



## Objective frequency-specific hearing thresholds definition for medicolegal purposes in case of occupational NIHL: ASSR outperforms CERA

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### ABSTRACT

Audiological use of the 40 Hz-ASSR (auditory steady state responses) could be valuable for objectively estimating the frequency-specific threshold in adults undergoing an expertise examination for medicolegal and/or compensation purposes. The present prospective study was set up to clarify the relationship between the thresholds obtained by cortical evoked response audiometry (CERA) and by 40 Hz-ASSR, in the same ears, within a large homogeneous sample of 164 subjects (328 ears) with NIHL and well documented exposure to noise. All these subjects claimed financial compensation for occupational NIHL, and there was a suspicion of exaggeration of the reported NIHLs. ASSR thresholds show a good correlation with the CERA thresholds. However, a systematic shift is noticed, ASSR thresholds being on average (1–2–3 kHz) 4.38 dB lower (i.e. showing less hearing loss) than CERA thresholds. Moreover, the binaural multiple ASSR technique allows a considerable time gain when compared to the CERA.

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### 1. Introduction

Suspicious audiometric findings are not uncommon in a medicolegal context; in the case of an insurance system with compensation for occupational diseases, such as NIHL (noise induced hearing loss), the prospect of financial advantages may encourage to either deliberately exaggerate hearing impairment or possibly unconsciously raise response criteria (DeJonckere et al., 1992, 2000, 2009; DeJonckere and Coryn, 2000; DeJonckere and Lebacqz, 2005; DeJonckere, 2011). Specific requirements of the medicolegal context are: frequency specificity, validity and reliability of threshold values, non-invasiveness and good tolerance on the part of the subject being examined, and low sensitivity to (sedative) drugs. A 30-year experience at FEDRIS (the Federal Agency for Occupational Risks; Brussels, Belgium) with electrophysiological definition of hearing thresholds in medicolegal context corroborated our original choice for cortical evoked response audiometry (CERA): indeed, with this technique, most of the criteria are fulfilled, except the sensitivity to sedative drugs (DeJonckere et al.,

2000). In fact, CERA has two limitations: (1) the duration (hours) required to define thresholds for different frequencies in each ear and (2) the overestimation of the actual (psychophysiological) hearing thresholds: the difference scores CERA - PTA (pure tone audiometry) in (supposedly) fully reliable subjects with NIHL, are about 13, 10 and 9 dB<sub>HL</sub> for the frequencies 1, 2 and 3 kHz respectively (DeJonckere et al., 1992; Albera et al., 1991).

Auditory steady state responses (ASSRs) are electrophysiological responses to auditory stimuli presented at rates between 1 and 200 Hz or by periodic modulations (at similar rates) of the amplitude and/or frequency of a continuous ('steady state') tone. This tone is characterized by a specific frequency, the so-called carrying frequency (CF). It is possible to record auditory steady-state responses from electrodes on the scalp. The EEG signal is amplified about 80,000 times and a bandpass of 5–100 Hz is applied for filtering. The ASSR is occurring at the same rate as the modulation frequency, hence it is suited for analysis by frequency-domain methods. The spectrogram of the response will reveal a peak at the modulation frequency (Dimitrijevic and Cone, 2015). The ASSRs can be objectively detected using frequency-based analyses (Picton et al., 2003; Rance, 2008; Yüksel et al., 2020). The evidence of an ASSR depends on properly functioning both auditory peripheral structures (cochlea, auditory nerve) for the CF, and central auditory pathways (Dimitrijevic and Cone, 2015).

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In awake subjects, the ASSRs are particularly identifiable at modulation rates around 40 Hz (Picton et al., 2003). Another, less prominent peak can be recognized in the range 80–100 Hz, but at higher modulation frequencies, the response tends not to emerge above the noise floor (Purcell and Dajani, 2008). At modulation rates around 40 Hz, the response is supposed to be primarily generated at cortical level (Yüksel & al., 2020; Rance, 2008), with contributions of the brainstem, auditory midbrain, and 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). Responses to high modulation frequencies (80 Hz and above) are predominantly originating from subcortical areas, and also brainstem (Yüksel & al., 2020; Rance, 2008; Ishida and Stapells, 2012). Practically, the amplitudes of the 40 Hz-ASSRs are about two to three times larger than the amplitudes of the 80 Hz-ASSR (Ishida and Stapells, 2012; Yüksel & al., 2020); these authors considered that the modulation rate around 40 Hz seems preferable in awake adults for threshold assessment (Yüksel & al., 2020). Alertness of the subject remains an important issue: it has been observed that the amplitudes of the ASSRs were considerably reduced if patients were sleeping or sedated (Picton & al., 2003; Korczak & al., 2012).

D'haenens et al., 2008 showed that ASSR thresholds demonstrate excellent test-retest reliability for all frequencies (0.5, 1, 2, 4 kHz).

Our purpose is not to perform an exhaustive review of the abundant ASSR literature; we focus on articles by authors who used a system or method that is comparable to that used in this study (preferably 40 Hz ASSR/1–2–4 kHz), and who investigated the correlation between ASSRs and CERA or behavioral thresholds.

An important specificity of ASSR consists in the possibility to test different frequencies simultaneously at the same ear by presenting each single CF (0.5, 1, 2 and 4 kHz) at a slightly different modulation rate, centered around 40 Hz, e.g. 39.06, 40.62, 42.19 and 45.31 Hz. These 4 stimuli elicit responses that can be separated in the spectral analysis of the EEG, making it possible to assign each response to the correct test frequency (Mühler et al., 2012; Yüksel & al., 2020). Similarly, both ears can even be tested simultaneously. However, using multiple stimuli simultaneously results in reducing the amplitudes for the 40 Hz-ASSR (Ishida and Stapells, 2012; Yüksel & al., 2020).

Several studies dealt with comparing the two techniques (single and multiple) in patients with sensorineural hearing loss (Luts and Wouters, 2005; Korczak & al. 2012): these investigators reported non-significant differences as to the ASSR thresholds. Herdman and Stapells (2001) demonstrated minimal differences across frequencies (0.5, 1, 2, 4 kHz) between the monaural and the binaural ASSR test conditions. Obviously, the multifrequency and binaural ASSR technique allows considerable shortening of the process.

