The comparison of auditory behavioral and evoked potential responses (steady state and cortical) in subjects with occupational noise-induced hearing loss

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ABSTRACT

Objective: To define difference scores between PTA, ASSR and CERA thresholds in subjects with occupational NIHL.
Design: 44 subjects undergoing a medico-legal expert assessment for occupational NIHL and fulfilling criteria of reliability were considered. Assessment included: PTA, 40 Hz binaural multiple ASSR and CERA (1-2-3 kHz).
Results: The respective average difference scores (ASSR - PTA) for 1, 2 and 3 kHz are 13.01 (SD 10.19) dB, 12.72 (SD 8.81) dB and 10.38 (SD 8.19) dB. The average (CERA - ASSR) difference scores are 1.25 (SD 14.63) dB for 1 kHz (NS), 2.73 (SD 13.03) dB for 2 kHz (NS) and 4.51 (SD 12.18) dB for 3 kHz. The correlation between PTA and ASSR (0.82) is significantly stronger than that between PTA and CERA (0.71). In a given subject, PTA thresholds are nearly always lower (i.e., better) than ASSR thresholds, whatever the frequency (1-2-3 kHz) and the side (right − left). A significant negative correlation is found between the difference score (ASSR − PTA) and the degree of hearing loss.
Conclusion: ASSR outperforms CERA in a medicolegal context, although overestimating the behavioral thresholds by 10–13 dB.

1. Introduction

In a medical legal context, dealing with lack of reliability as to behavioral audiometric findings is not uncommon. When occupational diseases (e.g. NIHL: noise induced hearing loss) are likely to be covered by an insurance system providing financial compensation the prospect of a potential benefit may encourage some insured workers to either deliberately worsen their actual hearing loss or to raise - to some extent unconsciously − their behavioral response criteria (DeJonckere et al., 1992, 2000, DeJonckere and Lebacq, 2005, 2009, 2011). In a previous study (DeJonckere et al., 2021), we demonstrated that the 40 Hz binaural multiple ASSR (Auditory Steady State Response) technique is adequate for medico-legal evaluation of hearing thresholds in adults who are claiming

financial compensation for work related NIHL, as soon as the traditional methods of behavioral audiometry lack reliability. As a matter of fact, the electrophysiological ASSR approach of the hearing level is totally noninvasive, well-tolerated and frequency specific. ASSR thresholds correlate well with the CERA results, which are generally considered today as the gold standard in frequency specific objective measurement of hearing. However, our study showed an average shift, ASSR-thresholds being on average 4.38 dB better (i.e., indicating better hearing) than CERA-thresholds. Fully reliable subjects appeared to be indispensable for a further validation, also and particularly in order to define the average difference scores ASSR - PTA (pure tone audiometry) per frequency. Of course, the characteristics of these reliable subjects, as well as the context and conditions, needed to be similar to those of the original study.

In practice, CERA has two significant limitations: (1) the long duration (hours) necessary to precisely evaluate the thresholds for each relevant frequency in each ear and (2) the fact that the actual (psychoacoustic) hearing thresholds are overestimated: in subjects assumed to be fully reliable with NIHL, difference scores CERA - PTA

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of about 13, 10 and 9 dB have been reported for the frequencies 1, 2 and 3 kHz (Albera et al., 1991; DeJonckere et al., 1992).

An ASSR is an electrophysiological response to acoustical stimuli that are presented at rates of 1–200 Hz, or to periodic amplitude and/or frequency modulations (at similar rates) of a 'steady state', i.e. continuous tone. Such a tone has a specific frequency, which is called the carrying frequency (CF). ASSRs can be recorded from scalp electrodes. The EEG signal must be amplified approximately 80,000 times and filtered (bandpass 5–100 Hz). The frequency of the ASSR is determined by the modulation frequency; hence frequency-domain methods are suited for analysis. A peak at the modulation frequency will be revealed by a spectrogram of the response (Dimitrijevic et Cone, 2015). So, frequency-based analyses can objectively detect the ASSRs (Picton & al. 2003; Rance, 2008; Yüksel et al., 2020). Of course, a properly functioning of both peripheral hearing structures (cochlea and auditory nerve) and central auditory pathways is required. (Dimitrijevic et Cone, 2015).

In awake subjects, modulation rates around 40 Hz are best suited to identify the ASSRs (Picton et al., 2003). At these modulation rates, the response is believed to be primarily elicited at cortical level (Yüksel et al., 2020; Rance, 2008), however with participation of the brainstem, the auditory midbrain, and the thalamus (Spydell et al., 1985; Johnson et al., 1988; Hari et al., 1989; Mäkelä et al., 1990; Kiren et al., 1994; Herdman et al., 2002; Korczak et al., 2012). Several authors consider a modulation rate around 40 Hz (rather than around 80 Hz) as better suited for threshold assessment in awake adults (Ishida and Stapells, 2012; Yüksel et al., 2020). Mental arousal of the subject remains an important issue: considerably reduced amplitudes of ASSRs have been observed in sedated or sleeping patients (Picton et al., 2003; Korczak et al., 2012).

D' haenens et al., 2008 reported that ASSR thresholds show a very satisfactory test-retest reliability, whatever the frequency (0.5, 1, 2, 4 kHz).

An important particularity of the ASSR consists in the possibility to simultaneously explore different frequencies at the same side by presenting each single CF (0.5, 1, 2 and 4 kHz) at a slightly different rate of modulation around 40 Hz, e.g., 39.06, 40.62, 42.19 and 45.31 Hz. The four distinct stimuli elicit responses that the spectral analysis of the EEG can identify and separate: this allows to link each response to the corresponding test frequency (Mühler et al., 2012; Yüksel et al., 2020). Moreover, it also becomes possible to simultaneously test both ears (Herdman and Stapells, 2001). However, the simultaneous use of multiple stimuli results in a reduction of the response amplitudes for the 40 Hz–ASSR (Ishida and Stapells, 2012; Yüksel et al., 2020).

As to the correlation between ASSR thresholds and PTA thresholds, Herdman and Stapells (2003) noticed that, in adults with a mild to profound hearing loss, the multifrequency ASSR (amplitude modulation 77–105 Hz) technique allows to adequately estimate configuration as well as degree of the hearing loss. Specifically, these authors found, for frequencies from 500 to 4,000 Hz, a good agreement (correlation coefficients 0.75 to 0.89) between ASSR thresholds and PTA thresholds. In patients with hearing loss, the ASSR thresholds for pure tones of 1,2 and 4 kHz (multifrequency technique) were, in 93, 93 and 100% of the cases, within 20 dB of the respective behavioral thresholds. The type of the sensorineural hearing loss (flat/shallow slope vs. steep slope) had not more than an insignificant effect on the accuracy of the ASSR threshold prediction.

