneva, 2009.

[5] ISO 389-8. Acoustics - Reference zero for the calibration of audiometric equipment - Part 8: Reference equivalent threshold sound pressure levels for pure tones and circum-aural earphones. Technical report, International Organization for Standardization, Geneva, 2004.

[6] L.A. Han and T. Poulsen. Equivalent threhsold sound pressure levels for the sennheiser HDA 200 headphone and the etymotic research ER-2 insertearphone in the frequency range 125 Hz to 16 kHz. *Scan. Audiol.*, 2:105–112, 1998. doi: 10.1080/010503998420342.

[7] T. Poulsen. Reference thresholds for Eartone-3A insert earphones. *Scan Audiol*, 20(3):205–207, 1991. doi: 10.3109/01050399109074955.

[8] B. L. Karlsen, M. Lydolf, and A. O. Santillán. Audiometric tests with various earphones, signals of short duration and signals of high frequencies. Technical report, ISO/TC 43/WG 1, Doc. Nr. 309, 2000.

[9] T. Poulsen and S. Oakley. Equivalent threshold sound pressure levels (ETSPL) for Sennheiser HDA 280 supra-aural audiometric earphones in the frequency range 125 Hz to 8000 Hz. *Int J Audiol*, 48(5):271–276, 2009. doi: 10.1080/14992020902788982.

[10] T. Poulsen. Equivalent Threshold Sound Pressure Levels (ETSPL) for Interacoustics DD 45 supra-aural audiometric earphones. *Int. J. Audiol.*, 11:850–855, 2010. doi: 10.3109/14992027.2010.500625.

[11] M. Zebian, J. Hensel, T. Fedtke, and S Vollbort. Equivalent hearing threshold levels for the etymotic research er-10c otoacoustic emission probe. *Int JAudiol*, 51(7):564–568, 2012. doi: 10.3109/14992027.2012.669050.

[12] Torben Poulsen. Equivalent threshold sound pressure levels (ETSPL) for Sennheiser HDA 280 supra-aural audiometric earphones in the frequency range 125 Hz to 8000 Hz (vol 48, pg 271, 2009). *Int J Audiol*, 53 (4):287–288, 2014. doi: 10.3109/14992027.2013.860559.

[13] Cheng-Yu Ho, Pei-Chun Li, and Shuenn-Tsong Young. Reference equivalent threshold sound pressure levels for Apple EarPods. *J Acous Soc Am*, 141(2):115–119, 2017. doi: 10.1121/1.4976110.

[14] U. Richter and T. Fedtke. IReference zero for the calibration of audiometric equipment using 'clicks' as test signals. *Int J Audiol*, 44(8):478–487, 2005. doi: 10.1080/14992020500060230.

[15] T. Fedtke and U. Richter. Reference zero for the calibration of air-conduction audiometric equipment using 'tone bursts' as test signals. *Int J Audiol*, 46(1):1–10, 2007. doi: 10.1080/14992020601050361.

[16] Torben Poulsen and Soren Vase Legarth. Reference hearing threshold levels for short duration signals. *Int J Audiol*, 47(10):665–674, 2008. doi: 10.1080/14992020802203330.

[17] Kristian Gotsche-Rasmussen, Torben Poulsen, and Claus Elberling. Reference hearing threshold levels for chirp signals delivered by an ER-3A insert earphone. *Int J Audiol*, 51(11):794–799, 2012. doi: 10.3109/14992027.2012.705901.

[18] T. Frank. High-frequency (8 to 16 kHz) reference thresholds and intrasubject threshold variability relative to ototoxicity criteria using a Sennheiser HDA 200 earphone. *Ear Hear*, 22(2):161–168, 2001. doi: 10.1097/00003446-200104000-00009.

[19] A. Rodriguez Valiente, J. R. Garcia Berrocal, A. Roldan Fidalgo, A. Trinidad, and R. Ramirez Camacho. Earphones in extended high-frequency audiometry and ISO 389-5. *Int J Audiol*, 53(9):595–603, 2014. doi: 10.3109/14992027.2014.903339.

[20] ISO 3741. Acoustics – Determination of sound power levels and sound energy levels of noise sources using sound pressure – Precision methods for reverberation test rooms. Technical report, International Organization for Standardization, Geneva, 2010.

[21] Morten Lydolf. *The threshold of hearing & contours of equal loudness – a study of measuring methods and normal hearing*. Department of Electronic Systems, Aalborg University, Aalborg Universitetsforlag, 1999.

[22] U. Richter. Determination of the equivalent threshold sound pressure levels for a circumaural earphone in the conventional frequency range. Technical report, ISO/TC 43/WG 1, Doc. Nr. 284, 1999.

[23] U. Schönfeld, W. Reuter, R. Fischer, and M. Gross. Hearing thresholds of otologically normal subjects in the extended high frequency range using the earphone hda200. Technical report, ISO/TC 43/WG 1, Doc. Nr. 263, 1993.

[24] M. Bug and T. Fedtke. Equivalent threshold sound pressure levels (ETSPLs) for RadioEar DD65v2 circumaural audiometric headphones. *Int J Audiol*, 59(8):624–630, 2020. doi: 10.1080/14992027.2020.1727034.