As to the correspondence with behavioral thresholds, Herdman and Stapells (2003) observed that in adults with mild to profound hearing losses, the multifrequency ASSR (amplitude modulated 77–105 Hz) method provides a correct estimate of both configuration and degree of the hearing loss. Specifically, these authors found significant correlations (correlation coefficient 0.75 to 0.89) between ASSR thresholds for frequencies from 500 to 4000 Hz and pure tone behavioral thresholds. In hearing impaired patients, the ASSR thresholds obtained with the multifrequency technique were, at pure tone frequencies of 1, 2 and 4 kHz, within 20 dB of the corresponding behavioral thresholds in 93, 93 and 100% of the cases. The configuration of the sensorineural hearing loss (steep slope vs. flat/shallow) had a negligible effect on the accuracy of the ASSR threshold prediction.

As to the specific relationship between ASSR and behavioral thresholds, Luts and Wouters (2005) (using the 'Master' system

with modulation frequency 90 Hz) reported difference scores (ASSR – PTA: ASSR thresholds being higher than PTA thresholds in cooperating subjects) of 12 (SD 8), 17 (SD 8) and 19 (SD 12) dB (10 hearing impaired subjects). Petitot et al. (2005) confirmed that ASSRs overestimate the behavioral thresholds, but pointed out that those obtained with 40 Hz modulation are closer to behavioral thresholds than those obtained with 80 Hz. Rance et al. (1995) noted that average differences between thresholds decrease (i.e., ASSR thresholds become closer to behavioral thresholds) when the hearing loss is more severe and when higher frequencies are tested.

In the past two decades, the primary clinical application of ASSR has been the hearing assessment of infants and children (Dimitrijevic and Cone, 2005). The low frequency range (500 Hz) can also be explored with ASSR (Frank et al., 2017). However, audiological use of the 40 Hz-ASSR could also be of interest for expert assessments in adults undergoing assessment in a medicolegal context or for compensation purposes (Yüksel & al., 2020) (11 subjects).

As specifically to the relation between ASSR and CERA thresholds, the data are controversial: Van Maanen and Stapells (2005) reported that 40 Hz-ASSRs showed lower (i.e. better) thresholds, thus closer to the behavioral thresholds, than the slow cortical potentials (2 groups of 23 subjects), while Tomlin et al., 2006 concluded that, at 4000 Hz, cortical evoked potentials were typically recorded at levels closer to the behavioral threshold than 40 Hz-ASSRs (30 subjects). Yeung and Wong (2007) noted that, even though pure tone thresholds seem defined slightly more accurately by CERA than by ASSRs (63 ears), the difference may not be clinically important.

Hence, the present prospective study was set up to clarify this relation between the thresholds obtained by the two electrophysiological methods, as well as to implement the use of ASSR for medicolegal purposes in subjects with NIHL. The study covers the period: 2016–2019, and aims at comparing the CERA and ASSR hearing thresholds in the same ears, within in a large, homogeneous sample of 164 subjects (328 ears) with NIHL and well: documented exposure to noise. All of the subjects were claiming compensation for occupational NIHL, but with a suspicion of exaggeration of the reported NIHL.

## 2. Material & methods

### 2.1. Design & protocol

164 successive claimants for compensation at the Federal Agency for Occupational Diseases (FEDRIS, Brussels) and fitting our inclusion criteria were included in the present prospective study, running over 52 months. In all cases, the occupational career was checked by the Engineering Dept. of FEDRIS prior to medical examination in order to reasonably accept a noise exposure of at least one year to at least 85 dB<sub>A</sub> (Time Weighted Average, i.e.  $L_{EX,8h}$  = or >85 dB<sub>A</sub>), according to the European Directive on health and safety requirements regarding the exposure of workers to noise. (17th Directive according to Article 16 (1) of Directive 89 391/EEC). Possible use of individual hearing protection was not taken into account. The duration of noise exposure, as considered in this study, was obtained by a combined critical review of the complete subject's career (as provided by the Crossroads Bank for Social Security) and the report of the engineering Dept. The latter does not necessarily cover the entire career, provided that the last/current employment is considered sufficient to account for significant NIHL.

The Belgian scale for compensation of NIHL considers an average of the air conduction thresholds on 1, 2 and 3 kHz at the best ear, taking into account a weighting (5/6 best ear – 1/6 worse ear) in cases of asymmetry. The main criterion for inclusion in the present

study was a suspicion of exaggeration of the reported NIHL, resting on a significant worsening ( $\geq 5$  dB in average at the best ear) of the thresholds obtained in Pure Tone Audiometry (PTA) during the medical-forensic expert assessment at FEDRIS (labelled PTA1 in the current study), compared to those of the audiogram provided by the claimant together with his/her application form. The underlying rationale is that the PTA at FEDRIS is performed in optimal conditions, i.e. with a regularly calibrated clinical audiometer, a large soundproof double-walled booth designed for evoked potentials, by a team of highly experienced audiologists and several test-retests without any time constraint. Furthermore, in the vast majority of cases, a significant temporary threshold shift (TTS) is practically ruled out, as the time interval since the last potential exposure to occupational noise always exceeds 15 h. The common rule is that the PTA-thresholds measured at FEDRIS are found slightly lower (better) than those obtained either in an environment of occupational medicine, or in an ENT-outpatient clinic. In the case of such a discrepancy, the patient was given a new appointment, usually a few weeks later, for another PTA (labelled PTA2 in the present study) followed by an electrophysiological assessment, consisting in both a CERA and an ASSR definition of hearing thresholds. The examination was completed – both the first and the second time – by a tympanometry, a recording of the acoustic stapedial reflexes, and when relevant and possible, Békésy-audiometry and prosthetic audiometry. As a rule, for each worker's visit at FEDRIS, the claimant's travelling expenses are reimbursed and the employer is compensated for the lost working day. All subjects received adequate information about the different examination procedures. No subject refused the examinations. In a medicolegal context, any invasive examination is clearly ruled out.

Prior to any investigation, each subject underwent a bilateral otoscopy to rule out ear wax or any foreign object. Further exclusion criteria were middle ear pathology and conductive hearing loss (either uni- or bilateral), poor health, cognitive impairment or important difficulties in communicating due to language problems. Referring to our previous study (Dejonckere & al., 2000), that dealt with influence of neuroleptic, sedative, hypnotic drugs on CERA, the subjects were systematically asked about their drug use. Those who reported use of such drugs were excluded from this study, but there was no possibility of control. However, arousal was permanently controlled during the whole duration of the exam.

Age, gender and duration of exposure were systematically registered.