Luts and Wouters (2005) investigated the specific relationship between behavioral and ASSR thresholds. They used the 'Master' system with a modulation frequency of 90 Hz) and found that, in 10 cooperating hearing impaired subjects, the difference scores (ASSR − PTA thresholds) were 12 (SD 8) (1 kHz), 17 (SD 8) (2 kHz) and 19

(SD 12) (3 kHz) dB in. Also Petitot et al. (2005) came to the conclusion that the behavioral thresholds were overestimated by the ASSRs. They noticed, however, that ASSRs obtained with 40 Hz modulation were closer to PTA thresholds than those obtained with the 80 Hz modulation. Rance et al. (1995) observed that average differences between ASSR and behavioral thresholds decrease (i.e., ASSR thresholds become closer to PTA thresholds) when the degree of hearing loss is more pronounced and when the tested frequencies are higher.

Data from the literature are controversial when specifically dealing with the relation between CERA and ASSR: Van Maanen and Stapells (2005) pointed out that 40 Hz-ASSRs showed lower (i.e. better) thresholds, hence closer to the PTA thresholds, than the CERA (2 groups of 23 subjects), whereas Tomlin et al., 2006 reported that, at 4 kHz, cortical potentials were observed at levels typically closer to the PTA threshold than 40 Hz-ASSRs (30 subjects). However, Yeung and Wong (2007) considered that, even though although PTA thresholds seem to be a little more accurately defined by CERA than by ASSRs (63 ears), the difference may not be clinically relevant.

Hence, the current study was prospective and designed to clarify - in reliable subjects - the relation between the thresholds obtained - in the same ears - by using the two electrophysiological methods - CERA and ASSR − and to compare them with the behavioral thresholds, in order to document the use of ASSR in a medico legal context in subjects with occupational NIHL and claiming for compensation. A relevant point in the study is the fact that the sample of reliable subjects used must be very comparable to the sample of 164 subjects (suspected of exaggerating their reported NIHL) of the previous study: medicolegal context, occupational NIHL, age, gender, duration of exposure to noise and degree of hearing loss.

2. Material & methods

2.1. Design & protocol

Forty-four subjects claiming for benefit at the Federal Agency for Occupational Risks (FEDRIS, Brussels) and acceptable for inclusion in our analysis were considered in the present study, that ran over a period of 22 months. As in our previous study (DeJonckere et al., 2021), their occupational history was scrutinized by the Engineering Dept. of FEDRIS before medical examination, so as to only include cases with an exposure to noise ≥ one year to ≥85 dB$_A$ (Time Weighted Average, i.e. $L_{EX,8h}$ ≥ 85 dB$_A$), complying to Article 16 (1) of the 17th 89 391/EEC European Directive on Health and Safety rules on workers' exposure to noise. Use of personal hearing protection was not included in our selection criteria.

The Belgian scale allowing financial benefit for NIHL considers an average of air conduction thresholds on 1, 2 and 3 kHz at the best ear, weighted by the corresponding thresholds at the worse ear (5/6 better ear − 1/6 worse ear) in the cases of asymmetry. The essential test for inclusion in our previous study (DeJonckere et al., 2021) was a suspicion of excessive reported NIHL, based on a worsening (≥5 dB$_{HL}$ on average at the best ear) of the threshold values obtained in PTA during the evaluation at FEDRIS, compared to those of the audiogram supplied by the claimant in his/her application document. The rationale of this approach has been explained in our previous article (DeJonckere et al., 2021).The main inclusion criterion in the present study was the opposite of that of our previous study, i.e. the strict absence of any PTA threshold measured at FEDRIS that is higher (worse) than the corresponding one in the audiogram of the PTA supplied by the claimant with his/her application. When this condition was fulfilled, the subject was proposed to undergo a more in-depth electrophysiological

investigation of his hearing status, consisting in both an ASSR and a CERA evaluation of hearing thresholds. Furthermore, all evaluation sessions were completed by a tympanometry, an analysis of acoustic stapedial reflexes, and whenever relevant and feasible, a Békésy-audiometry and a prosthetic audiometry. All subjects were duly informed about the whole procedures and they all accepted them. It should be recalled that they are claimants for compensation, and that they are asking themselves for a medical-forensic expert exam. In a medico-legal context, any invasive examination is clearly ruled out.

In all subjects, a bilateral otoscopy was carried out before audiological investigations to prevent possible bias due to ear wax or foreign objects. Supplementary criteria for discarding subjects from the study group included pathology of the middle ear and uni- or bilateral conductive hearing loss, general health problems, cognitive troubles or limited communication linked to language. After our earlier work (DeJonckere and Coryn, 2000) considering the influence of sedative, hypnotic or neuroleptic drugs on CERA, cases reporting use of such drugs were not included in this work, however without any possibility of controlling the subjects' report. Arousal level was continuously monitored during the whole procedure of the examination.

Duration of exposure, as well as gender and age were systematically recorded.

In cases of no measurable response at maximal stimulus level, whichever the method, the threshold was set as 120 dB_{HL}/dB_{nHL}.Only octave frequencies (pure tone at 0.5, 1, 2 and 4 kHz) are available for ASSR, but 0.5 kHz is not considered here as it is not is not considered for the Belgian compensation scale for occupational NIHL. Arithmetical means of the thresholds measured at 2 and 4 kHz were used for 3 kHz in calculations: this has been considered acceptable when thresholds at 3 KHz are not available (Monsell, 1995).

3. Material and methods

For conventional audiometric evaluations (including PTA 125–8000 Hz, bone and air conduction, test-retest, masking when relevant) we used a Madsen Orbiter 922 before mid-2017 and a Madsen Astera[2] (Natus Medical Denmark) after mid-2017.

We used a Grason Stadler GSI Tympstar Middle Ear Analyzer (ViaSys Healthcare, Madison, USA) for impedance audiometry, comprising tympanogram and definition of acoustic-stapedial reflex thresholds at 0.500, 1, 2 and 4 kHz.

We used a Bio-Logic Navigator PRO system (Bio-logic Systems Corp) for CERA with the following parameters settings: 50 ms stimulus tone-burst at 1 Hz; filtering at 0,1–10 Hz; 600 ms analysis epoch; 50 to 250 stimuli. ASSRs were recorded by means of the Neuro-Audio.Net system (Neurosoft Ltd). Stimuli settings were 0,5–4 kHz pure tones, 100% amplitude and 10% frequency modulated at about 46 Hz.

