A Somatosensory Evoked Potential Monitoring Algorithm Using Time Frequency Filtering

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Abstract—A new method of detecting somatosensory evoked potentials (SSEP) is proposed using a time-frequency based windowing to enhance the signal to noise ratio (SNR) of the recorded SSEP signals. A sequential computation of maxima and minima was then used to find the location of characteristic positive and negative peaks of the SSEP. The algorithm rejects trials with high peak value as they are corrupted with noise. The performance of the proposed algorithm was observed to be within acceptable clinical margins even with the use of only 30 consecutive trials at a time, thus proving to be very efficient for intraoperative neurophysiological monitoring during surgical procedures.

I. INTRODUCTION

Intraoperative neurophysiological monitoring (IONM) systems are used to ensure consistency of the nervous system response, with predefined performance metrics. Somatosensory evoked potentials (SSEP) are one of the useful protocols utilized during surgeries involving spinal cord such as deformity correction, spinal fracture repair and tumor removal [1], [2]. Moreover, this indicator is used to measure the performance in procedures affecting brain and peripheral nervous system [3–5].

The measurement part of SSEP monitoring is performed using scalp EEG recording channels of Cz−Fz and C3−C4 in standard 10-20 International System of EEG recording [6]. Meanwhile, the stimulation is applied to lower extremity using scalp cord such as deformity correction, spinal fracture repair and tumor removal [1], [2].

Moreover, this indicator is used to measure the performance in procedures affecting brain and peripheral nervous system [3–5].

The positive and negative peaks of an SSEP are labeled P and N respectively. For a typical SSEP, the P is observed to be at 37ms and N at 45ms after the stimulation. Consequently, they are called P37 and N45. The ultimate goal of an effective SSEP monitoring system is to be able to measure the peak-to-peak amplitudes and the exact time latencies of these two points and monitor them continuously throughout the surgery.

Most of the practical and widely used methods of SSEP monitoring require multiple stimulations in the order of 200-2000 to extract one SSEP signal by time domain integration or time averaging multiple recordings [8]. Based on averaging theory coherent integration of N signals added with white Gaussian noise improves the SNR √N times. In the following study, an innovative system comprising of input filters, trial rejection, time-frequency filtering and detector is proposed where the number of required trials can be reduced all the way to 30 while the expected results are to remain consistent. This improves the morphology of the SSEP over our earlier study [9] where the focus was placed, more on detecting the peaks and latencies.

II. AUTONOMOUS MONITORING METHOD

The morphological characteristics of the SSEP signal are patient specific and among other things depend on the anesthesia used to facilitate the procedure [10]. As a result, most of the SSEP monitoring algorithms require some form of averaging in the initialization step to create a baseline signal for comparison of the upcoming SSEP trials. The schematic diagram of the algorithm is depicted in Fig. 1.

A. Band Pass Filtering

An important point to consider when analyzing SSEP signals in the time domain is the careful selection of a given digital filter to be applied to optimize the detection of SSEP. Ideally, the selected filter should have a linear phase response to provide a constant group delay in the desired frequency range. This is the reason why most practical SSEP monitoring methods use some form of moving average filter, which is a linear phase response filter, for smoothing the signal in time domain. Considering discrete trials, each 100ms long, a fast Fourier transform (FFT) based finite impulse response (FIR) filter with linear phase response filtering is applied.

In FFT-based filtering all of the time domain samples for a single SSEP trial are transferred into frequency domain using FFT. The unwanted components are then annihilated and remaining components are transferred back to the time domain using inverse-FFT (IFFT). Prior to the application of FFT, a tapering window is used to limit the side-lobes and power leakage from adjacent frequencies. Here a Chebychev window is used on centralized time domain data in which the location of the actual SSEP signal is moved toward the middle of the time data by zero padding in the beginning based on a normal SSEP signal. For a typical SSEP, the evoked potential is centered at 41ms (mean of 37ms and 45ms). Considering that a 100ms data is recorded, data may be centralized by adding 12ms of zeros to the beginning of
recorded samples ensuring minimal signal distortion by the tapering process. Subsequently, the FFT coefficients between 50-500Hz are kept and all others are set to zero before performing the inverse Fourier transform.

B. Reject Corrupted Signals

In a surgical procedure utilizing SSEP monitoring, there are some trial data that get corrupted by interference either due to electrode movement or physical pressure to the nervous system during the operation. These trials should be rejected before entering the processor to prevent unrealistic outputs. As can be seen in Fig. 2 rejecting high amplitude trials results in a very clean SSEP signals. Setting a constant threshold may cause the system to reject all the signals in a pack of trials which is not desirable. Thus the criteria here is to select some trials with the lowest peak absolute value among a group of consecutive trials. This method ensures that there would be a guaranteed output after some pre known number of trials. The number of accepted trials may be lowered which results in a better SSEP morphology because normally the high peaks of a trial are created by the interference and not the SSEP signal. On the other hand, decreasing the number of signals used for further processing makes the results less consistent. Here, the results are based on selecting 20 trials from a group of 30.

C. Averaging

Consider that there are ‘M’ number of trials that have passed the rejection criteria. The general processing method for SSEP is to increase the SNR by averaging these M trials. This method requires for the trials to be highly correlated in the SSEP interval and uncorrelated elsewhere. If the trials are also highly correlated outside the SSEP interval then the averaging method only combines the signals from M trials providing some kind of consistency over different processing intervals and limited signal to noise improvement is achieved. In Fig. 2 the green plot shows the SSEP by averaging all the blue plots in the figure.

