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OPTIMAL DENOISING OF BRAINSTEM AUDITORY EVOKED RESPONSE (BAER) FOR AUTOMATIC PEAK IDENTIFICATION AND BRAINSTEM ASSESSMENT

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ABSTRACT

Brainstem Auditory Evoked Responses (BAER) are transient signals embedded in the EEG recorded from scalp electrodes, when a subject is presented with a series of acoustic clicks. These signals typically have a signal-to-noise ratio (SNR) well below -10 dB. The extraction of BAER signals from the EEG for the purpose of automatically computing features of interest from the BAER waveform(s) is described in this paper. These features are: 1) Presence of an actual BAER response (at least peak I), 2) Presence of peak V, 3) Inter-peak latency I-V. We propose to combine a signal-adaptive denoising technique based on complex wavelets with a signal quality metric referred to as the F_{SP} variance ratio for quantitative evaluation of signal quality in order to optimally denoise BAER signals and perform reliable waveform analysis.

1. INTRODUCTION

Brainstem auditory evoked responses (BAER) or potentials (BAEP) are useful for diagnostic applications related to possible damage to the brainstem. Unlike imaging techniques, BAER analysis provides a functional assessment of the brainstem. BAER responses are small transient responses to periodic stimuli presented to a resting subject via headphones. A normal BAER waveform comprises seven peaks, labeled I through VII, present in the first 10 ms following the start of the acoustic stimulus. Wave I is generated by the *auditory VIII nerve*, waves II-V originate in the *pons* (see [1], Table I). Waves VI-VII are usually ignored by clinicians.

These transients are of small amplitude, in the order of a microvolt, and are phase-locked to the stimuli. The EEG in which they are buried is a zero-mean random signal which is not phase locked, and can have peak-to-peak amplitude up to 100 mV. Therefore BAER extraction always involves synchronized averaging of epochs in order to improve the signal to noise ratio. Note that the term *epoch* is used here to mean a fixed sized EEG segment starting at the start of an acoustic stimulus. The terms *sweep* and *frame* are also commonly used in BAER literature. The power spectrum of typical BAER waveforms have energy largely in the frequency band 100-1500Hz, so the EEG signal is usually band-pass filtered before epoch averaging in order to minimize its influence on the reconstructed BAER.

It is of interest to be able to automatically analyze BAER waveforms and to reliably answer the following questions: 1) Is there a BAER?, 2) If so, are peaks I and V present in the response?, 3) What is the inter-peak latency I-V? In most medical studies involving BAERs, the analysis of the waveforms is performed manually, by trained EEG experts.

In this work, we show that we can combine the wavelet-base adaptive filtering (AFW) proposed in [2] for BAER extraction/denoising with the computation of F_{sp} proposed by Elberling et al. in [3-4]. The AFW algorithm was inspired by the FFT-based optimal filtering work of Fridman, John *et al.* published in [5]. Note that in [2], we used simulated BAER signals that were generated using realistic signal models. This had the advantage of enabling us to compute an objective measure of reconstructed waveform quality, the SNR, since the underlying true BAER response was known. In this work we use actual signals acquired by recording human EEG and SNR measurements are no therefore no longer possible. Still, to be able to rely on a signal quality metric such as F_{sp} for denoised BAER waveforms greatly reduces the chance to misidentify peaks.

2. EXPERIMENTAL PROCEDURE

Data acquisition was performed on a Nicolet Endeavor Instrument. The sampling rate was 8 kHz. Recording was performed on five frontal electrodes referred to as Fp1, Fp2, Fpz, F7, F8 in the classic 1020 electrode montage and two earlobes (A1, A2), all referenced to electrode Fz. Rectangular clicks of alternating polarity were delivered at a frequency of 28 Hz at 95 dB p.e. SPL (4000 repetitions in each ear). All 5 channels were re-referenced to the contra-lateral ear (ear opposite to the one where the stimuli are presented), before processing.

A typical BAER response for a 19 year old male is shown in Fig. 1 where 1000 epochs have been band-pass filtered in the range 100-1500 Hz and averaged.