For the whole duration of electrophysiological procedures, the subject was lying comfortably in a relaxed position on an examination couch with his head resting on a pillow. Impedance was controlled (<5 kΩ) in all electrodes. Two Telephonics TDH-39 headphones Acoustic were used to provide stimuli to the subject. The audiologist was sitting in the booth next to the subject, continually checking his arousal, and operating the computer.

At each intensity level, CERA responses were recorded four times (see Fig. 1). As in our earlier study (DeJonckere et al., 1992, 2000), the CERA threshold was defined as the smallest stimulus intensity (in dB_{nHL}, steps of 5 dB) producing a clearly identified averaged evoked response, namely the expected P1–P2–N2 pattern visible when superimposing four displayed averaged CERA tracings obtained with identical stimulations (amplitude 2–10 μV;

P1 (50–80 ms); P2 (150–200 ms); N2 (180–300 ms)]. As shown in Fig. 1, at each intensity level and at each frequency (in this case 4x75 sweeps at 2 kHz), averaged CERA responses were superimposed. The expected pattern of the late potential is clearly recognized in the lower tracing (60 dB_{nHL}), but not in the upper tracing (55 dB_{nHL}). Hence the threshold is 60 dB_{nHL}.

The definition of the ASSR threshold is illustrated in the screen copy of Fig. 2 as a function of time (minutes). After the start of stimulation, the algorithm tries to detect a significant response in each of the channels. The algorithm and the recording stop in a particular channel when the level of significance is reached (*e.g.* 55 dB_{nHL} at 1 kHz right), and they immediately resume at a 5 dB lower intensity, while the procedure continues in the other channels. The sequence is repeated until no significant response is detected after 6 min (*e.g.* 45 dB_{nHL} at 1 kHz right). Thresholds for the right ear are 50, 55 and 65 dB_{nHL} at 1, 2 and 4 kHz respectively. A: signal amplitude (nV); RN: residual noise.

The software program of Neurosoft always gives an 'estimated threshold' based on the ASSR response (see Fig. 3).

In our data-set, the correction factor applied in the Neurosoft program could easily be deduced: at 1 kHz, $\leq$ 10 dB_{nHL}: no correction; $\geq$15 $dB_{nHL} \leq$ 65 dB dB_{nHL}: - 5 dB; $\geq$ 70 dB_{nHL}: - 10 dB; at 2 kHz, $\leq$ 15 dB_{nHL}: no correction; $\geq$20 $dB_{nHL} \leq$ 55 dB dB_{nHL}: - 5 dB; $\geq$ 60 dB_{nHL}: - 10 dB; at 4 kHz, $\geq$ 20 dB_{nHL}: - 10 dB.

4. Statistics

Statistical computations and graphs were made using the Statistica software (Statsoft Inc., Tusla, USA). A Kolmogorov-Smirnov d-statistic was first applied to all threshold-variables: the hypothesis that the distribution is normal could in no case be rejected. Comparisons were made using ANOVA and Student's T-test for dependent samples. For correlations, Pearson's r was computed.

5. Results

The distribution of ages has a gaussian shape, with a maximum of subjects in the age groups from 55 to 70 years (n total = 44). Mean age = 64.07 years; SD = 9.64. These values are very close to those of our previous study in subjects suspected to exaggerate their occupational NIHL.

Most subjects were males (42/44). The proportion is very similar to the one of our previous study (155/164).

The same comment applies to the main duration of exposure, that in the present study mainly ranging between 20 and 35 years, but with a wide dispersion (see histogram of Fig. 4).

Table 1 gives the mean threshold values in $dB_{nHL/HL}$ (and SD) per method, frequency and side (N = 44).

A triple histogram (with Laplace fits) of all data (1-2-3 kHz; Right and Left): PTA, ASSR and CERA is presented in Fig. 5. Global mean values are 64.68 dB_{HL} (SD 20.83) for PTA, 75.10 dB_{nHL} (SD 19.67) for ASSR and 79.35 dB_{nHL} (SD 20.56) for CERA. CERA thresholds are higher (*i.e.* indicating a more important hearing loss) than ASSR thresholds (p = 0.000073), and ASSR thresholds are higher (*i.e.* indicating a more important hearing loss) than PTA thresholds (p < 0.00001).

As shown in Fig. 6, whatever the frequency and the side, PTA thresholds are lower (*i.e.,* better) than either ASSR or CERA thresholds. This becomes even more evident when right and left ears are averaged (whiskers indicate 1 and 1,96 SE) (Fig. 7).

ANOVA indicates that average PTA, ASSR an CERA thresholds highly significantly differ, whatever the side and frequency (1, 2, 3 kHz): all p values are < 0.00001. Average PTA thresholds are systematically lower (better) than ASSR thresholds, whatever side and frequency (1, 2, 3 kHz): all p values are < 0.00001 (T test for
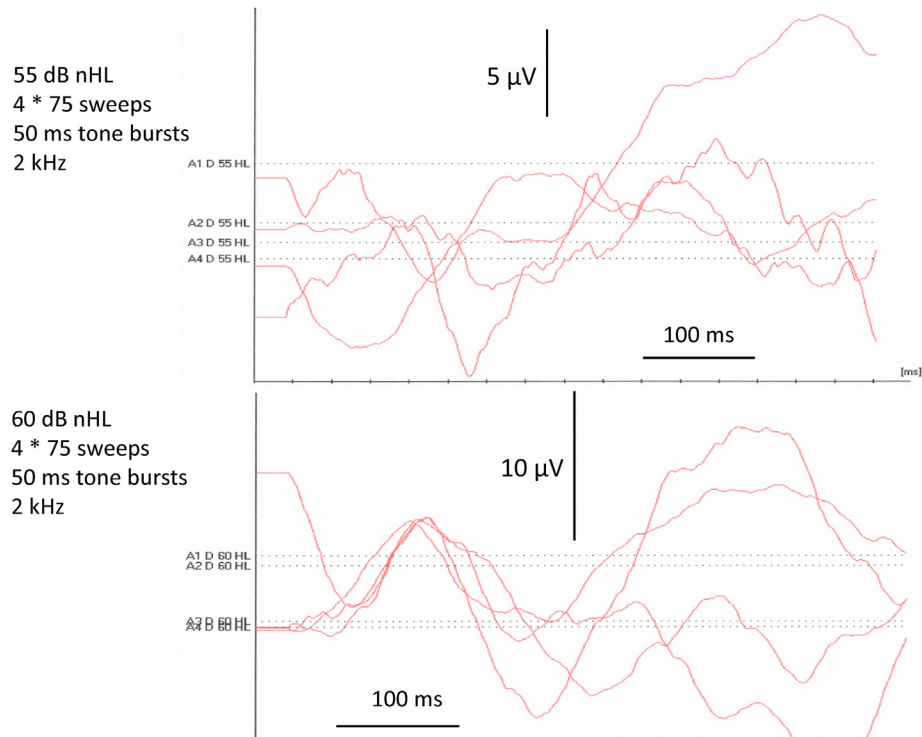
Fig. 1. Definition of CERA threshold on a CERA screen. At each frequency, in this case 2 kHz, and for each intensity, four records are averaged (in this case 4x75 sweeps) and superimposed. The expected late potential is detectable in the lower tracing (60 dB$_{nHL}$), but not in the upper one (55 dB $_{nHL}$). In this case, 60 dB $_{nHL}$ is thus the threshold.


