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A portable, modular, and low cost auditory brainstem response recording system including an algorithm for automatic identification of responses suitable for hearing screening

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***Abstract*— The recording of auditory brainstem response (ABR) signals is a common measure applied to assess hearing impairments. However, most of the available commercial devices able to record ABR signals can be unaffordable for many medical centers because of their cost and low flexibility. This paper describes a system that allows the recording of high quality ABR. Its low cost, easy handling, high performance, and portability make its use appropriate in low budget institutions. Furthermore, the flexibility and open nature of this system allow its use as a research tool. The ABR recording system includes a new algorithm for automatic evaluation of the quality of responses and the estimation of the latencies and amplitudes of the waves, the *fitted parametric peaks* (FPP). The performance of this technique is contrasted with a well-established method for quality evaluation based on the correlation coefficient. The encouraging results of this test suggest that the fitted parametric peaks could be used as a method for automatic ABR quality assessment and identification of the peaks.**

I. INTRODUCTION

Auditory brainstem response (ABR) signals represent the electrical activity of the auditory nerve associated to a stimulus. This biological response is characterized by waves (peaks) that occur whithin the first 10 ms post-stimulus interval [1]. Peaks are labelled by roman numerals as proposed Jewett in [2]. ABR signals are widely used in hospitals and clinics around the world as a hearing screening method to detect hearing threshold and hearing impairments [1], [3]. Moreover, the study of auditory evoked potentials is of great interest in audiology since it allows the analysis of the mechanisms involved in the process of hearing [1].

This paper describes a high performance, portable, modular, and low cost auditory brainstem response recording system. There already exist several commercial devices able to record ABR; nevertheless most of the current clinical systems only allow users to select a few parameter settings, are expensive, require connection to the electrical network, and most of them give no access to raw recording data [4]. In contrast, the system described on this paper gives users full control of the parameters. Users are able to specify the intensity of stimulation, decide whether use the conventional stimulation technique or any other more advanced, select the number of biological responses to consider in the averaging process, set the stimulation frequency, define the analog to digital sample frequency, program the stimulation signal, change its polarity, set the filter settings, or implement advanced artifact rejection techniques. In addition, users have total access to raw recording data, which means that advanced digital processing can be implemented off-line. Furthermore, the low cost nature of this system and its high performance allow a reliable use in many low-budget institutions.

The flexibility provided by the ABR recording system described on this paper allows its use as a research tool. The ABR recording system incorporates a new software module that provides an automatic evaluation of the quality of ABR signals based on the use of templates. This methodology is called *fitted parametric peaks* (FPP). The automatic analysis of the quality of ABR recordings can be useful to take the decision of automatically stop averaging, avoiding the recording of unnecessary responses when there already exists an ABR signal of enough quality and therefore, reducing recording time [5]. It also allows an automated identification of the parameters of the peaks, i.e., amplitudes and latencies [6], which can be used to provide an automated interpretation of the auditory brainstem response [7]. Besides, automated algorithms remove the need for subjective interpretations of ABR, reducing human errors, and ensuring consistency among patients, test conditions, and screening personnel [8]. These advantages led the Joint Committee on Infant Hearing Year 2000 Position Statement to declare: "screening technologies that incorporate automated response detection are preferred over those that require operator interpretation and decision making" [9]. The fitted parametric peaks methodology is validated in this study contrasting its performance with a well-established method for quality assessment of ABR recordings based on the correlation coefficient [10]. The main advantages of the proposed methodology for automated ABR quality assessment are discussed on this paper.

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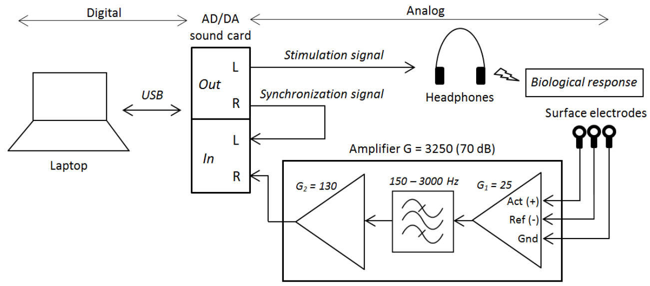

Fig. 1. General scheme of the system.