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3. ALGORITHM REQUIREMENTS

The denoising of BAER waveform is only the first step toward performing waveform analysis. We specify below our algorithmic requirements for this analysis:

1) Spurious peaks due to EEG, instrument noise and noise from neighboring medical equipment in the recording room should be eliminated or at least strongly attenuated by the denoising process.
2) In order to have any confidence in automatically identified peaks, peak identification should be performed on several reconstructed waveforms W_1, … W_T, rather than a single one.
3) Any waveform which does not meet an objective quality criterion should be removed from the peak identification analysis.
4) Bandpass filtering has been shown to significantly influence the morphology of BAER waveforms. High-pass cutoff frequencies between 30 and 300 Hz have been used in the literature but Hall cautions in [6] that response amplitude for wave V especially is reduced when using a high-cut off. It is therefore desirable to use as wide a passband as possible. However, since most of the energy of the EEG signal is below 50 Hz a trade-off is in order.
5) Signal-adaptive filters, either FFT-based or wavelet based are a way to perform additional filtering based on phase variance [2]. This processing is ideally suited to the hypothesis that BAER responses are fixed transients time-locked with the stimulus.

4. SIGNAL QUALITY METRIC: F_{SP}

The F_{sp} variance ratio introduced by Elberling and Don in [3] is a statistical quality estimation measure for averaged auditory brainstem responses. It is widely used in biomedical devices which perform hearing assessment using BAER. Consider a set of N BAER epochs:

$$Ei[n] = S[n] + Ni[n], \text{ where } 1 \le i \le N \qquad (1)$$

where $N_i[n]$ represents the sum of the biological noise contributed by the EEG as well as equipment noise and $S[n]$ is the BAER response which is assumed to be constant over the duration of data acquisition. The F_{sp} variance ratio is defined by Elberling and Don as:

$$Fsp = \frac{\mathrm{var}(\overline{Ei})}{\mathrm{var}(\overline{SP})}, \qquad (2)$$

where $\mathrm{var}(\overline{Ei})$ is the variance of the averaged response in the time interval [1 – 11 ms], and $\mathrm{var}(\overline{SP})$ is a single-point estimate of the variance of the averaged background noise. F_{sp} is therefore conceptually similar to the signal-to-noise ratio.

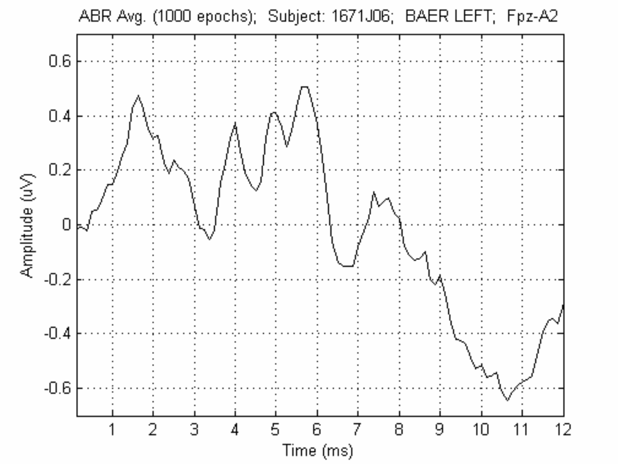

Fig 1: BAER LEFT response for a 19 year old male. Synchronized average of 1000 epochs (no artifact rejection, no bandpass filtering). Electrode: Fpz, reference electrode: A2. Sampling rate: 8 kHz.

5. SIGNAL DENOISING

We used the adaptive complex wavelet-based filtering method described in [2] for signal denoising. *Sub-average* or *trial* size was 768 epochs with 50 % overlap between trials. In order not to contaminate the trials with large amplitude noise due to electrode movement, patient movement (eye movement artifacts, muscle artifacts), we computed, for each electrode *k*, the standard deviation σ_k of the EEG signal values and set an epoch rejection threshold for that electrode equal to $T_k = max(2\sigma_k, 35)$.

The EEG signal was band-pass filtered using a wide band-pass filter with high-pass cutoff frequency of 40 Hz and low-pass cutoff of 3 kHz. The algorithm used as many trials as were available given the number of EEG epochs remaining after artifact rejection. F_{sp} was computed after the application of the adaptive filter which enabled us to objectively evaluate the denoising contribution of the adaptive filter. Note that this was done using Eq. (2), where the single point noise variance estimate was computed on individual BAER epochs that went through the denoising filter.

5.1. F_{sp} results

Table I shows the large improvements in terms of F_{sp} of reconstructed BAER waveforms when adaptive wavelet-based filtering is used. For subject "20544" in particular, the low values of the F_{sp} before AFW filtering could lead one to believe that the BAER waveform is not present in sub-averages of 768 epochs. After adaptive filtering however, the F_{sp} increases on average by a factor of 3.7, corresponding to an average increase by 270%. The AFW algorithm is therefore extremely successful in removing noise left over after the averaging process.

