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On the Objective Assessment of the Auditory Brainstem Response Measurement Quality

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Abstract— **Auditory Brainstem Responses (ABRs) are commonly used in clinical practice to determine hearing impairments and hearing thresholds. Although many research groups work on automatic recognition of ABRs – in order to decrease the acquisition times – measures to determine the quality of ABR measurements objectively are still missing. In fact, recently released new standards for electroencephalographic measurements in auditory examinations require an objective measurement quality assessment for neurodiagnostic devices. Thus there is a pressing need for the development and evaluation of such a quality control. In this study, we propose (a) a novel technique for the assessment of the ABR measurement quality and (b) evaluate and compare this technique to two other approaches which have been suggested in literature as required by the new standards.**

I. INTRODUCTION

At the present time, objective methods for the determination of hearing loss and hearing thresholds (HTs) are commonly used [1]. These methods include mainly auditory brainstem responses (ABRs) and Otoacustic Emissions (OAEs). The analysis of ABRs is considered to be the most robust method and it is of great relevance in the case of non–cooperative patients, i.e., newborns. Many methods have been proposed for an automatic recognition of ABRs with various success rates (e.g. [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15]. However, these methods are based on large–scale averaging procedures for the final analysis.

Over the last years our focus has been to analyze single sweep responses of auditory evoked potentials in general, such as frequency specific ABRs [16], auditory late responses, or as recently shown in [17], the analysis of event related response (ERP) images. In all these different experimental setups, we always try to avoid massive averaging techniques in order to reduce the measurement time and/or extract features which are not available in the averaged response such as regular latency and amplitude jitters. We recently shown that Hardy space projections can applied efficiently to extract information from ABR single sweeps, e.g., see [18], [19].

Nowadays, standardized objective measures to evaluate the quality of ABR measurements are still missing. In fact, recently released new standards for electroencephalographic measurements in auditory examinations require an objective measurement quality assessment for neurodiagnostic devices (e.g, DIN EN 60645–7 in Europe). Thus there is pressing need to introduce and evaluate such measures. In this study, we propose (a) a novel technique for the assessment of the ABR measurement quality and (b) evaluate and compare this technique to two other approaches which have been suggested in literature. Such objective methods might also used as stopping criteria if a certain quality of signal is acquired, i.e., no more sweeps need to be obtained.

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II. METHODOLOGY

A. Stimuli:

Click and Chirp stimulations were used to evoke ABRs. The clicks were square signals with a duration of 80 μsec. Chirps stimuli were calculated as described in ([20] referred as A-chirps) and [18] using a frequency range of 0.1 to 10 KHz and intensity levels of 40 and 30 dB (HL), which resulted in the respective durations of 7.84, and 9.21 ms. All stimuli had an alternating polarity in order to avoid stimulus artifact and a repetition rate of 20 Hz. See [21] and references therein for details about the calibration. Examples of the resulting waveforms are shown in Fig. 1. All stimuli was calibrated according to [22], [23], [24], i.e., their peSPL was measured, for details we refer to [18].

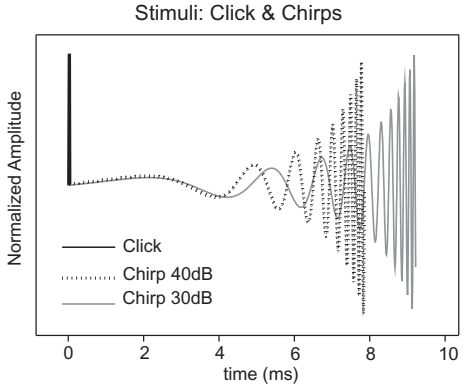

Fig. 1. Waveform examples of the stimuli used to evoke ABRs: chirps and clicks. The chirps had a frequency range of 0.1-10KHz, and were calculated for the intensity levels of 30 and 40 dB. From right to left, chirp for 30 dB (HL), chirp for 40 dB (HL) and click of 80 μsec . The stimuli had a repetition rate of 20 Hz.