In the case of no measurable threshold, whatever the method, (i.e. no response at maximal level of stimulus) the threshold was considered to be 120 dB<sub>HL</sub>. For ASSR, only octave frequencies are available, i.e., 0.500, 1, 2 and 4 kHz (pure tone). The 0.5 kHz frequency is not considered in the current study, as it is not relevant for the Belgian compensation scale for occupational NIHL. For 3 kHz, the arithmetical mean between the thresholds at 2 and 4 kHz was considered for computations.

## 2.2. Material

For conventional audiometric procedures including PTA 125–8000 Hz, air and bone conduction with masking when relevant and test-retest: a Madsen Orbiter 922 (until mid- 2017), and a Madsen Astera<sup>2</sup> (Natus Medical Denmark) (from mid-2017 on) were used.

For impedance audiometry including tympanogram and definition of acoustic-stapedial reflex thresholds at 0.500, 1, 2 and 4 kHz: we used a Grason Stadler GSI Tymstar Middle Ear Analyzer (ViaSys Healthcare, Madison, USA).

For CERA we used a Bio-Logic Navigator PRO system (from Bio-logic Systems Corp) (Stimulus 50 ms tone-burst, 1/s; filtering:

0,1–10 Hz; analysis epoch: 600 ms; # stimuli: 50 to 250). ASSRs were obtained with the *Neuro-Audio.Net* system from Neurosoft Ltd. Stimuli are pure tones (0,5–4 kHz) 100% amplitude and 10% frequency modulated (modulation frequency around 46 Hz).

For electrophysiological testing, the subject was lying on an examination couch, in a relaxed position, with the head resting on a pillow, and remained awake for the whole duration of the electrophysiological testing. Impedance checks were completed for all electrodes (<5 k $\Omega$ ). The audiologist was sitting beside the subject, inside the sound-proof booth, operating the computer and continually controlled the arousal.

CERA responses were recorded four times at each intensity level (Fig. 1). Similarly to our previous work (Dejonckere et al., 1992; 2000), the criterion for defining a CERA threshold was the lowest stimulus intensity (in dB<sub>HL</sub>, steps of 5 dB) evoking an unequivocal averaged response, i.e. the expected pattern P1–P2–N2 clearly identified when superimposing four displayed averaged CERA tracings obtained with identical stimulations [amplitude 2–10  $\mu$ V; P1 (50–80 ms); P2 (150–200 ms); N2 (180–300 ms)].

Conventional as well as electrophysiological audiometric procedures were performed in a sound-proof double-walled booth (background noise measured inside 27 dB<sub>A</sub>), also operating as a Faraday cage. Acoustic stimuli were provided to the subject via two TDH-39 headphones.

## 3. Results

The subjects were in overwhelming majority males (155/164) (328 ears in total).

Fig. 2 shows the histogram of ages. The main age category is 55–70 years.

The main duration of exposure ranges between 25 and 40 years, although with a broad dispersion, as can be seen in the histogram of Fig. 3.

Four thresholds for 1, 2 and 3 kHz at each ear were compared (Figs. 4–6):

PTA1 (threshold obtained during the first medical-forensic expert assessment at FEDRIS), PTA2 (threshold obtained during the second medical-forensic expertise at FEDRIS, a few weeks later), CERA (threshold obtained during the second medical-forensic expertise at FEDRIS using cortical evoked response audiometry) and ASSR (measured ASSR thresholds).

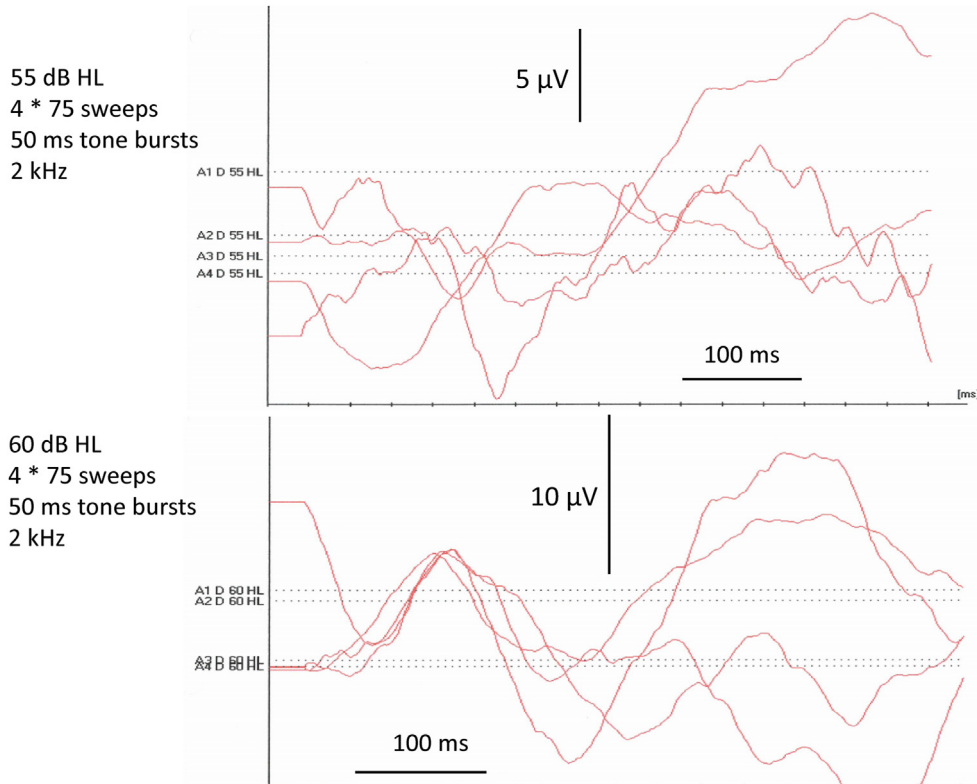
The mean (with SD) values of the thresholds (in dB HL) per ear, per method and per frequency are given in Table 1:

In Fig. 7, the average threshold (1–2–3 kHz) per subject (N = 164) is plotted across the four different approaches (mean values and Standard Errors of the mean), with the statistical comparisons (Student's *t*-Test for dependent samples).