Fig. 2. Definition of ASSR threshold on an ASSR screen as a function of time (in minutes). When stimulation has been initiated, a significant response is sought for by the algorithm in all channels. If significance is reached in one of them, recording ceases in this channel (e.g. 55 dB at 2 kHz right), while it continues in the other ones. In the channel where significance was found, the stimulation resumes at a 5 dB$_{nHL}$ lower intensity; the routine continues until no significant response is obtained after 6 min (e.g. 45 dB$_{nHL}$ at 2 kHz right). Thresholds for the right ear are 50 dB$_{nHL}$ at 1 kHz, 55 dB$_{nHL}$ at 2 kHz and 65 dB$_{nHL}$ at 4 kHz. A = amplitude of the signal (nV); RN = residual noise.

dependent samples).

Average (CERA - ASSR) difference scores are 1.25 (SD 14.63) dB for 1 kHz (NS), 2.73 (SD 13.03) dB for 2 kHz (NS) and 4.51 (SD 12.18) dB for 3 kHz (p = 0.02) (T test for dependent samples).

Average (CERA − PTA) difference scores are 14.26 (SD 14.60) dB for 1 kHz (p < 0.00001), 15.45 (SD 14.41) dB for 2 kHz (p < 0.00001) and 14.37 (SD 13.59) dB for 3 kHz (p < 0.00001) (T test for dependent samples).
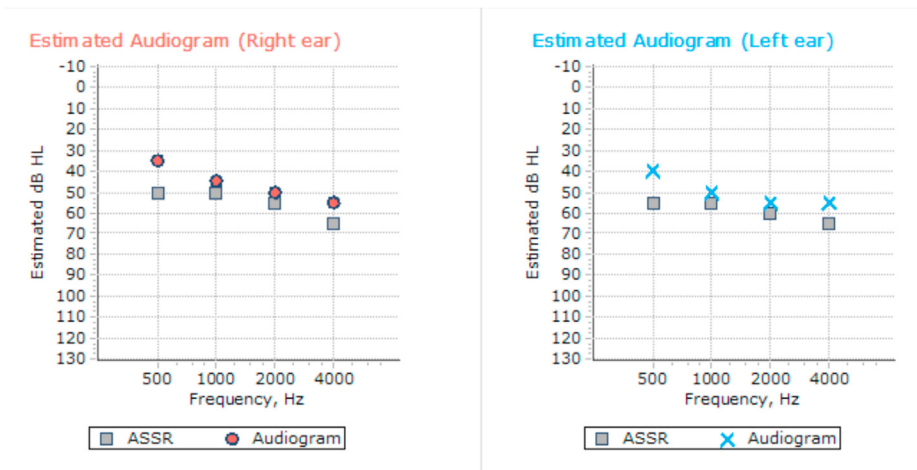
Fig. 3. ASSR thresholds and estimated true thresholds for the results displayed in Fig. 10. ASSR thresholds are 50, 55 and 65 dB$_{nHL}$ for the right ear and 55, 60 and 65 dB$_{nHL}$ for the left ear (1, 2 and 4 kHz respectively). Estimated thresholds are 45, 50 and 55 dB$_{HL}$ in the right ear and 50, 55 and 55 dB$_{HL}$ in the left ear.
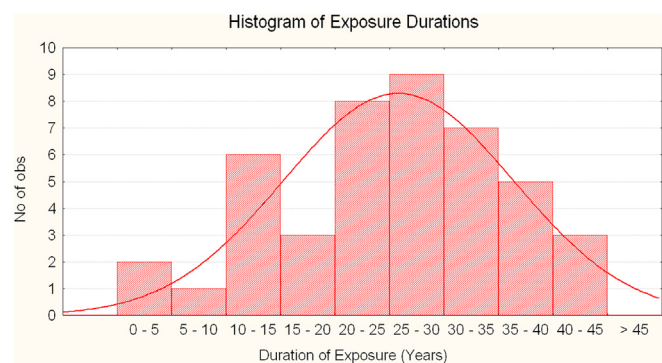
Fig. 4. Histogram of durations of exposure to noise. A maximum of subjects is in the exposure groups from 20 to 35 years. Mean is 27 years ± 11.4 (SD).

Table 1
Mean threshold values in dB$_{nHL/HL}$ (and SD) per method, frequency and side (N = 44) (ASSRest = estimated ASSR threshold by taking in account the correction factor applied by the manufacturer's program).

Method	Frequency	Side	Threshold Mean	Threshold SD
PTA	1 kHz	Right	51.25	18.80
ASSR	1 kHz	Right	66.36	17.93
CERA	1 kHz	Right	64.54	20.37
ASSRest	1 kHz	Right	59.20	16.14
PTA	2 kHz	Right	62.84	16.61
ASSR	2 kHz	Right	77.16	17.06
CERA	2 kHz	Right	77.04	17.46
ASSRest	2 kHz	Right	67.61	15.76
PTA	3 kHz	Right	73.52	17.50
ASSR	3 kHz	Right	84.54	13.31
CERA	3 kHz	Right	87.27	17.93
ASSRest	3 kHz	Right	74.77	12.66
PTA	1 kHz	Left	57.95	23.75
ASSR	1 kHz	Left	68.86	22.38
CERA	1 kHz	Left	73.18	21.57
ASSRest	1 kHz	Left	61.48	20.50
PTA	2 kHz	Left	67.04	20.21
ASSR	2 kHz	Left	78.18	17.79
CERA	2 kHz	Left	83.75	18.90
ASSRest	2 kHz	Left	68.86	17.18
PTA	3 kHz	Left	75.45	17.51
ASSR	3 kHz	Left	84.83	14.98
CERA	3 kHz	Left	90.45	15.88
ASSRest	3 kHz	Left	75.17	14.71

Figs. 8 and 9 give correlation plots between average (1-2-3 kHz) ASSR and average PTA thresholds, for the right and the left ears. In right ears, the coefficient (r) between average (1-2-3 kHz) ASSR and PTA thresholds is 0.86 (p < 0.00001). The average PTA threshold is always lower (better) or equal to the average ASSR threshold. In left ears, r = 0.87 (p < 0.00001). The average PTA threshold is lower (better) or equal to the average ASSR threshold, except in four cases, where the PTA threshold exceeds the ASSR threshold by 2, 3 or 4 dB. When right and left ears are averaged, the PTA threshold exceeds the ASSR threshold only in a single subject (by 1.67 dB).