B. Subjects:

Twenty volunteers (age 24.4±4 years; 13 female, 7 male) with no history of hearing problems and normal hearing thresholds (below 15 dB (HL)) participated in the study. The subjects signed a written informed consent form after a detailed explanation of the procedure.

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C. Setup and Experimental Procedure:

After skin preparation, passive sintered silver/silver chloride electrodes were placed (Schwarzer, Germany), according to the 10-20 system, as follows: ipsilateral to the stimulus at the right mastoid, contralateral to the stimulus at the left mastoid, common reference at the vertex and ground at the upper forehead. Impedances were always maintained below 5KΩ. A personal computer controlled the acquisition of the electroencephalographic activity, as well as the presentation and intensity level of the stimuli. The electroencephalographic activity was using a biosignal amplifier (gUSBamp, gTec, Austria) with a sampling frequency of 19.2 kHz and a bandpass filter with cutoff frequencies of 0.1 and 1.5 kHz. The biosignal amplifier was connected via USB port to the computer. The intensity level was controlled by means of a programmable attenuator headphone buffer (gPAH, gTec, Austria). Each sound file was generated together with its respective trigger signal. The audio channel that corresponded to the stimuli was connected to the attenuator and afterwards delivered to the subject via circumaural headphones (HDA–200, Sennheiser, Germany). The trigger channel was connected to a trigger conditioner box (g.Trigbox, gTec, Austria) which adequate the trigger signal in order to be acquired by the biosignal amplifier. The acquisition–processing program and all further post–processing were achieved using scientific computing software (Mathworks Inc., USA). After electrode placement, subjects were instructed to lay on a bed in an insulated room trying to remain quiet, with the eyes closed, and sleep if possible. After verifying correct values for the impedances, the headphones were placed and the lights turned off. Subsequently, ABRs were obtained using clicks for the intensity levels of 40, 30 dB (HL) and spontaneous activity (responses for no stimulation condition). Later the chirps were presented for the same intensity levels and in the same order. Each recording and condition consisted of 2000 artifact–free individual responses. Artifacts were rejected from the trial matrices with a threshold level set to 20μV. Each sweep had a duration of 400 msec, i.e. 768 samples.

D. Objective Evaluation Criteria:

For the quality analysis of a set $\mathcal{A} = \{\mathbf{s}_n \in \mathbb{R}^M : n = 1, 2, \ldots, N\}$ of N ABR sweeps (represented by M samples), we define the parameters α, β and ξ as follows.

1. Residual Noise Estimation: Let us denote the averaged ABR by $\overline{\mathbf{s}} = \frac{1}{N}\sum_{n=1}^{N}\mathbf{s}_n$. The residual noise estimation is computed as suggested in [25] by $g_m = \sqrt{\frac{1}{N(N-1)}\sum_{n=1}^{N}(s_{n,m} - \overline{s_m})^2}, (m = 1, 2, \ldots, M)$ which we further reduce to a residual noise quantifying scalar value by

$$\alpha = \|\mathbf{g}\|_2^2 = \sum_{m=1}^{M} g_m^2 \tag{1}$$

2. ABR Reproducibility: The reproducibility (e.g. see [17]) allows for another quantification of the ABR quality. For this, we introduce two sub–matrices $\mathbf{S}^e$ and $\mathbf{S}^o$ which carry the responses for even (upper index e) and odd (upper index o) numbered stimulations n ($n = 1, 2, \ldots, N$, N even) or rows of $\mathbf{S}$, respectively. Let us denote the averaged even and odd ABR data by $\overline{\mathbf{s}}^{e/o} = \frac{1}{N}\sum_{n=1}^{N/2}\mathbf{s}_n^{e/o}$ ($\overline{\mathbf{s}}^{e/o} \in \mathbb{R}^M$) and the additional average over the time by $\tilde{s}^{e/o} = \frac{1}{M}\sum_{m=1}^{M}\overline{s}_m^{e/o}$. The ABR–reproducibility is now just the Pearson's correlation coefficient $\beta \in [-1, 1]$ between the average of the even and odd numbered trials (or sweeps)

$$\beta = \frac{\sum_{m=1}^{M}(\overline{s}_m^e - \tilde{s}^e)(\overline{s}_m^o - \tilde{s}^o)}{\sqrt{\sum_{m=1}^{M}(\overline{s}_m^e - \tilde{s}^e)^2}\sqrt{\sum_{m=1}^{M}(\overline{s}_m^o - \tilde{s}^o)^2}} \tag{2}$$

Please note that α and β were previously introduced in [17] for the analysis of ERP images.