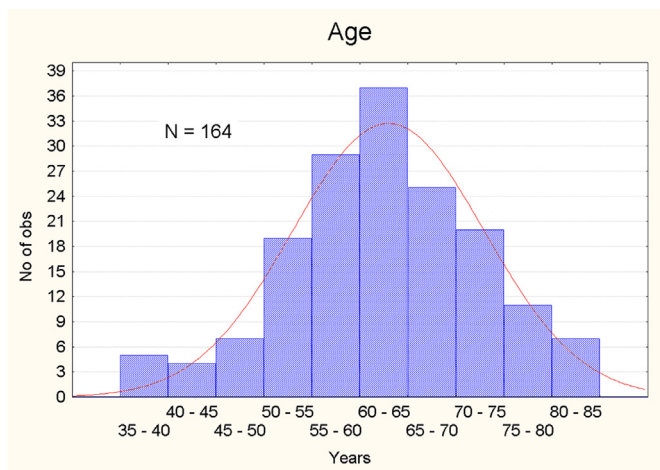
The difference scores with the SD (in dB<sub>HL</sub>) for the average 1–2–3 kHz thresholds across the methods are given in Table 2: The mean (CERA-ASSR) difference is the most relevant information: the current study primarily deals with a comparison between CERA and ASSR in medicolegal context (i.e. for defining physical impairment), and in this context each ear is considered separately, as the percentage of impairment is primarily based on the best ear. The mean difference score is computed for each of the 328 investigated ears.

CERA thresholds exceed ASSR thresholds, and the difference depends on frequency: on average by 2.35 dB at 1 kHz, by 5.31 dB at 2 kHz and by 6.81 dB at 3 kHz.

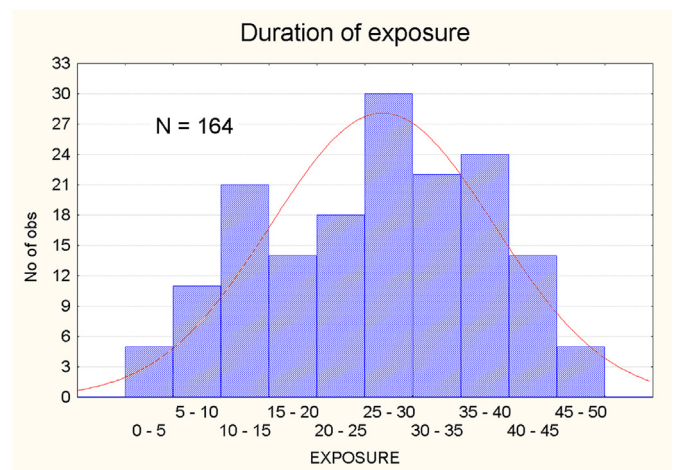
Pearson's correlation coefficients between CERA and ASST thresholds are 0.72, 0.68 and 0.63 for 1, 2 and 3 kHz respectively. The correlation coefficient between the ASSR and CERA average thresholds (1–2–3 kHz) is 0.76 and 0.75 for the right and left ears respectively. Scatterplots of the correlation between the average ASSR threshold and the average CERA threshold are presented in



**Fig. 1.** CERA – display, showing how threshold is defined. For each frequency (here 2 kHz) averaged CERA responses are recorded four times (in this case 4 × 75 sweeps) at each intensity level, and superimposed. In the lower tracing (60 dB HL), the expected pattern of the late potential is clearly recognized. In the upper tracing (55 dB HL), the characteristic pattern has disappeared. Hence the threshold is 60 dB HL.



**Fig. 2.** Histogram of ages. The main age category is 55–70 years.



**Fig. 3.** Duration of exposure: in the main cases, this duration ranges between 25 and 40 years, although with a broad dispersion.

Fig. 8 (right ear) and Fig. 9 (left ear). All these r-values are highly significant (N = 164; p < .001).

The Neurosoft software program also systematically and automatically indicates an ‘estimated threshold’ based on the ASSR response. As to the relation between the observed ASSR threshold and the ‘estimated’ threshold (as computed by the Neurosoft algorithm), the regression equations are:

- 1 KHz: Estimated threshold = -3.62 + 0.964 observed threshold
- 2 KHz: Estimated threshold = -2.19 + 0.927 observed threshold
- 3 KHz: Estimated threshold = -7.13 + 0.997 observed threshold

Considering our large data-set, we could easily specify the correction factor applied by the manufacturer’s program:

- 1 kHz: up to 10 dB: no correction; from 15 up to 65 dB: + 5 dB; from 70 dB on: + 10 dB
- 2 kHz: up to 15 dB: no correction; from 20 up to 55 dB: + 5 dB; from 60 dB on: + 10 dB
- 4 kHz: from 20 dB on: + 10 dB.

The mean ‘estimated thresholds’ (and S.D.) were 55.55 (S.D.



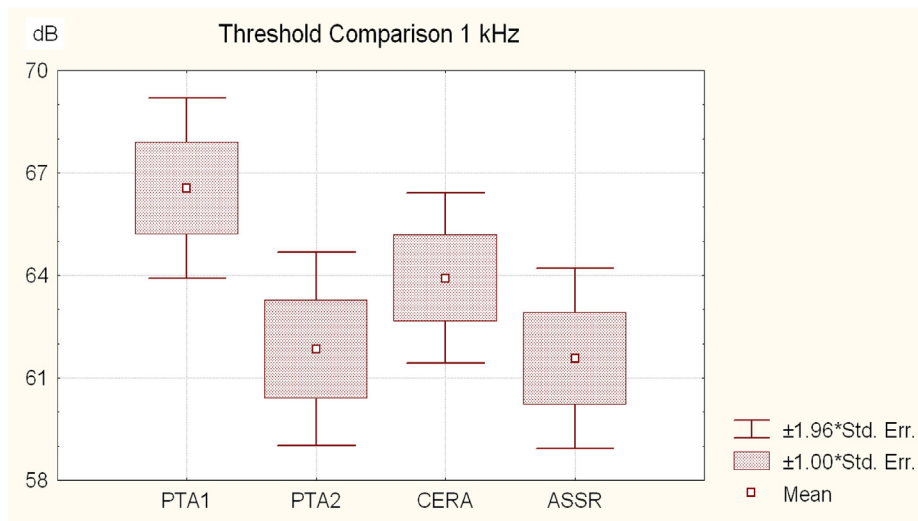


Fig. 4. Average thresholds ( $\pm 1$  and 1.96 standard error of the mean) on 1 kHz obtained by PTA1, PTA2, CERA and ASSR (measured threshold).