The global correlation coefficients (right and left; 1-2-3 kHz) between PTA and CERA, between PTA and ASSR and between CERA and ASSR are 0.71, 0.82 and 0.64 respectively (p always < 0.01). The correlation between PTA and ASSR (0.82) is significantly stronger (p = 0.002) than that between PTA and CERA (0.71).

The average difference scores (ASSR - PTA) are 13.01 (SD 10.19) dB for 1 kHz, 12.72 (SD 8.81) dB for 2 kHz and 10.38 (SD 8.19) dB for 3 kHz.

The average difference scores (ASSR − PTA) are plotted against the frequency (4 kHz was added) in Fig. 10. ANOVA shows a global significant difference among frequencies (p = 0.03). This difference is due to a significant difference between 3 kHz and 1 kHz (p = 0.01) and between 3 kHz and 2 kHz (p = 0.02). However, the global correlation coefficient r = - 0.09 is not significant.

The possibility of a correlation between the difference scores (ASSR − PTA) for 1, 2 and 3 kHz and the global hearing loss (mean PTA on 1, 2 and 3 kHz) was also examined (Fig. 11). All correlation coefficients (−0.29, −0.32 and −0.31 respectively) are significant (p < 0.05), although weak. When degrees of hearing loss and difference scores (ASSR − PTA) are considered separately, it appears that (1) the difference score (ASSR − PTA) for 1 kHz negatively correlates with the 1 kHz PTA threshold (mean of right and left ears) (r = −0.35; p = 0.02); (2) the difference score (ASSR − PTA) for 2 kHz negatively correlates with the 2 kHz PTA threshold (mean of right and left ears) (r = −0.57; p = 0.00004) and (3) the difference score (ASSR − PTA) for 3 kHz negatively correlates with the 3 kHz PTA threshold (mean of right and left ears) (r = −0.59; p = 0.00003). All difference scores thus decrease with the degree of hearing loss, particularly at higher frequencies.

As to the 'estimated' true threshold according to the correction proposed by the manufacturer, it globally appears to be slightly worse than the actual PTA threshold. The average 'estimated' threshold (1, 2, 3 kHz; right and left) (67.85 dB$_{HL}$ SD 12.38)
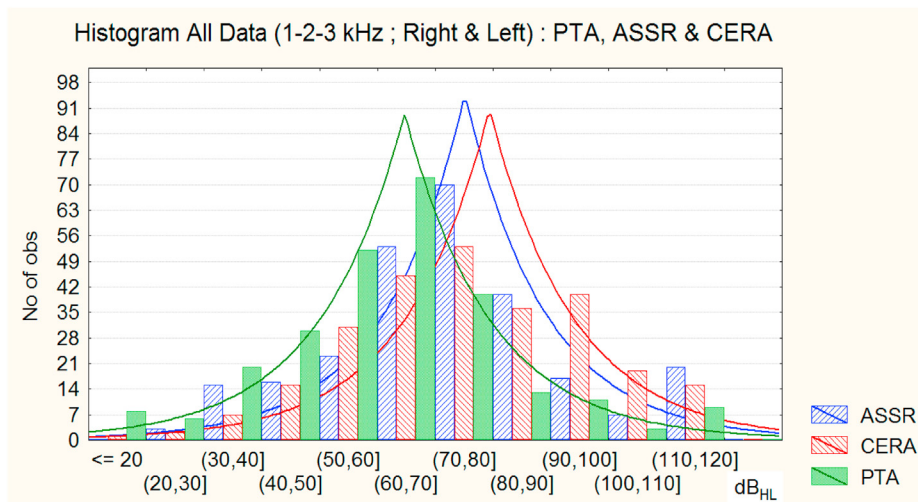
Fig. 5. Triple histogram of all data (1-2-3 kHz; Right and Left): PTA, ASSR and CERA. Global mean values are 65.68 dB$_{HL}$ (SD 20.83) for PTA, 75.10 dB$_{nHL}$ (SD 19.67) for ASSR and 79.35 dB$_{nHL}$ (SD 20.56) for CERA. ASSR thresholds are lower (= better) than CERA thresholds (p = 0.000073), and PTA thresholds are lower (= better) than ASSR thresholds (p < 0.00001).
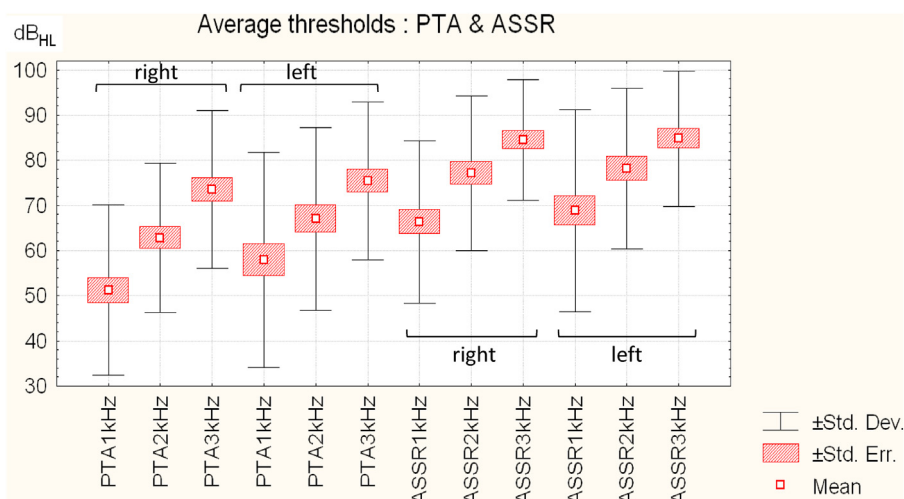
Fig. 6. Average PTA and ASSR thresholds (dB$_{nHL}$), per frequency (1-2-3 kHz) and for right and left ears separately, with SE and SD. Whatever the frequency and the side, PTA thresholds are lower (*i.e.,* better) than ASSR thresholds.

significantly exceeds the actual average PTA threshold (64.68 dB$_{HL}$ SD 13.41) (p = 0.013). The correlation between the average (1-2-3 kHz) hearing loss (right and left ears combined) as computed by PTA and by the ASSR correction algorithm is plotted in Fig. 12 (r = 0.80, p < 0.001). More specifically, in cases of moderate hearing loss, the correction algorithm (based on ASSR threshold) tends to overestimate the true threshold, while in cases of severe hearing loss, the correction algorithm tends to underestimate the true threshold.