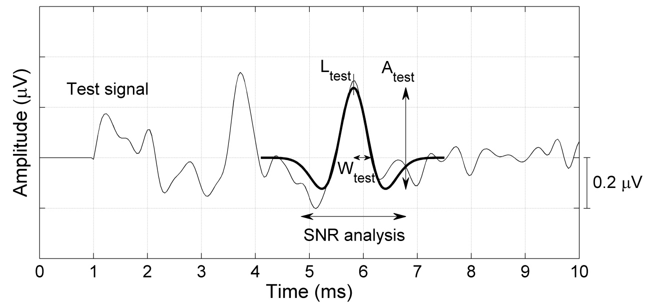

Fig. 2. Parameters involved in the SNR estimation based on fitted parametric peaks. The parametric peak fitted to the wave V of a test signal is shown in bold.

II. METHODS

A. System description

ABR signals are recorded conventionally through the presentation of a stimulus that excites the auditory system of a subject and the recording of its associated auditory electrical response. This biological response is collected by surface electrodes placed on the skin at different positions on the head. The low amplitude of this kind of signal (usually less than $1\mu V$) forces to make a high amplification. Evoked responses are contaminated by several sources of artifacts such us neuro-muscular activity of the subject, noise associated with the amplifier and electromagnetic & radiofrequency interferences. The methodology used to reduce the effects of these artifacts is the average of a large number of biological responses in order to improve the signal to noise ratio [11]. This system is battery powered in order to minimize the artifact produced by the electric network. Signal processing has been developed with MATLAB (The Mathworks, Inc.). The process of ABR recording is sketched on figure 1.

A specific signal composed of a sequence of a 0.1 ms duration clicks is generated by the laptop for both stimulation and synchronization purposes. The open nature of this system allows the use of any kind of stimulation sequence: conventional; MLS [12], [13]; CLAD [14], [15]; QSD [16]; or randomized stimulation [17]. These techniques allow the recording of ABR at different stimulation rates, which can be useful in some applications such as reducing the recording time [18], or detecting certain pathologies at an early stage [19]. The intensity of the stimulation can also be controlled by setting the amplitude of the clicks. The stimulation and synchronization signal is sent synchronously through the left and right outputs of an external Analog-Digital/Digital-Analog (AD/DA) sound card. The right output of the AD/DA sound card is connected to its left input, so the recording of the synchronization signal allows the system to determine the exact moment in which stimuli are produced. The left output of the sound card connects a pair of headphones, through which the stimulation signal excites the auditory system of a subject. The auditory electrical response associated to each stimulus is recorded by three Ag/AgCl surface disc electrodes. The electroencephalogram (EEG) captured by the electrodes is preamplified by a factor $G_1 = 25$, band-pass filtered (150-3000 Hz), and amplified by a factor $G_2 = 130$. Therefore, the gain of the amplifier for the band-pass frequencies is set at about $G_{amp} = 3250$ (70 dB). The auditory response after filtering and amplification, and the synchronization signal are recorded synchronously by the right and left inputs of the external AD/DA sound card. Both signals are sampled at a frequency of 25 kHz and stored using 16 bits of quantization. Finally, the auditory evoked response is obtained through the average of the auditory responses. The rough cost of this ABR recording system (laptop not included) is lower than $500. A full description of the ABR recording system can be browsed in [20].

B. Quality assessment of ABR responses

The described ABR recording system incorporates a new approach for automatic assessment of quality of ABR recordings. We have called this quality evaluation technique *fitted parametric peaks* (FPP). This new procedure is based on the use of templates that fit the ABR response, and are used as reference to evaluate the quality of the ABR signal. The use of templates for this purpose is a well-established method [6]. The fitted parametric peaks methodology uses as template the following function:

$$x(t, A, L, W) = A \cdot \left(1 - \frac{(t-L)^2}{W^2}\right) \cdot e^{-\frac{(t-L)^2}{2 \cdot W^2}} \qquad (1)$$