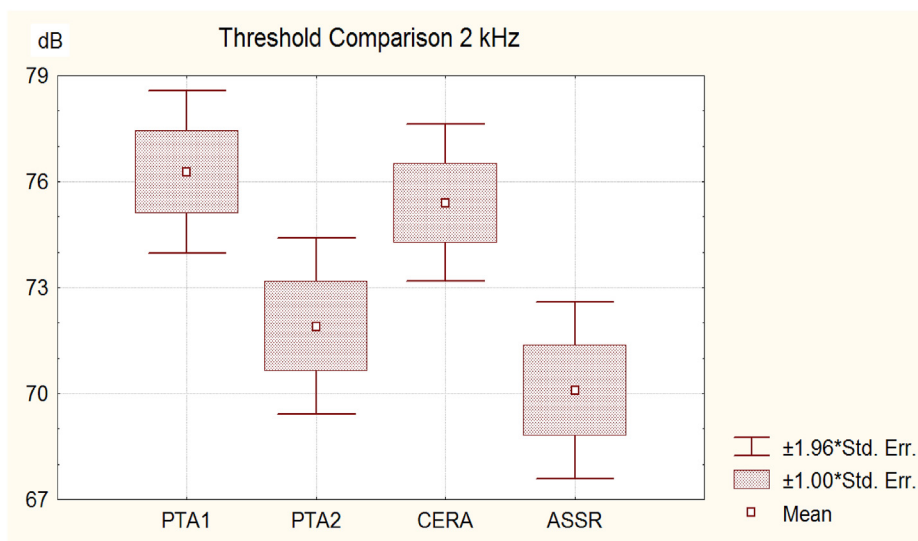


Fig. 5. Average thresholds ( $\pm 1$  and 1.96 standard error of the mean) on 2 kHz obtained by PTA1, PTA2, CERA and ASSR (measured threshold).

24.54), 63.25 (S.D. 22.19) and 68.46 (S.D. 21.06) dB<sub>HL</sub> for 1, 2 and 3 kHz respectively. The mean difference score (ASSR – ASSR<sub>est</sub>) was 7.03 ( $\pm 2.28$ ) dB<sub>HL</sub>.

The duration of a complete ASSR procedure was not systematically registered. However, ASSRs are still in daily use and without any change in the protocol. The duration is (except in a few cases) between 40 and 75 min with a reasonably estimated median of 60 min.

#### 4. Discussion

Our sample is homogeneous, well characterized and by far larger than the previously published series.

##### 4.1. ASSR and CERA thresholds

CERA thresholds exceed ASSR thresholds, and the difference score increases with frequency. The global mean difference CERA – ASSR (4.38 dB<sub>HL</sub>) is of major importance for the insurance system, as it corresponds to the difference in physical impairment, which is

directly related to the permanent financial compensation.

This is in line with the findings of Van Maanen and Stapells (2005), who compared 40 Hz-ASSRs, 80 Hz-ASSRs, and slow cortical potentials (N1/P2) in adults with either normal hearing or sensory/neural hearing loss (2 groups of 23 subjects each, and 3 normal subjects in each group). They used amplitude- and frequency-modulated tones, as in the present study. They found an average (0.5-1-2 kHz) difference score of 8.7 dB<sub>HL</sub> between CERA thresholds and 40 Hz-ASSR scores, the ASSRs showing better (lower) thresholds, i.e. closer to the behavioral thresholds. This is slightly more than our findings, but the frequencies considered are different.

On the contrary, Yeung and Wong (2007), testing 63 ears with ASSR (modulated tones 40 Hz) and CERA, concluded that the differences between pure tone thresholds and CERA thresholds were smaller than those between pure tone thresholds and ASSR thresholds. However, they noted that even though CERA seems to define pure tone thresholds with slightly more accuracy than ASSR (63 ears), the difference may not be of clinical significance.

Tomlin & al. (2006) compared 40 Hz-ASSR thresholds with CERA

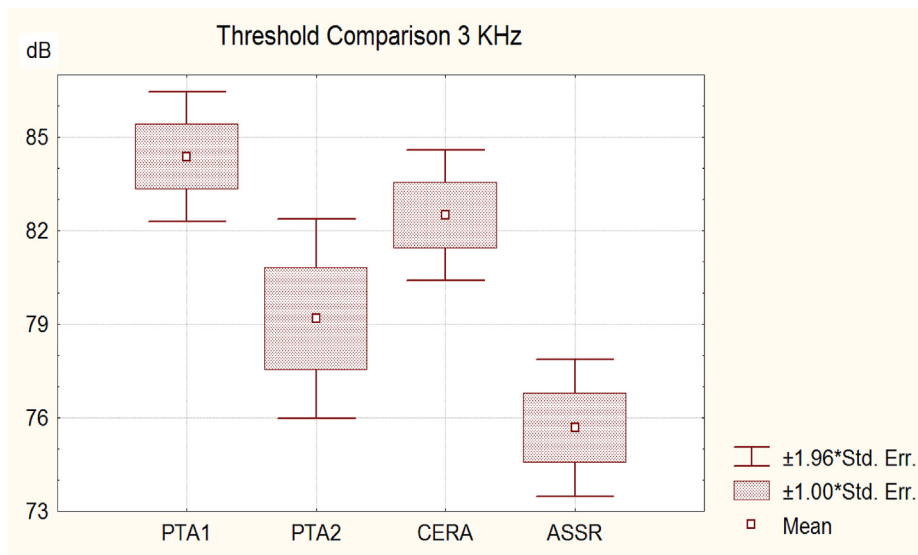


Fig. 6. Average thresholds ( ±1 and 1.96 standard error of the mean) on 3 kHz obtained by PTA1, PTA2, CERA, and ASSR (measured threshold).

Table 1

Mean values (with SD) values of the thresholds (in dB<sub>HL</sub>) per ear, per method and per frequency.

Method/Frequency	Mean Threshold Right in dB ( ±1 S.D.)	Mean Threshold Left in dB ( ±1 S.D.)
PTA1 1 kHz	64.94 ( ±22.14)	68.17 ( ±26.51)
PTA1 2 kHz	74.63 ( ±19.85)	77.93 ( ±22.58)
PTA1 3 kHz	83.11 ( ±18.09)	85.64 ( ±20.12)
PTA2 1 kHz	60.24 ( ±24.72)	63.44 ( ±27.37)
PTA2 2 kHz	70.98 ( ±22.52)	72.83 ( ±23.54)
PTA3 3 kHz	79.18 ( ±20.95)	80.24 ( ±21.77)
CERA 1 kHz	63.96 ( ±22.79)	68.87 ( ±23.43)
CERA 2 kHz	75.52 ( ±20.69)	80.27 ( ±20.39)
CERA 3 kHz	83.03 ( ±20.78)	86.95 ( ±18.01)
ASSR 1 kHz	60.43 ( ±24.73)	62.71 ( ±24.16)
ASSR 2 kHz	69.05 ( ±24.53)	71.13 ( ±21.65)
ASSR 3 kHz	75.35 ( ±21.44)	77.71 ( ±18.73)

