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Single stimulus evoked potential estimation using adaptive noise cancelling with reference alignment

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Abstract

The objective of this work is to improve Evoked Potential (EP) estimation trough the use of an adaptive noise canceller with an enhanced reference signal. Averaging several EPs is a common method; it produces better results when the signal has been 'period-to-period' aligned by the maximization of its cross-correlation with a pattern signal. A disadvantage of the averaging method is the large number of stimuli needed to get a good visualization of a useful EP. We use a two channel adaptive canceller to obtain single stimulus evoked potentials. The canceller reference signal is the quasi-periodic extension of an average EP over a few periods, aligned by cross-correlating it with the primary signal. The Widrow-Hoff LMS algorithm is used to determine the filter weights by the noisy steepest descent method. The described technique was applied to simulated signals based on actual registers obtained from visually stimulated subjects. The proposed adaptive cancellation technique provides, with fewer stimuli, better *individual* estimates, permitting the analysis of the EPs variability between stimuli.

Key words: Adaptive cancelling, evoked potential, LMS algorithm, electroencephalography, averaging.

Estimación de potenciales evocados individuales usando cancelación adaptiva de ruido con referencia alineada

Resumen

El objetivo de este trabajo es mejorar la estimación de potenciales evocados (PE) a través de un cancelador adaptivo con señal de referencia alineada. La promediación es el método comúnmente empleado para la obtención de PE; esta técnica produce mejores resultados cuando la señal se alinea periodo a periodo mediante la búsqueda de los máximos de su correlación cruzada con una señal patrón. Una desventaja de la promediación es la gran cantidad de estímulos necesarios para obtener una buena visualización de un PE útil. Es este trabajo se usa un cancelador adaptivo de dos canales para obtener potenciales evocados únicos. La señal de referencia del cancelador es la extensión cuasi-periódica de un PE promediado sobre unos pocos periodos, alineado mediante correlación cruzada con la señal primaria. Para determinar los coeficientes del filtro cancelador se usa el algoritmo LMS de Widrow-Hoff. El método descrito fue aplicado a señales simuladas basadas en registros reales, obtenidos de sujetos estimulados visualmente. La técnica de cancelación adaptiva propuesta permite obtener, con pocos estímulos, un mejor estimado individual del potencial evocado, permitiendo el análisis de la variabilidad de los mismos entre estímulos.

Palabras clave: Cancelación adaptiva, potenciales evocados, algoritmo LMS, electroencefalografía, promediación.

Introduction

Evoked Potentials (EPs) are the electrical responses of the brain to controlled sensory stimulation. They have a lot of clinical applications [1], such as critical care and operating room monitoring, and are very useful signals for diagnosing neurological disorders and carrying out psycho physical and pharmacological research.

EPs, which are buried in the ongoing Electroencephalogram (EEG) at very low Signal to Noise Ratio (SNR), are obtained through the application of some processing method to extract them from the scalp-recorded brain response to a controlled stimulus. Averaging is the method commonly used to improve SNR [2, 3], but a large number of stimuli are required to get just one useful average EP, whose shape is blurred by the averaging process due to the existence of stochastic asynchronicities between the stimuli and the real EPs. To obtain the response to a single stimulus is important for two reasons:

a) whenever the average is not a valid estimate of the brain response [4]; and

b) to study variations that may constitute a parameter of neurophysiological or psychological significance.

Since, recently, from the medical researchers viewpoint, it is very attractive to obtain the response to a single stimulus [5, 6, 7, 8] a great number of methods, whose goal is to extract a single (maximum SNR) EP signal with a minimum of stimuli repetition, have appeared recently: Adaptive Fourier Estimation of Time-Varying Evoked Potentials [9], Modified Adaptive Line Enhancement [10], adaptive cancellation [11, 12, 13, 14, 15], and Wavelets and Time-Frequency distributions [16].