This parametric function corresponds to the second derivative of a Gaussian function of amplitude A, mean L, and standard deviation W. In this parametric peak, L represents the latency, W is the semi-width, and A is the amplitude of the peak (figure 2). Given an auditory brainstem response signal, the parameters A, L, and W can be iteratively estimated with a criterion of minimum mean square error. In order to evaluate the quality of an ABR recording, the reference parameters (A_{ref}, L_{ref}, and W_{ref}) can be obtained for waves III and V according to previous literature. The reference parameters considered in this study are the followings: $A_{ref} = 0.26\mu V$ for wave III and $A_{ref} = 0.28\mu V$ for wave V; $L_{ref} = 3.75ms$ for wave III and $L_{ref} = 5.80ms$ for wave V, and $W_{ref} = 0.4ms$ for both waves [1]. The parameters (A_{test}, L_{test}, and W_{test}) for waves III and V are then estimated in the test signal in intervals around the reference parameters: $L_{test} \in L_{ref} \pm 0.5$ ms, $W_{test} \in [0.4 \cdot W_{ref}\ , 2 \cdot W_{ref}]$, $A_{test} \in [0.2 \cdot A_{ref}\ , 4 \cdot A_{ref}]$. The SNR can be

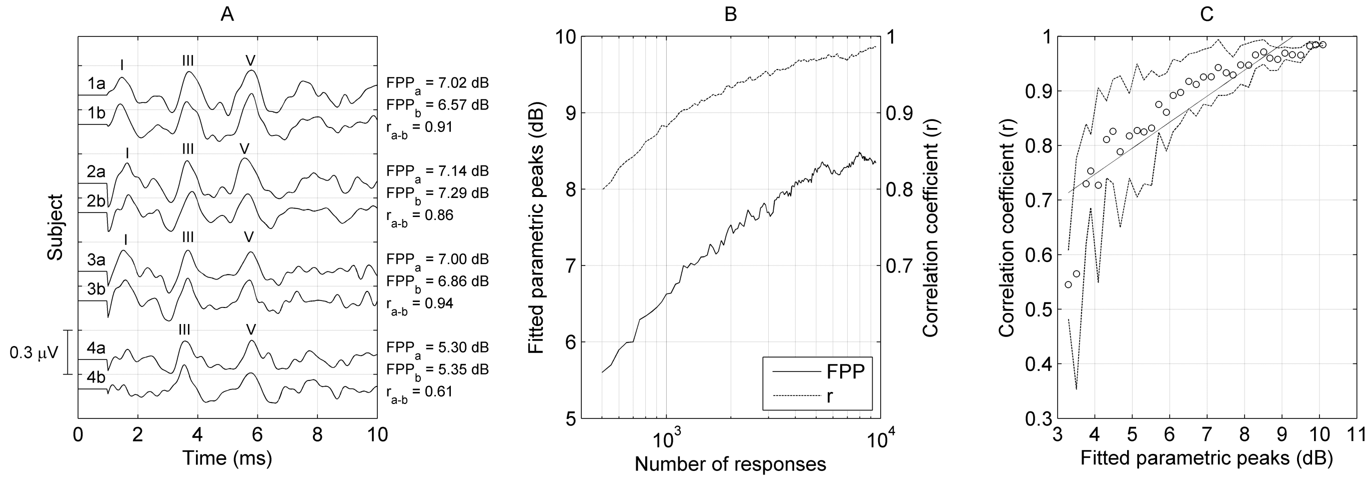

Fig. 3. A) Examples of ABR signals from 4 subjects: ISI=22ms, 70 dBnHL, 1000 auditory responses. The quality evaluation of these recordings by both methodologies is presented. B) Evaluation of the quality of ABR recordings obtained at different number of averaged responses according to the fitted parametric peaks (FPP) and to the correlation coefficient (r) methodologies. C) Relationship of the quality of ABR signals assessed by the fitted parametric peaks and by the correlation coefficient techniques. The averaged experimental data are adjusted to a first order model. The dashed line represents the standard deviation of the experimental data.

estimated independently for each wave as the ratio between the pewer of the parametric peak and the pewer of the noise (estimated as the difference between the ABR response and the parametric peak). The SNR for each peak is estimated in an interval $[L\text{-}4W \quad L\text{+}4W]$. This way, the evaluation of an ABR recording does not degrade because of small fluctuations in the amplitude, latency or width with respect to the reference signal. This criterion for the evaluation of the response approaches the subjective evaluation provided by an experienced audiologist, essentially based on the grade of identification of the most important waves.

The performance of the proposed fitted parametric peaks (FPP) methodology is compared to a standard ABR quality assessment based on the correlation coefficient (r). This parameter points out the grade of similarity between two ABR responses. A high possitive correlation coefficient would indicate a high quality ABR if both signals are recorded in similar conditions [21]. Compared to other automatic quality evaluation techniques, the correlation coefficient remains as the most consistent technique to score the quality of ABR recordings [10].