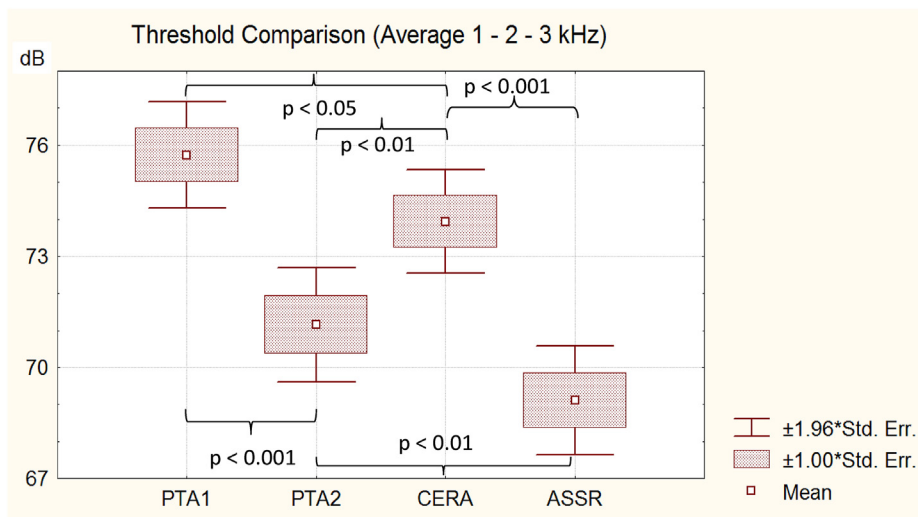


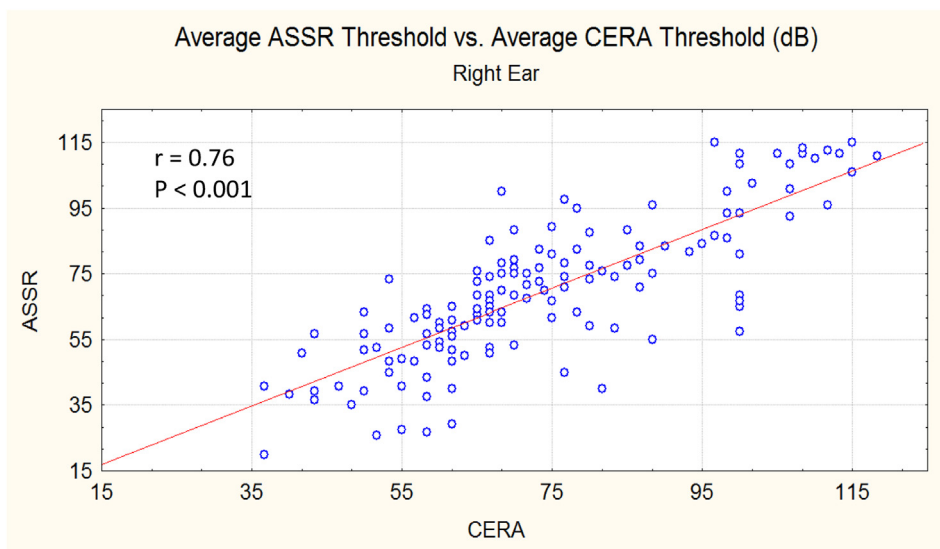
Fig. 7. Average values ( ±1 and 1.96 standard error of the mean) of the mean threshold for 1, 2 and 3 kHz obtained by PTA1, PTA2, CERA and ASSR (measured threshold).

thresholds in 30 awake adult subjects with sensorineural hearing impairment: difference levels were calculated by subtracting the behavioral hearing threshold from the electrophysiological

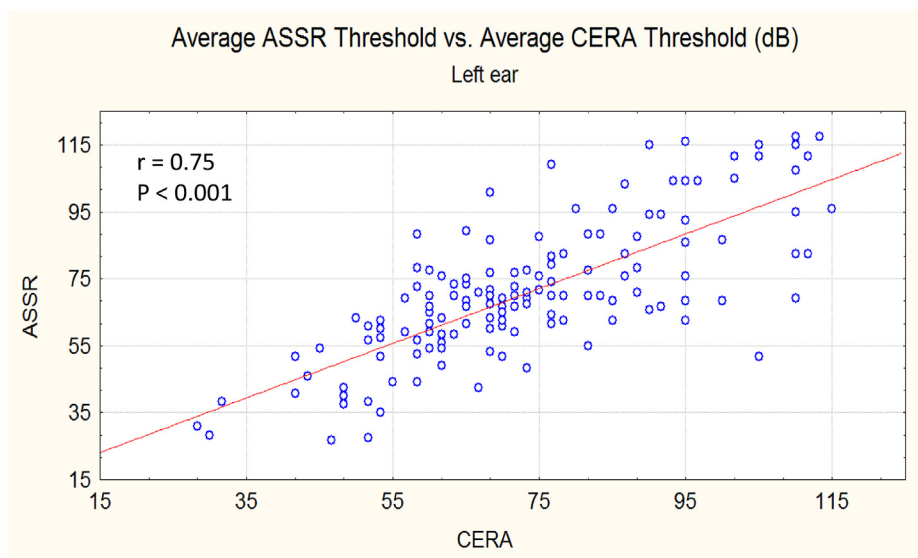
threshold. Only 500 Hz and 4000 Hz were investigated. At 4000 Hz, a difference (ASSR threshold – behavioral threshold) of about 23 dB was found, while the difference (CERA threshold – behavioral

**Table 2**  
Mean difference scores with the SD (in dB<sub>HL</sub>) for the average 1-2-3 kHz thresholds across the methods.

Difference Scores across Methods		
Method	Mean difference	Standard Deviation
PTA1 - PTA2	4.38 dB <sub>HL</sub>	16.52
CERA - PTA2	3.03 dB <sub>HL</sub>	21.61
PTA2 - ASSR	1.56 dB <sub>HL</sub>	19.20
CERA - ASSR	4.38 dB <sub>HL</sub>	16.53



**Fig. 8.** Scatterplot of the correlation between the average ASSR threshold and the average CERA threshold (1-2-3 kHz) (right ear).