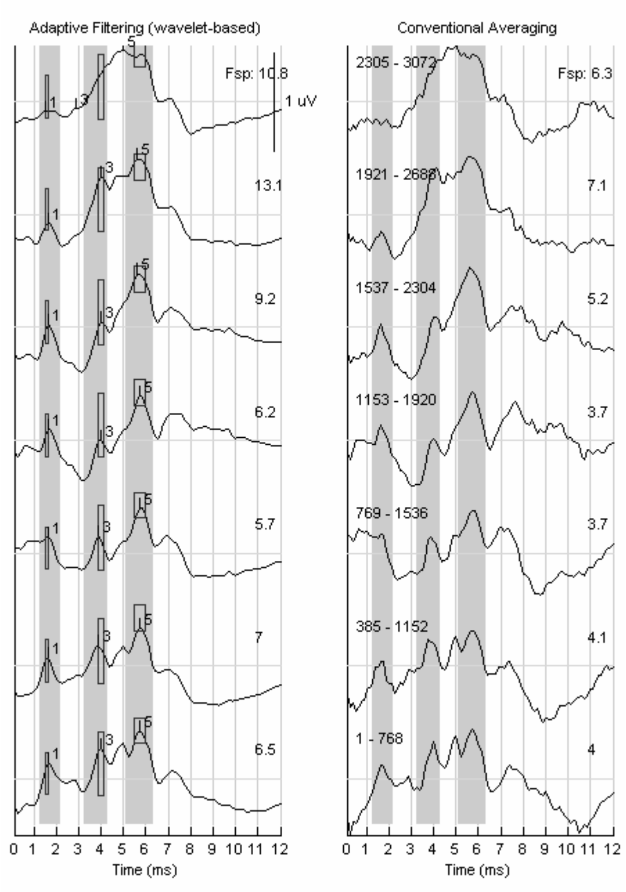

Fig 2: BAER LEFT response for a 19 year old male (subject: "1671J06"). Electrode: Fpz, reference electrode: A2. Sampling rate: 8 kHz. Right: BP filtering 45-3000 Hz, Averaging (trial size: 768 epochs). Left: Additional AFW filtering.

Table I: Comparison of F_{sp} measures for 2 BAER extraction algorithms; F_{sp} values are given as: average (standard deviation) for a collection of sub-averages of size 768 epochs.

Subject ID	**Fsp (BP + Avg)**	**Fsp (BP + AFW)**
1671J06	4.9 (1.4)	8.4 (2.8)
20544	1.3 (0.5)	4.9 (1.9)
20543	1.3 (0.6)	5.6 (3.4)

5.2. Visual inspection of BAER waveforms

One can see from the denoised sub-averages shown on the left side of Figs 2-3 that adaptive filtering results in a smoother signal, with fewer spurious peaks. It does however preserve the morphology of the simply averaged BAER waveform. In the case of subject "20544" in Fig. 3, the raw EEG data which contains the BAER signal is clearly corrupted by high energy noise with power mostly around 1.2 kHz which may come from nearby instruments in the ER where this EEG was recorded. Unlike the BAER however, this noise is not phase-locked to the acoustic stimulus and is successfully removed by the adaptive filter. It is clear from visual inspection of Fig. 3 that peak identification on the waveforms in the left column is much more likely to be reliable that the same done on the waveforms on the right.