3. Measurement Quality Using Hardy Space Projections: Based on our results in [19], we introduce a new measure to quantify the ABR measurement quality by means of Hardy space projections and circular clustering. Using some Hardy space projection $\mathcal{T}_\psi$ to the basis ψ of ABRs depending on a scale parameter a and time parameter b, e.g., Gabor Frames as we used in [19] or the complex continuous wavelet transform as in [18], the instantaneous phase ϑ of a sequence $S = \{s_n \in L^2(\mathbb{R}) : n = 1, \ldots, N\}$ of N ABR single sweeps is given by $\vartheta_{a,b}(n) := \arg\left((\mathcal{T}_\psi s_n)(a, b)\right)$. We define the measurement quality by ξ_a of $\mathcal{A}$ using the circular data $\vartheta_{a,b}(n)$ by

$$\xi_a = \sum_{m=1}^{M} e^{-(\sigma r_m(\{\vartheta_{a,m}(n):n=1,\ldots,N\}))^2}, \tag{3}$$

where $r_m(\{\vartheta_{a,m}(n) : n = 1, \ldots, N\})$ is the Rayleigh test [26] of circular statistics with the null hypothesis that the set of angles $\{\vartheta_{a,m}(n) : n = 1, \ldots, N\}$ is uniformly distributed around the circle. In other words, for a fixed point in time and discrete time sample, respectively, b and scale a we evaluate the distribution of angles across the individual sweeps. In Eq. 3 we have the exponentially σ weighted sum of this test for all the sample points (or a subset thereof). Throughout this study, we used the complex continuous wavelet transform as in [18] with the 4th derivative of the complex Gaussian as $\mathcal{T}_\psi$ and $\sigma = 250$ (determined by validation).

III. RESULTS AND DISCUSSION

For the analysis of the three quality measures, ABR datasets containing N= 200, 500, 800 and 1500 sweeps were used. Fig. 2 shows the general results for the 20 subjects from top to bottom results for α, β and ξ, respectively. The values presented in this figure are relative to the spontaneous activity. Note that the spontaneous activity serves as model for the worst measurement quality as there is no stimulus locked signal at all. The parameter α represents the level of noise in the signal, which means that large values of α means a bad quality ABR measurement, while the opposite represent a good acquisition. In the case of the correlation values, it is easy to see that β showed large values for all the stimulation cases with N$\geq$500 sweeps.

The optimal scale for the analysis was according to [19], were the best results were obtained for lower frequency

channels, i.e.,160 – 320 Hz and 320 - 480 Hz. The scale a=30 represents a pseudo–frequency of 320 Hz. Note that β and ξ increase when increasing N, which is expected due to the improved signal–to–noise ratio. Note also that β and ξ for chirp stimulations were in general larger than their corresponding values for the same intensity values using clicks. This is also expected as is generally known that chirps evoke larger responses than clicks at the same peSPL [27], [16]. The latest is due to (1) larger duration of chirp stimulations and (2) the tonotopic organization of the cochlea, which means that the temporally organized frequency components of a chirp stimulus, i.e., delaying high frequency from low frequency components, compensate the temporal dispersion of a traveling wave which means that low and middle frequency components should reach their sensation locus at -almost the same as the high frequency components. It is noticeable that ξ could represent the presence of ABRs even for sets containing a small amount of sweeps, i.e., N=200 sweeps. In all the stimulation conditions the behavior of ξ was very similar, showing reproducible results.