D. FFT filter

FFT filter in this step is the same as the band pass filter used for pre filtering of each trial but the higher cut-off frequency is lowered to 120Hz to have a smoother SSEP signal. It is important to attenuate the unwanted sharp peaks for better results in the detector section. Moreover, application of the time tapering Chebychev window further reduces noise components outside the desired SSEP interval facilitating the extrema detection process.

E. Extrema Detector

The positive and negative peaks of the filtered signal should be detected along with their respective time delays for further processing and comparison to the baseline data. A simple yet powerful method is based on using the Walsh transform for peak detection [11]. Here a method based on segmentation is introduced where the global maxima and minima are detected in progressively shorter intervals. The algorithm is as follows:

1) Find the global extremum
2) Divide the data to right and left sections from the extremum
3) Find the global extremum of opposite sign in each side
4) Select two sections, one from the beginning to the first extremum and the other from the second extremum to the end of the signal
5) Find global extremum of opposite sign in each section
6) Repeat step (4) and (5) two times

In general the algorithm returns five negative peaks and four positive peaks.

F. Comparator

Now that the extrema of the filtered SSEP are detected they can be compared with the baseline data. The nearest positive peak to the baseline P37 is considered as the measured P37 and the nearest negative peak to the baseline N45 is considered as measured N45. The peak-to-peak amplitude...
is compared to the baseline SSEP amplitude. If the amplitude deviates by more than 50% from baseline value then the operator is informed about a possible alarm. Moreover, more than 5% difference between measured P37 and N45 and their respective baseline values creates an alarm too.

In the next section the described algorithm is applied to the recorded SSEP data of two sample patients and the results would be discussed.

III. SIMULATION RESULTS

The algorithm is applied to real data recorded from two different patients under different procedures. Data has been recorded in two different times for each patient and the objective is to evaluate consistency of SSEP monitoring. Baseline SSEP latencies are shown for two patients in Table I. Patient one underwent T4-S1 posterior spinal fusion procedure and patient two underwent the surgery of posterior spinal fusion for scoliosis. As can be seen here latencies are lower for the younger patient but they are near normal 37ms and 45ms expected latencies. For each patient two sets of trials are provided for different stages of the procedure. In each set there are more than 80 consecutive SSEP stimulations and recordings. Each step of the algorithm is applied to these sets of data and the results are evaluated to be within accepted margins. Each step of the algorithm is shown when applied to the first set of trials for patient one for clarification.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age</th>
<th>C3−C4</th>
<th>C2−Fz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>66</td>
<td>36.9</td>
<td>42.2</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>32.2</td>
<td>39.5</td>
</tr>
</tbody>
</table>

A. Band pass filter

The first 30 trials are shown in red in Fig. 3, which are the original inputs to the algorithm. In this case the recorded data is already filtered using a moving average filter on the equipment. The average of the 30 input signals is also shown here. These signals are passed through the band pass filter and the results are shown in Fig. 4. The band pass filter rejects components over 500Hz.

B. Rejecting Corrupted Signals

From the pack of 30 trials a set of 20 trials are selected which have the minimum peak value. This set is also shown in Fig. 4. Trials selected for the rest of the algorithm are shown in green. As can be seen from red and green plots, signals with lower P37 values in the interval 30-40ms pass the rejection process.

C. Averaging

The remaining 20 accepted trials are averaged at each time sample so that a single SSEP signal of the same length is generated. The average signal is shown in blue Fig. 4.

D. FFT filter

The average signal is passed through the FFT filter described earlier with pass band range of 50Hz to 120Hz. The Chebychev window used in the band pass and FFT filters tends to attenuate unwanted signals adjacent to the SSEP window. In Fig. 5 the average SSEP along with the FFT filtering result may be seen.

E. Extrema detector

The maxima and minima of the signal are detected using the proposed method of segmentation. First the global minimum is calculated which usually stands for N45 but the algorithm continues to find other local minima just in case there is an interference causing negative peaks other than N45.

The data samples are segmented to left and right of the global minimum and in each segment the global maximum is calculated. The new segments would be from 0msto the
first maximum and from the second maximum to the end. Now global minimum is calculated in each segment and this process goes on for another two rounds. The result normally would be 5 negative and 4 positive peaks. The positive and negative peaks nearest to the baseline time latencies for P37 and N45 are selected and the difference between their amplitudes is considered to be the peak-to-peak amplitude of the SSEP. The detected points for positive and negative peaks are shown in Fig. 6.

![FFT Filtering of the average SSEP](image)

**Fig. 5. FFT Filtering of the average SSEP**

![Extracting positive and negative peaks](image)

**Fig. 6. Extracting positive and negative peaks**

### F. Comparator

The comparator unit gets the baseline data from baseline calculator and compares it to the data obtained from the extrema detector. If the latencies and amplitudes of the calculated SSEP are within the predefined limits (10% for time latencies and 50% for amplitudes) the patient status is reported as good, otherwise an alarm is raised.

### IV. Conclusion

The proposed method for monitoring the SSEP signal could successfully extract the characteristics of the evoked potential in the recordings with a limited number of trials. Setting the rejection block to accept 20 out of 30 trials causes the algorithm to generate outputs less frequently but simultaneously there would be fewer false alarms. On the other hand when the algorithm is set to accept 5 out of 10 trials in the rejection block, the false alarm rate would increase along with the output update rate. The choice of rejection parameters affects the false alarm rate and can be regarded as a technical variable that is set during an operation based on accepted false alarm rate.

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### References