The performance of the fitted parametric peaks methodology is contrasted in this paper with the quality assessment technique based on the correlation coefficient. 20 000 auditory responses were recorded from 4 normally hearing adults at an intensity of 70 dBnHL, and at the stimulation rate 45,45 Hz − Interstimulus interval (ISI) = 22 ms. All available auditory responses were grouped in blocks of a specific number of responses. The number of responses of each block varied from 500 to 9500. For instance, there were 40 blocks of 500 auditory responses, 20 blocks of 1000 responses, and 2 blocks of 9500 responses in each subject. The quality of the ABR signal obtained in each block was evaluated using the fitted parametric peaks methodology. Then, all evaluations corresponding to blocks of the same number of responses were averaged to obtain a final quality evaluation based in FPP. The quality evaluation based on the correlation coefficient was performed by calculating the correlation coefficient between all possible combinations of ABR corresponding to blocks of the same number of responses and same subject, taking two at a time; and finally, averaging all these evaluations.

The quality evaluation technique based on fitted parametric peaks was validated by contrasting its performance with the methodology based on the correlation coefficient. The functional dependence between both methodologies was analysed making groups of 0.2 dB from quality evaluations provided by the FPP, and calculating the mean and standard deviation of the corresponding quality evaluations based on the correlation coefficient.

III. RESULTS

Figure 3.A shews two examples per subject of ABR signals obtained using 1000 auditory responses in the averaging process. The most important waves can be identified in all subjects, in exception of subject four, that wave I cannot be clearly idenfied. Waves I, III, and V are labelled in the figure. This figure also remarks differences in the morphology among subjects. All subjects present similar amplitudes and latencies, which are consistent with previous literature [6], [7], [1]. The evaluation of the quality of these recordings by the fitted parametric peaks (FPP) and by the correlation coefficient (r) methodologies is presented in the figure.

Figure 3.B presents the evaluation of the quality of ABR recordings obtained at an increasing number of averaged responses by both the FPP and by the correlation coefficient methodologies. This figure shews that the quality of the responses increases with the number of averaged responses

in both techniques. The ABR recording system mentioned in this article allows the recording of high quality ABR using a fair number of auditory responses in the averaging process (r ≈ 0.9 at 1000 averaged responses).

The evaluation of quality provided by the FPP methodology is compared to the evaluation given by the correlation coefficient technique (figure 3.C). Despite both methodologies assess quality by different means, this graphic shows that both techniques present in average a similar tendency. This tendency is characterized by a linear regression analysis of the experimental data ($r = 0.88$). Consequently, both techniques could be used to provide automatic evaluation of quality of ABR recordings. Moreover, a subjective evaluation given by an experienced audiologist suggest that the quality evaluation method FPP is more consistent because the correlation coefficient could provide an inaccurate high evaluation when comparing two ABR recordings contaminated, i.e., by a strong stimulus artifact.

IV. DISCUSSION AND CONCLUSION

This paper describes an ABR recording system. The high performance and low-price of this system could make its use appropriate in low-budget institutions and medical centers from developing countries. The high portability provided by this battery powered system could also spread a hearing screening protocol to rural and other difficult access areas by driving the device to such areas, instead of restraining its use in medical centers. In contrast to many commercial devices, the proposed ABR recording system could also be used as a research platform due to its open nature and flexibility. The described ABR recording system includes a software module that provides an automatic evaluation of the quality for an ABR recording. This technique is called *fitted parametric peaks* (FPP). The performance of this technique was contrasted with the well-established quality evaluation method based on the correlation coefficient. In comparison with this technique, the FPP methodology: (a) requires only one ABR recording to provide a quality estimation, which can be useful in applications where clinical test time is a critical parameter, such as in ongoing quality assessment applications; (b) is more consistent in certain situations such as evaluating the quality in recordings contaminated by a large stimulus artifact, in which an evaluation of the quality based on the correlation coefficient would result into an inaccurate high quality evaluation; and (c) provides an automatic identification of the amplitude and latency of the peaks. The preliminary results presented on this paper suggest (a) that the ABR recording system presented in this paper can be used to obtain reliable and high-quality ABR recordings, and (b) that the proposed FPP can be considered a valid procedure to provide an automatic assessment of the quality of ABR recordings and identification of the peaks.

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