We present here a technique for obtaining single EP estimates using a two channel adaptive canceller [17, 13, 14, 15]. The primary signal has EP + EEG. The reference signal is the quasi-periodic extension of an average EP, over a few stimuli [12], which has been 'period-to-period' aligned with the primary signal by the maximization of its cross-correlation. This signal is fed to an adaptive transversal filter, whose coefficients are adjusted by the Widrow-Hoff adaptive algorithm [17, 14]. This procedure, known as Noisy Gradient or Least Mean Squares algorithm, seeks to minimize the mean square error between the filter output and the primary channel. Due to this process, the filter output becomes a very good approximation to the EP present in the primary channel. The filter order and convergence factor were determined empirically.

Experiments were performed with simulated signals, based on actual registers obtained from visually stimulated subjects, at various SNR values. Results are compared with those obtained with the averaging and cross-correlation averaging methods.

Section 2 contains the discussion of the adaptive canceller scheme. Section 3 presents the methodology and experiments. Conclusions are presented in section 4.

Adaptive Noise Cancelling Filter

Figure 1 shows a schematic of a two-channel adaptive noise canceller. The signal s_0 is contained in the primary channel, and the signal s_1, highly correlated with s_0, in the reference channel. These signals are corrupted by additive noise n_0 and n_1, assumed to be uncorrelated with each other and with both signals, respectively.

The error signal e is defined as the difference between the primary signal and the filter output y. When $E[e^2]$ is minimal, the filter output will be the best square minimal estimation of the signal s_0. The minimum power results when $y = s_0$; in that case y will be completely noise free. The condition $y = s_0$ is impossible to obtain due to the influence of noise n_1.

The normalized Estimation Error Spectrum (NEES) defined as the ratio of the output noise power spectrum divided by the signal power spectrum result in [18]:

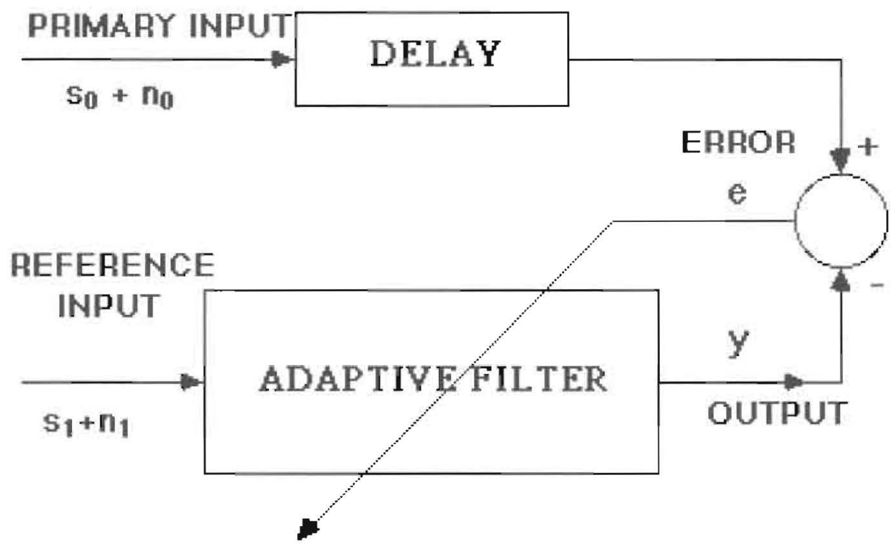

Figure 1. A two-channel Adaptive Noise Canceller.

$$NEES = 1 / (1 + SNR_1(z)) \quad (1)$$

where $SNR_1(z)$ is the SNR density function of the reference input. Then, the NEES diminishes as SNR of the reference input increases. Based upon this premises, we need:

a) s_1 related to s_0

b) n_0 uncorrelated with the filter input.

c) High SNR of the reference signal.

With this conditions in mind, we will construct a good reference signal.