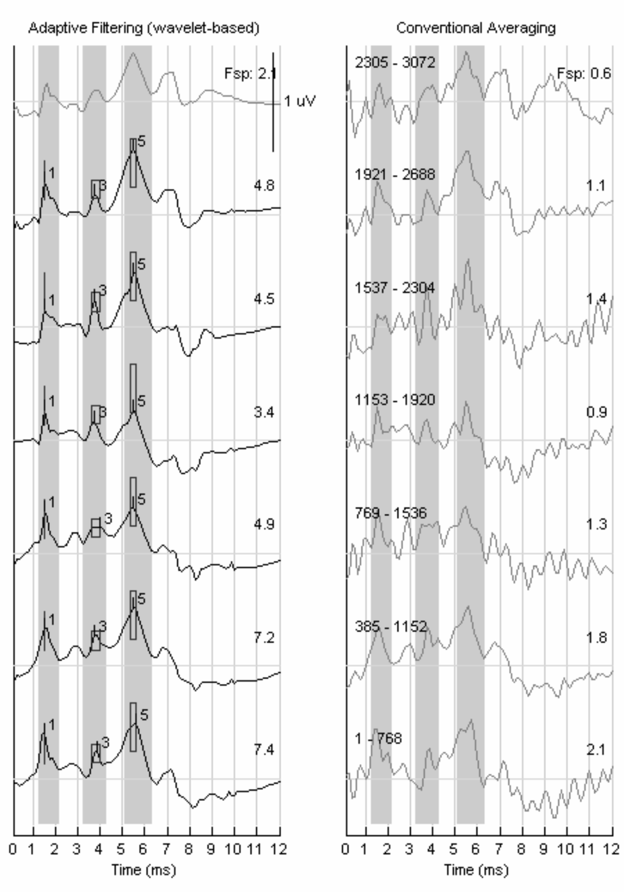

Fig 3: BAER LEFT response for a 32 year old male (subject: "20544") recorded in the Bellevue ER. Electrode: Fpz, reference electrode: A2. Sampling rate: 8 kHz. Right: BP filtering 45-3000 Hz, Averaging (trial size: 768 epochs). Left: Additional AFW filtering.

6. IDENTIFICATION OF PEAKS

6.1. Significance of the presence (or absence) of BAER peaks

Automatic identification of peaks I through V in a BAER waveform has value for the diagnosis of subjects who have received a head injury and/or end up in the ER unconscious. BAERs have been shown not to affected by drugs (including sedatives anesthetics) and are a good indicator of possible structural damage to the brainstem. Peak I is always present unless the subject has major sensory pathologies (cochlear or auditory VIII nerve damage). Absence of peak V is sometimes found in coma patients with a dire prognosis. When peaks I and V are both present, inter-peak latency I-V is strongly correlated with intracranial pressure. We therefore would like our automatic peak detector to reliably answer the following questions:

1) Is a BAER response present? (e.g. at least peak I)
2) Is peak V present?

3) What is the inter-peak latency I-V?

6.1. Peak detection and identification strategy

Peaks I through V were automatically identified in the AFW-denoised responses by an algorithm based on zero-crossings of the first derivative and measures of "peak strength". Verification of peak latencies determined by the algorithm was done by an expert technician.

ABR response at "Fpz" was used for peak identification. Peaks were identified one at a time within normative, age-regressed latency ranges taken from [7]. Peaks are identified in the following order: V, I, III.

Successive values of the first-order derivative in the expected peak latency range are coded as ternary strings of the form "1111122221110222", where "1" represents a positive slope, "2" represents a negative slope and "0" represents a flat slope. For example, with a slope threshold of 0.01, the series of slope values: 0.25, 0.10, 0.002, -0.10, -0.05, 0.02 results in the code: "110221". The presence of patterns of type "12", "102", "1002" indicates zero-crossings of the first derivative (local maxima). Each local maximum is a potential true BAER peak.

A measure of peak strength was implemented in order to eliminate spurious peaks which might be left over after denoising. This measure was computed as the sum of the magnitudes of positive slope values before the peak (until a negative value is found) and negative slope values after the peak (until a positive value is found). An additional unilateral measure of peak strength was implemented for the identification of peak V which is typically followed by a sharp "negative complex SN10" [6].

6.2. Peak detection results

Results from peak detection conducted in this manner are shown in the left columns of Figs. 2-3. Identification of peaks I,III,V is conducted independently on each AFW-denoised sub-average for which the F_{sp} is larger than a minimum value chosen to be 3.2. Confidence intervals are shown for peaks of each type. The center of the confidence interval is the mean peak latency and value. The width and height correspond to a deviation of 2σ around the mean. Confidence intervals for Peaks I,III,V for 3 subjects are listed in Table II.

Table II: Confidence intervals (mean (σ)) in milliseconds for latencies of peaks I, III, V, for three subjects. Sub-averages of 768 samples denoised using AFW algorithm.

Subject ID	**Peak I**	**Peak III**	**Peak V**
1671J06	1.59 (0.04)	3.97 (0.05)	5.73 (0.10)
20544	1.50 (0.05)	3.85 (0.08)	5.52 (0.04)
20543	1.87 (0.05)	3.65 (0.33)	5.04 (0.05)

7. CONCLUSION

This paper demonstrates the feasibility of an algorithm for extraction of clean BAER waveforms and subsequent automatic peak identification in order to perform functional assessment of the brainstem. The adaptive, complex wavelet-based denoising algorithm first introduced in [2] is combined with a measure of waveform quality, F_{sp}, which allows the algorithm to ignore sub-averages of insufficient quality prior to performing peak detection. This increases the reliability of the detection of peaks I, III, V of the BAER to a level where automatic brainstem assessment can be reliably performed.

8. REFERENCES

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