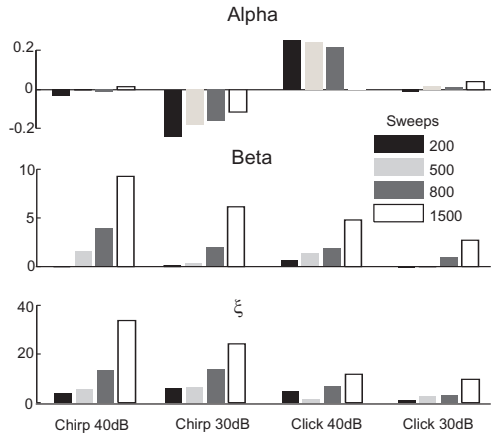

Fig. 2. General results over all the subjects. From top to bottom, α, β and ξ. The black bars represent the results when using 200 sweeps, light and dark grey represent 500 and 800 sweeps, respectively; while white represent the results when using packages of 1500 sweeps.

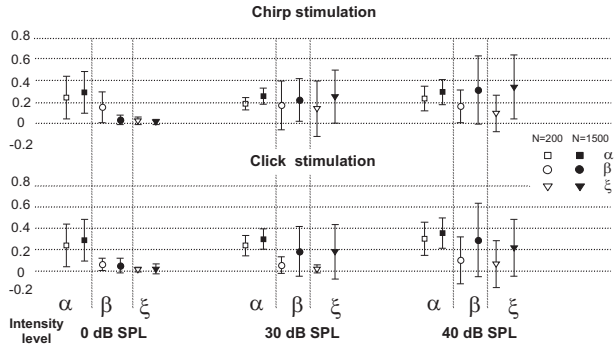

Fig. 3. The upper row shows the results of α, β and ξ chirp stimulations using N=200 and 1500 for the different stimulation intensities including the no stimulation condition (spontaneous activity), which is used as a reference value; the lower row shows the same but for click stimulations. The bars indicate standard deviations.

Similar behavior can be seen in Fig. 3, which shows a comparison of the 3 features α, β and ξ obtained using a set of N=200 and 1500 sweeps for chirp (up) and click (bottom) stimulations and displayed as absolute values, i.e., they are not related to their respective spontaneous activity condition (no stimulation condition). In this last Fig., the values of α, β and ξ for the no stimulation condition are also shown. As expected, α values are larger than their respective stimulation condition values, which is an expected behavior, i.e. the more sweeps included the less noisy resultant signals. In the case of β, the expected behavior is to increment in case of a presence of a physiological response, i.e., the larger the number of sweeps the better the reproducibility of the resultant signal. And for ξ, the analysis of the phase has been shown to be more robust than amplitude analysis [19] and therefore, shows better results even for small N, but nevertheless, the more sweeps included in the analysis the better the result.

In Fig. 3 a clear separation between the no stimulation and stimulation condition for both stimuli can be seen for the 3 features (This means that in the case of a no stimulation condition a simulated "deaf" condition is tested for the subject who will be further examined with clicks or chirps). This separation is more clear compared to α and β for ξ even using 200 sweeps for the analysis. Taking again into account that chirp stimulations evoked larger responses than clicks for the same peSPL it is worth to mention that the behavior of the features is almost the same for both stimuli but nevertheless, chirps reflect also better values in the proposed quality measures using already 200 sweeps as compared to chirps, which was also assumed.

Based on the results presented in this work, we can conclude that the quality measures used showed a good performance, and ξ could shown a good performance when the number of individual responses used were as small as 200. The results presented here are very promising but further analysis still has to be done including single sweeps of ABRs collected from different commercial devices and in different clinical setups.

IV. CONCLUSIONS

Three different variables were tested to objectively estimate quality of ABR measurements. The introduced quality measure using Hardy space projections provided the most consistent results as compared to the time–domain residual noise and the reproducibility. We conclude that this measure provides a promising estimation of the ABR quality, even when using a small number of single sweep responses of ABRs, down to 200.

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