Adaptive transversal filter coefficients are adjusted by the Widrow-Hoff LMS algorithm [17, 14]:

$$a_j = a_{j-1} + \mu\, e_j\, x_j \quad (2)$$

were: a is the coefficient vector; μ is the convergence factor; and x_j is the input signal vector

The filter order, the arbitrary initial values of the filter weights, and the convergence factor μ are required by the algorithm. A delay, equal to one-half the order of the adaptive filter, is included in the primary channel to achieve the performance that would be obtained if the optimum filter were non-causal [18].

Methodology

The described techniques were applied to simulated signals, based on actual registers obtained from subjects stimulated by visual checkerboard inversion patterns. These signals were fed to a 12-bit Analog to Digital converter, operating at 250 Samples/Sec.

The simulated signals were constructed as follows:

1. The pattern signal is the average of recorded responses to 100 stimuli.
2. The primary signal is the quasi-periodic extension of the pattern, randomly displaced (0-9 samples). This periodic extension of the pattern is the signal to estimate. This signal, corrupted by a spontaneous EEG record scaled to provide various signal to noise ratios (SNR) will be the primary signal.
3. The construction of the reference signal will be explained in the experiments.

To assess the performance of the scheme, the Normalized Mean Square Error (NMSE) over N samples is used.

Experiments

First, the filter order and convergence factor were determined empirically based on the minimal NMSE obtained, for period Nº 35, in experiments with various values of SNR of the input, filter length and convergence factor. A filter length of 12 and a convergence factor of 0.001 were selected for all the experiments.

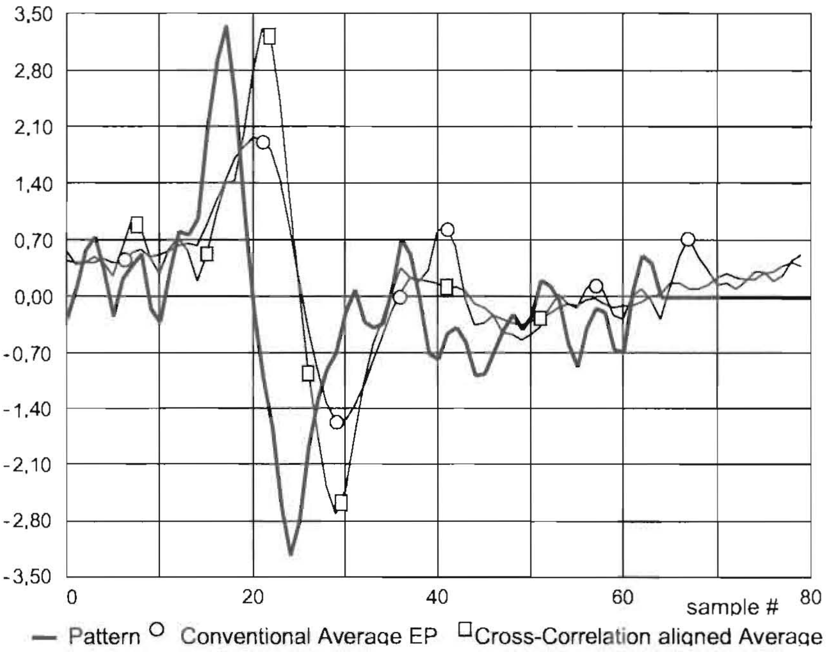

Figure 2. Comparison of the Pattern and conventional average EP over 100 periods (SNR=-6.9 dB) and cross-correlation aligned average EP over 100 periods (SNR=-6.9 dB).

The waveform obtained by averaging 100 periods of the variable latency primary signal with SNR=-6.9 dB, is shown in Figure 2. The output is a smeared version of the pattern also shown for comparison. A way to obtain better results could be to align the segments prior to computing the average, taking as synchronization markers the maximum of the cross-correlation [14] between the primary signal and an average EP over 100 periods of the primary signal. The new average EP obtained with this alignment process will be called the cross-correlation aligned average also shown in Figure 2. The comparison with the pattern allows us to conclude that the alignment process improves the average.