**Fig. 9.** Scatterplot of the correlation between the average ASSR threshold and the average CERA threshold (1-2-3 kHz) (left ear).

threshold) was found to be about 14 dB. At 500 Hz, both differences are quite similar, around 10 dB. The authors concluded that, at 4000 Hz, cortical evoked potentials were typically recorded at levels closer to the behavioral threshold than 40 Hz-ASSRs.

The reason for the discrepancy with our results is perhaps the duration of a single ASSR recording, that ranged from 22 to 89 s. In our study, recording times were longer.

It may be expected that a longer test duration is associated with

an improvement of the signal-to-noise ratio (John et al., 1998), which will provide more accurate behavioral threshold estimates (Luts and Wouters, 2004). Frequencies were also different.

#### 4.2. ASSR thresholds and behavioral thresholds

In our study, behavioral thresholds (i.e., PTA<sub>1</sub> as well as PTA<sub>2</sub>) cannot serve as a reference, as considering our inclusion criteria,

they are suspected to be unreliable.  $PTA_2$  thresholds appear to be significantly better than  $PTA_1$ , which is understandable because the subject is aware that he is asked to return for completing the assessment by an electrophysiological investigation that does not require his cooperation. Interestingly, the  $PTA_2$ -thresholds (average 1–2–3 kHz) are significantly better (i.e., demonstrate less hearing loss) than the CERA-thresholds, but significantly worse (i.e. demonstrate more hearing loss) than the ASSR-thresholds. Nevertheless, as appears obviously in some cases, even the  $PTA_2$ -thresholds of our study may not be considered reliable. Except in the case of central neurological disease, it is assumed that an electrophysiological response to a sensory stimulus occurs for a slightly higher stimulus intensity than the true perception threshold. Hence the most plausible explanation for our results is that the ASSR thresholds better match the actual behavioral thresholds than the CERA thresholds, and this is the important point from a medicolegal point of view. Ongoing research deals with fully reliable subjects presenting NIHL.

The Van Maanen and Stapells' study (2005) reported a comparison of the three methods: the 40 Hz-ASSRs, the 80 Hz-ASSRs, and the slow cortical potentials (N1/P2) in (supposedly reliable) adults with either normal hearing or sensorineural hearing loss (2 groups of 23 subjects each, and 3 normal subjects in each group). They used amplitude- and frequency-modulated tones, as in this study. Multiple 40 Hz-ASSRs showed the smallest difference between the electrophysiological thresholds and those obtained by behavioral audiometry. They found an average (0.5–1–2 kHz) difference score of 12.1 dB<sub>HL</sub> between behavioral thresholds and 40 Hz-ASSR scores, while the difference score between behavioral thresholds and CERA thresholds appeared to be 20.8 dB<sub>HL</sub>. In addition, the recording time for the 40 Hz-ASSRs and the slow cortical potential was less than the recording time for the 80 Hz-ASSRs. The conclusion of the authors was that the 40-Hz ASSR technique is the method of choice for estimating auditory thresholds in adults.

Moreover, since Picton & al. (2005), who used modulation frequencies between 78 and 95 Hz, it is known that as a rule, electrophysiological thresholds are closer to behavioral thresholds in hearing impaired patients (sensorineural hearing loss) than in subjects with normal hearing. The electrophysiological thresholds are nearly identical to the behavioral thresholds near 90 dB but about 30 dB higher than the behavioral thresholds when these are near 0 dB<sub>HL</sub>. In regression plots, the Y-intercepts demonstrate that in normal subjects (e.g. with a threshold at 10 dB<sub>HL</sub>), the ASSR thresholds exceed the behavioral thresholds in the low frequencies by as much as 40 dB, whereas in mid and high frequencies, the ASSR thresholds more closely match the behavioral thresholds. (Dimitrijevic and Cone, 2015).

This is consistent with the previous findings of Aoyagi et al., 1993, who showed that 40 Hz-ASSRs were recorded at 11–18 dB above puretone thresholds in normal hearing adults (N = 15) and at 8–13 dB above puretone thresholds in hearing impaired adults (N = 18).

In hearing-impaired adolescents, the mean difference score between the ASSR threshold and the behavioral pure tone threshold was found to range from 5 to 13 dB (multifrequency ASSRs, frequencies 1000, 2000 and 4000 Hz) (Lins et al., 1996; Dimitrijevic et al., 2002).

Luts and Wouters (2005) (modulation frequency 90 Hz) reported difference scores (ASSR – PTA) of 14 (SD: 8) (1 kHz), 16 (SD:7) (2 kHz) and 21 (SD: 11) (4 kHz) dB (10 hearing impaired and 10 normal hearing subjects).

In a meta-analysis, Tlumak et al., 2007 reported mean differences between ASSR and behavioral thresholds – for hearing-impaired adults – of 11.14, 11.98 and 8.73 dB for 1, 2 and 4 kHz

respectively.

Mühler et al., 2012 calculated differences of  $8.1 \pm 8.6$  dB (1 kHz),  $12.0 \pm 7.8$  dB (2 kHz) and  $10.9 \pm 9.8$  dB (4 kHz) between multiple ASSR thresholds and behavioral thresholds in hearing impaired subjects (n = 16).

'Estimated' thresholds based on ASSR artificially outperform of course all other thresholds.