The data of the present study further confirm the slight asymmetry of occupational NIHL on PTA in reliable subjects: the average 1-2-3 kHz threshold for the right ear is 62.54 dB$_{HL}$ (SD 19.76) and 66.82 dB$_{HL}$. NIHL is significantly more severe in the left ear (p = 0.03). (DeJonckere and Lebacq, 2021). Information about handedness is missing, but none of the 44 subjects was a hunter/shooter.

6. Discussion

Our sample is very similar to that of the previous study (in less reliable compensation claimants), it is well defined regarding age,

gender, exposure duration and degree and type of hearing loss, and it is homogeneous. This optimizes the combination of the two studies.

(1) ASSR and CERA thresholds

As to the two objective approaches, the results of the present study are in line with our previous findings in less reliable subjects showing comparable NIHL. In the latter, CERA thresholds exceeded ASSR thresholds on average by 2.35 dB at 1 kHz, by 5.31 dB and by 6.81 dB at 3 kHz (DeJonckere et al., 2021).

A discussion about the relationship between CERA and ASSR thresholds and a literature review are to be found in our previous article (DeJonckere et al., 2021).

(2) Behavioral (PTA) and ASSR thresholds

Contrary to the case of our previous work, the PTA thresholds (PTA) can now serve as the reference. The average difference scores (ASSR - PTA) are 13.01 (SD 10.19) dB for 1 kHz, 12.72 (SD 8.81) dB for 2 kHz and 10.38 (SD 8.19) dB for 3 kHz.
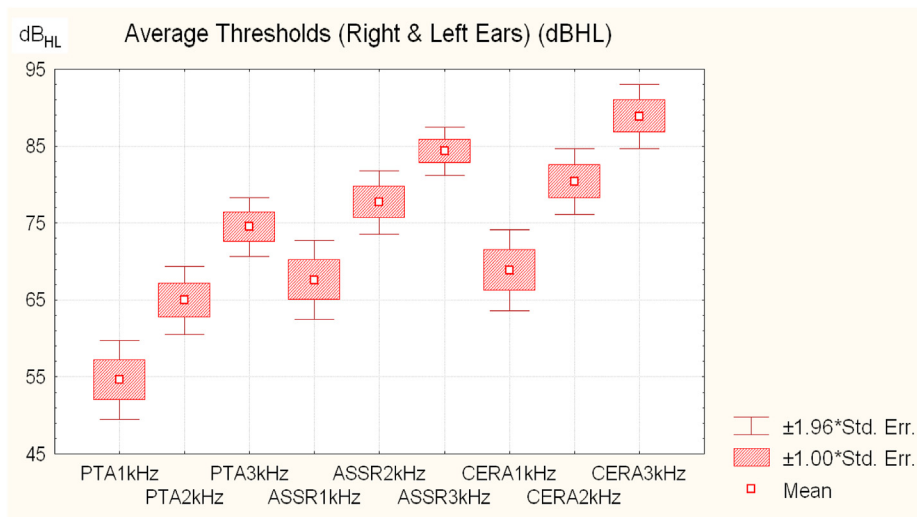
Fig. 7. Average PTA, ASSR and CERA thresholds (dB $_{HL/nHL}$) per frequency (right and left ears combined) with SE.
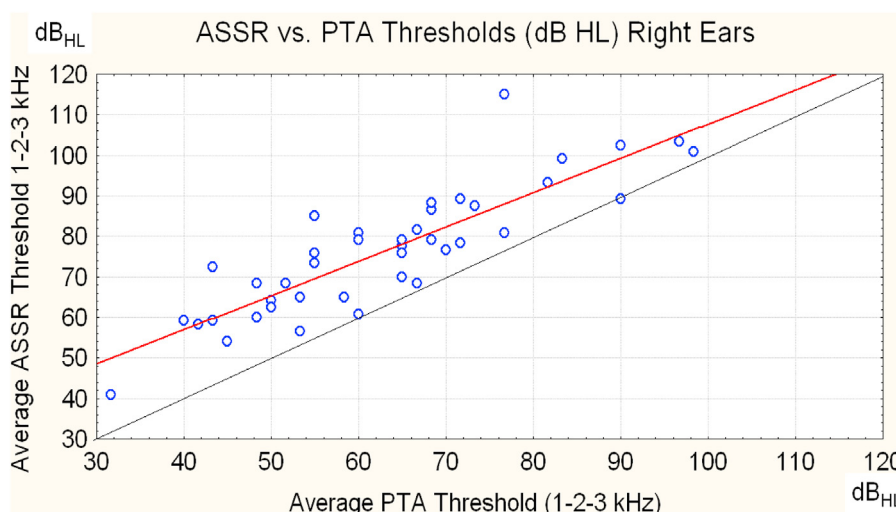

Fig. 8. Correlation between average (1-2-3 kHz) ASSR and PTA thresholds (r = 0.86; p < 0.00001) (Right ears). The average PTA threshold is always lower (better) or equal to the average ASSR threshold.

Van Maanen and Stapells (2005) used tones modulated in amplitude and frequency, as in the present study. The smallest difference between electrophysiological and PTA thresholds was observed using multiple 40 Hz-ASSRs. They recorded a mean (0.5-1-2 kHz) difference score of 12.1 dB between 40 Hz-ASSR scores and behavioral thresholds, and the difference score between CERA and behavioral thresholds amounted to 20.8 dB. Accordingly, these authors concluded that in adults, thresholds were best evaluated by the 40-Hz ASSR method.

Moreover, we found that all difference scores (ASSR - PTA) decrease with the degree of hearing loss, particularly at higher frequencies.

Indeed, after Picton et al., 2005, who applied ASSR frequencies modulated between 78 and 95 Hz, it is admitted that thresholds measured electrophysiologically are usually nearer to those obtained by behavioral methods in patients with sensorineural hearing loss than in normal subjects. Electrophysiological thresholds are almost identical to behavioral ones around 90 dB$_{HL}$ but they tend to be about 30 dB larger near 0 dB$_{HL}$. In regression analysis, the Y-intercepts show that in subjects with normal hearing, whose thresholds are around 10 dB$_{HL}$, in the lower frequencies,

ASSR thresholds are larger than behavioral ones by up to 40 dB, while they are nearer to behavioral ones in higher frequencies (Dimitrijevic and Cone, 2015).