In the experiment 1 the reference signal is a periodic extension of a cross-correlation aligned average over 35 periods. This signal will be named cross-correlation reference. In the experiment 2, to improve the tracking of the latency variations, the reference signal is generated as the quasi-periodic extension of the average cross-correlation aligned EP enhanced by 'period-to-period' alignment by the maximization of its cross-correlation with the primary signal. This signal will be named cross-correlation aligned reference.

Results and Discussion

Figure 3 compares the NMSE of the estimate EP for differents SNR of the primary signal, obtained by:

a) conventional average;

b) adaptive cancelling using a reference signal generated as the periodic extension of the cross-correlation aligned average (EP Nº 35);

c) adaptive cancelling with a cross-correlation aligned Reference (EP Nº 35); and

d) cross-correlation aligned average.

Both cancelling techniques show better results than the conventional average EP. The NMSE of the PE estimated by Adaptive Cancelling with a Reference signal based on the cross-correlation aligned average is half the NMSE of the conventional average. The NMSE of the Adaptive Cancelling with a cross-correlation aligned Reference is still better. The NMSE of the cross-correlation aligned average EP is the lowest. However, averaging techniques are unable to provide a single EP.

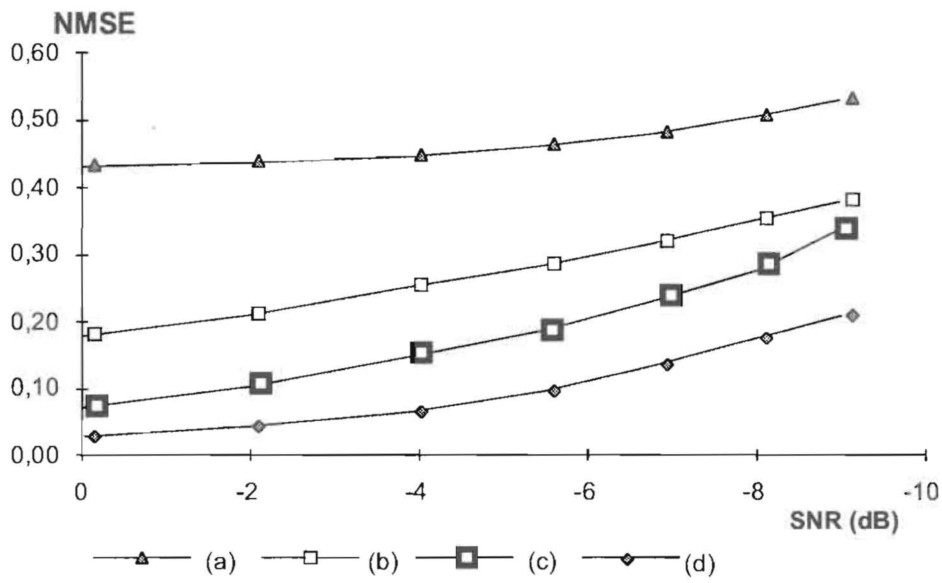

Figure 3. NMSE vs SNR of the Variable Latency Primary Signal for: a) Conventional average. b) Adaptive Cancelling with a Reference signal based on the cross-correlation aligned average (EP Nº 35). c) Adaptive Cancelling with a cross-correlation aligned Reference (EP N°35). d) Cross-correlation aligned average.