#### 4.3. Further comparison between CERA and ASSR: defining thresholds

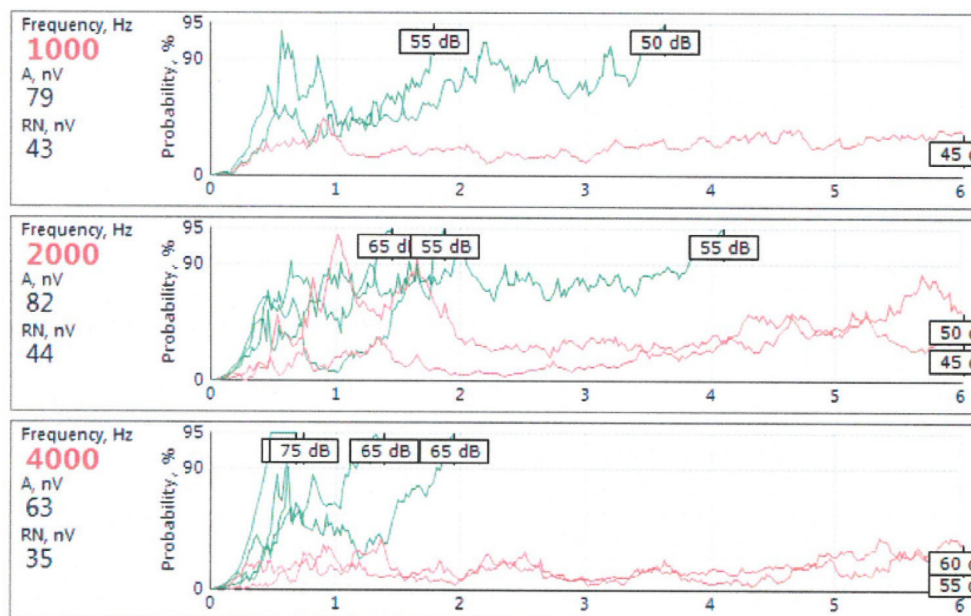
Although CERA is an objective test, the decision of the presence/absence of response remains to some extent subjective. The signal-to-noise ratio is a fundamental issue for pattern recognition and depends, near the threshold, on the artefact rejection limits and on the number of sweeps. Therefore, it is necessary, in the case of dubious responses, to continue averaging until a certain signal-to-noise ratio is attained, that makes it utterly implausible that the signal is a matter of pure coincidence. Moreover, every stimulation (i.e. at a given frequency at a given intensity for the right or left ear) was repeated four times, and the curves were superimposed, in order to maximally increase the validity of the final decision: presence or absence of a response (Dejonckere & al., 1992) (Fig. 3). This makes CERA time consuming. Our difference scores (CERA – PTA) in the control group of (supposed) reliable subjects with NIHL were 13.23, 10.02 and 9.45 dB for 1, 2 and 3 kHz respectively.

In ASSR measurements, an adaptive recording algorithm prevents such an interpretation: after the stimulation is started, the algorithm seeks for a significant response in each of the channels. As soon as the level of significance is reached, the algorithm stops the recording in this particular channel (e.g. 55 dB at 2 kHz left), whereas recording continues in the other channels. In the channel wherein a significance is reached, the stimulation automatically restarts with a 5 dB lower intensity, and the process is repeated until no significant response is obtained after 6 min (Fig. 10). The time progress of the eight channels is permanently displayed, and the system also displays an 'audiogram' indicating the different frequency specific thresholds. This process avoids any subjective interpretation. However, also in ASSRs, the residual noise is the essential factor for the quality of the results. In a restless subject, the ASSR threshold will be enhanced. The residual noise is usually around 40 nV, and the signal amplitude around 80 nV (a typical example is shown in Fig. 10). Additionally to the ASSR audiogram, 'estimated' behavioral thresholds are automatically indicated, according to an automatic computation of the software, that takes frequency and intensity into account: the 'estimated' thresholds are 0–10 dB lower (i.e. better) than the electrophysiological ASSR-thresholds. According to the literature (Picton et al., 2005), the gap decreases with intensity as well as with frequency, but the details of the computation are not supplied by the manufacturer. Therefore these 'estimated' behavioral thresholds are not considered in our study. In fact, fully reliable subjects with NIHL are necessary to adequately define potential correction factors to the electro-physiological threshold.

#### 4.4. Neurological patients

Care is to be taken with ASSRs in the case of neurological pathology: a study of Noh and Lee, 2020 demonstrated that, in patients with neurological damage, the estimated ASSR thresholds seem to be better than the PTA thresholds, and that ASSR may underestimate the severity of hearing loss. A discrepancy in hearing thresholds between PTA and ASSR was also noted by Shinn and Musiek (2007), but with different results: they found that ASSRs will overestimate the actual degree of hearing loss in patients with





**Fig. 10.** ASSR – display, showing how threshold is defined. After the stimulation has started, the algorithm seeks for a significant response in each of the channels. As soon as the level of significance is reached, the algorithm stops the recording in this particular channel (e.g. 55 dB at 2 kHz left), whereas recording continues in the other channels. In the channel wherein a significance is reached, the stimulation automatically restarts with a 5 dB lower intensity, and the process is repeated until no significant response is obtained after 6 min. Thresholds are 50 dB (1000 Hz), 55 dB (2000 Hz) and 65 dB (4000 Hz). Horizontal axis is time (minutes). A = amplitude of the signal (nV); RN = residual noise (nV).

a pathology of the central auditory nervous system. These same authors also demonstrated that ASSR and behavioral hearing thresholds exhibited wider discrepancies in case of neurological pathology (brainstem, sub-cortical, and/or cortical lesions). In our series of claimants for compensation of occupational NIHL, who all underwent a medical anamnesis and a clinical ORL-exam, no case of neurological pathology was reported or identified.

#### 4.5. Duration of the examination

The major disadvantage of the CERA is the time required for a full battery of tests: the duration of the examination was not systematically registered, but it varied widely between subjects (restlessness) and was roughly between two and 4 h, even with a trained audiologist.

In Herdman and Stapell’s study (2003), the mean total recording times for threshold estimation with multiple 80 Hz-ASSR were around 44 and 49 min for hearing-impaired subjects with steep-sloping or flat-sloping audiograms respectively. [Yeung and Wong \(2007\)](#), testing 63 ears with ASSR (modulated tones 40 Hz), found that the ASSR procedure appeared to be less time consuming than the CERA testing. [D’haenens et al., 2010](#) reported total test durations of between 43 and 46 min.

This fully fits with our own experience: between 40 and 75 min (except in a few cases) for a complete ASSR-procedure, of course using ‘multiple ASSR’ and binaural stimulations.

#### 4.6. Further studies

Further research has to deal with:

- (1) a comparison between behavioral thresholds and ASSR thresholds in fully reliable subjects with NIHL of degrees of severity comparable to the sensitivity: this will document the opportunity to apply a correction factor to the electrophysiological threshold (‘estimated threshold’).

- (2) The sensitivity of 40 Hz binaural multiple ASSR to hypnotic, neuroleptic and sedative drugs, as their use cannot be controlled in a medicolegal context.

### 5. Conclusion

Audiological use of the 40 Hz binaural multiple ASSR technique is of actual interest for medicolegal hearing threshold estimation in adults claiming compensation for occupational NIHL, as soon as traditional behavioral audiometry lacks reliability. Indeed, this electrophysiological approach is noninvasive, frequency-specific and well-tolerated by the subject. ASSR thresholds show a good correlation with the CERA, which can be considered as the gold standard in frequency specific objective hearing measurement. However, a systematic shift is noticed, ASSR-thresholds being on average 4.38 dB better (i.e. showing less hearing loss) than CERA-thresholds. Further validation with fully reliable subjects with similar conditions is still necessary.

Furthermore, the binaural multiple ASSR-technique allows considerable gain of time when compared to the CERA.

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