This is in line with Aoyagi et al., 1993, who found, in normally hearing adults (N = 15), that 40 Hz-ASSRs values were higher than pure tone thresholds by 11–18 dB larger compared to 8–13 dB higher in deficient subjects (N = 18).

In hearing-impaired teenagers, ASSR and behavioral pure tone thresholds differed, on the average, by 5–13 dB (ASSRs using frequencies of 1000, 2000 and 4000 Hz) (Lins et al., 1996; Dimitrijevic et al., 2002).

Using modulation frequency at 90 Hz, Luts and Wouters (2005) found (ASSR − PTA) difference scores of 14 (±8) dB at 1 kHz), 16 (±7) dB at 2 kHz and 21 dB (±11) at 4 kHz (10 hearing deficient and 10 normal subjects).

Tlumak et al., 2007 reported, in a meta-analysis, mean differences (ASSR - PTA) thresholds of 11.14 dB at 1 kHz, 11.98 dB at 2 kHz and 8.73 dB at 4 kHz for hearing-deficient adults.

In their report, Mühler et al., 2012 found threshold differences (ASSR-PTA) of 8.1±8.6 dB at 1 kHz, 12.0±7.8 dB at 2 kHz and 10.9±9.8 dB at 4 kHz in impaired subjects (n = 16).
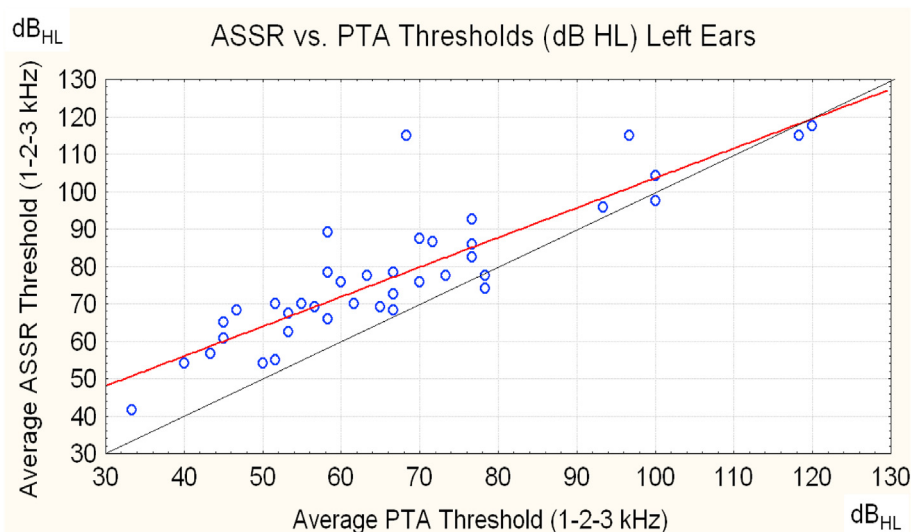
Fig. 9. Correlation between average (1-2-3 kHz) ASSR and average PTA thresholds (r = 0.87; p < 0.00001) (Left ears). The average PTA threshold is lower (better) or equal to the average ASSR threshold, except in four cases, where the PTA threshold exceeds the ASSR threshold by 2, 3 or 4 dB. When the right and left ears are averaged, the PTA threshold exceeds the ASSR threshold only in one single case (by 1.67 dB).
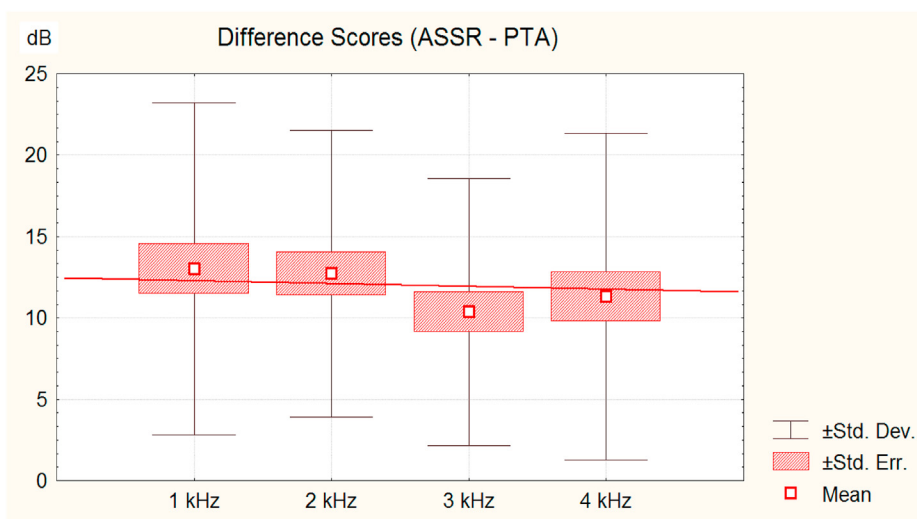
Fig. 10. Average difference scores (ASSR − PTA) for 1, 2, 3 and 4 kHz. ANOVA shows a global significant difference among frequencies (p = 0.03). This difference is due to a significant difference between 3 kHz and 1 kHz (p = 0.01) and between 3 kHz and 2 kHz (p = 0.02). However, the global correlation coefficient r = - 0.09 is not significant.

Recently, Swami and Kumar (2019) (modulation frequency 80−100 Hz) reported that − in a group of 25 cases of sensorineural hearing loss − ASSR consistently detected thresholds at about 10 dB higher than that of PTA. Difference scores (ASSR − PTA) were 10.0, 9.6 and 10.2 dB (1, 2 and 4 kHz respectively) for the right ears, and 9.7, 10.0 and 10.0 dB (1, 2 and 4 kHz respectively) for the left ears.

(3) The correction factor applied by the manufacturer's program

The 'corrected' threshold strongly correlates with the actual PTA threshold (r = 0.80), but globally it appears to be slightly but significantly worse than the actual PTA threshold (by 3.17 dB$_{HL}$ in average). More specifically, as shown in Fig. 12, in cases of moderate hearing loss, the correction algorithm (based on ASSR threshold) tends to overestimate the true threshold, while in cases of severe hearing loss, the correction algorithm tends to underestimate the true threshold. However, globally, the correction applied for 1, 2 and 4 kHz (5 or 10 dB depending on frequency and hearing loss) seems acceptable and is not exaggerated.