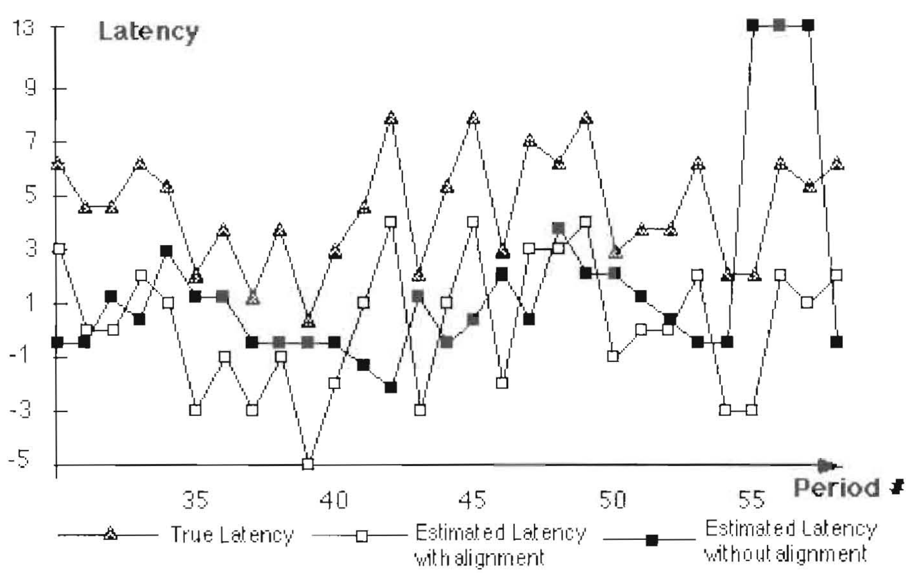

Figure 4. Latency variations vs. Period number.

The comparison of Figure 3b and 3c allows to conclude that the 'period-to-period' alignment used to improve the tracking of the primary signal latency variations, increases the correlation between primary and reference inputs (s0 and s1) producing better EP individual estimates. Figure 3b and 3c also shows that when the primary signal SNR decresases, the NMSE improvement is lower. This can be explained by noting that when the noise level increases, the positioning information produced by the crosscorrelation is less reliable.

Figures 4 shows the latency variation of the primary input with SNR=-9.1 dB (periods # 30 to # 60), and the latency variation of the estimated signal using the adaptive cancelling techniques with both a cross-correlation reference and a cross-correlation aligned reference. A constant latency offset, observed in figure 4, was kept for visualization purposes.

The latency changes are closely tracked using the alignment in the reference because the correlation between the signals in the primary and in the reference input is increased. In the segments where noise obscures the signal, latency changes aren't tracked and the noise peaks produce saturation of the, very simplified, search algorithm, however the latency tracking is remarkably good with an aligned reference. Figures 3 and 4 depicts the superior performance btained using the cross-correlation aligned ref - erence.

Conclusions

Averaging and adaptive canceling, produce better results when the signal has been 'period--to-period' aligned by the maximization of its cross-correlation with a pattern signal. The NMSE for the EP obtained by averaging is lower than the obtained for the estimated EP Nº 35 using adaptive canceling. However, this technique produces the EP for **each single stimulus**, even with random independent latency changes, and reduces the number of stimuli needed to extract an useful estimated signal. This allows the observation of EPs variability between stimuli and, therefore, to track the latency variations, in opposition to the averaging technique, that, after many stimuli, gives just one estimate of the EP, losing all the information about EP changes.

When the reference signal is aligned with the primary signal, through the correlation, the NMSE of the estimated signal (EP Nº 35) decreased, allowing the tracking of latency variations for primary signal SNR as poor as -9.1 dB.

The filter order, the convergence factor, and the number of periods averaged to generate the reference signal, were empirically chosen. However, due to variations between subjects and stimulation conditions, these values could be changed. In the near future, we will perform a statistical study to take these aspects into account.

The objective of this paper was to propose, and evaluate, a modified adaptive cancellation technique, based upon the construction of a good reference signal, in order to obtain better individual EP estimates. This technique, enhanced with reference alignment, produces a better estimate of the EP for each single stimulus, even with random independent latency changes and reduces the number of stimuli needed to extract a useful estimated signal. Using a similar number of stimuli as in traditional averaging, a better quality estimated EP is achieved, allowing to analyze the variability between stimuli. The application of the results of this work in clinical situations, will be a subject of future research.

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