(4) The right − left asymmetry

In another study (DeJonckere and Lebacq, 2021), we looked for and discussed the right - left asymmetry in subjects with moderate to severe occupational NIHL. The data were ASSR and CERA thresholds, as our subjects were suspected of exaggerating their loss. Our study confirms this slight asymmetry on PTA in reliable subjects: the average 1-2-3 kHz threshold for the right ear is 62.54 dB$_{HL}$ (SD 19.76) and 66.82 dB$_{HL}$ (SD 21.71). NIHL is significantly more severe in the left ear (p = 0.03).
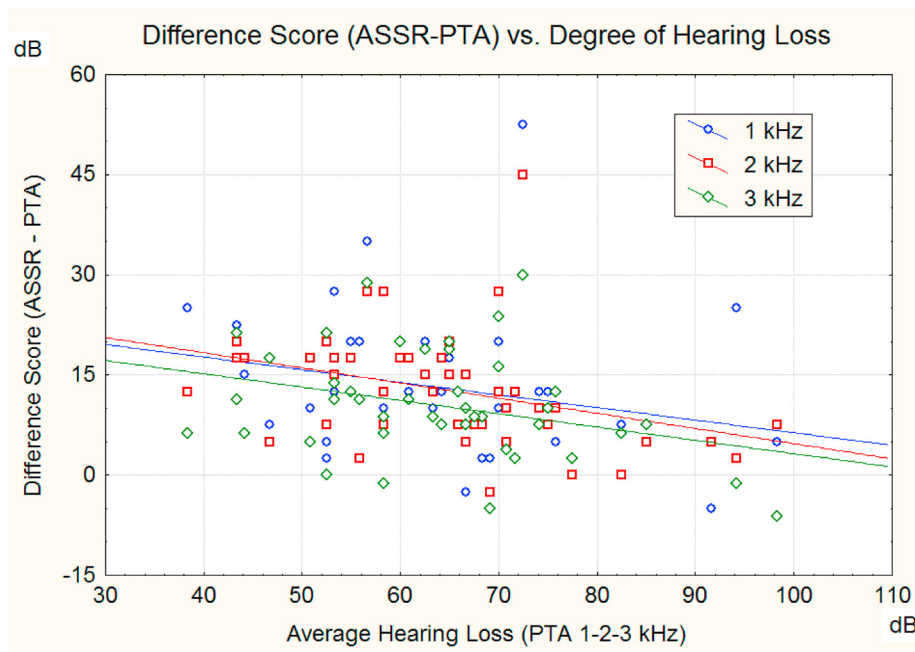
Fig. 11. Correlation between the difference scores (ASSR − PTA) for 1, 2 and 3 kHz and the average hearing loss (mean PTA on 1, 2 and 3 kHz). All correlation coefficients (−0.29, −0.32 and −0.31 respectively are significant p < 0.05). The difference score (ASSR − PTA) for 1 kHz negatively correlates with the 1 kHz PTA threshold (mean of right and left ears) (r = −0.35; p = 0.02). The difference score (ASSR − PTA) for 2 kHz negatively correlates with the 2 kHz PTA threshold (mean of right and left ears) (r = −0.57; p = 0.00004). The difference score (ASSR − PTA) for 3 kHz negatively correlates with the 3 kHz PTA threshold (mean of right and left ears) (r = −0.59; p = 0.00003).
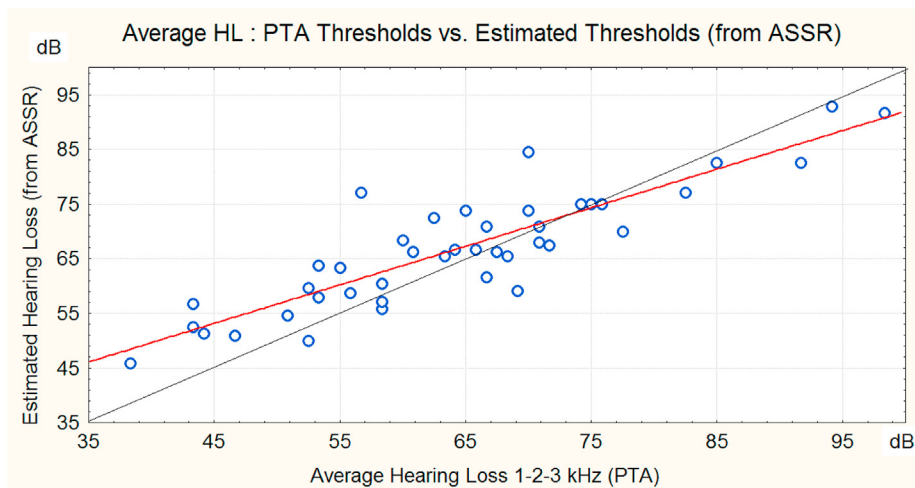
Fig. 12. Correlation between the average (1-2-3 kHz) hearing loss (right and left ears combined) as computed by PTA and by the ASSR correction algorithm. In cases of moderate hearing loss, the correction algorithm (based on ASSR threshold) tends to overestimate the true threshold, while in cases of severe hearing loss, the correction algorithm tends to underestimate the true threshold.

7. Conclusion

The 40 Hz binaural multiple ASSR method is useful in audiological medico-legal evaluations of frequency specific hearing thresholds in adults applying for a benefit related to occupational NIHL, when behavioral audiometric investigation is not reliable. This approach is indeed well tolerated by patients, and it is totally noninvasive.

In reliable adult subjects with moderate to severe occupational NIHL, PTA, ASSR and CERA thresholds correlate with each other: The global correlation coefficients (right and left; 1-2-3 kHz) between PTA and CERA, between PTA and ASSR and between CERA and ASSR are 0.71, 0.82 and 0.64 respectively (p always < 0.001).

The correlation between PTA and ASSR (r = 0.82) is significantly stronger (p = 0.002) than that between PTA and CERA.

However, ASSR thresholds are on average significantly lower (better) than CERA thresholds, and PTA thresholds are on average significantly lower (better) than ASSR thresholds (p < 0.00001). In a given subject, individual PTA thresholds are practically always lower (*i.e.* better) than ASSR thresholds, whatever the frequency (1-2-3 kHz) and the side (right − left).

No correlation is observed between the average difference score (ASSR − PTA) and the frequency (1-2-3-4 kHz), but a significant negative correlation is found between the difference score (ASSR − PTA) and the extent of hearing loss.

This study also confirms that moderate to severe occupational NIHL is significantly more severe in the left ear than in the right ear.

Declaration of competing interest

None.

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