Reducing the Effects of Electrocardiographic Artifacts on Electro-oculography in Automatic Sleep Analysis

Jussi Virkkala, Joel Hasan, Alpo Värrri, Eero Huupponen, Sari-Leena Himanen, Kiti Müller

Abstract—Removal of electrocardiographic (ECG) artifacts of QRS complexes from a single channel electroencephalography (EEG) and electro-oculography (EOG) can be problematic especially when no reference ECG signal is available. This study examined a simple estimation method excluding the possible QRS part of the EOG trace before spectrum estimation. The method was tested using a simple sleep classifier based on 0.5-30 Hz mean frequency of single channel sleep EOG, with the left EOG electrode referenced to the left mastoid (EOG L-M1). When QRS peaks were automatically excluded from the least square (LS) mean frequency estimation the average optimal mean frequency threshold decreased from 9.3 Hz to 8.8 Hz and agreement and Cohen's Kappa increased respectively from 89% to 90% and from 0.44 to 0.50 when compared to the traditional spectral estimation.

I. INTRODUCTION

ELECTROCARDIOGRAPHIC artifacts in EEG, EMG and EOG represent a problem in, for instance, automatic sleep analysis [1]. When the ECG signal is available, adaptive filtering can be used for the elimination. When multiple signals are recorded a blind source separation is also an alternative. With a single EEG or EOG signal and without the ECG signal the methods available are limited [2, 3].

Park et al. [2] eliminated the QRS part from the EEG and estimated autoregressive (AR) model parameters from this partial data. Estimates were then used to reconstruct the signal without QRS artifacts using the AR model. Later Park et al. [3] used a modified ensemble average subtraction method. The subtraction process is sensitive to false positive

QRS detections. In this study, the power spectrum of EOG was estimated using least square (LS) estimation with and without the data portion during the possible QRS. No reconstruction was used. Numerous options exist for QRS detection from the ECG signal [4]. In this study a relatively simple method was used on EOG to demonstrate the principle of the proposed QRS reduction algorithm. Results were evaluated using the mean frequency of EOG L-M1 as an indicator of sleep depth [5]. EOG electrodes record frontal EEG activity together with eyelid and pupil movements.

II. MATERIAL

Subjects were selected among the participants of a previous study [6]. Polysomnographic recordings were sorted by the amount of visually scored slow wave sleep (SWS). The recordings of every tenth subject in the sorted validation list were further analyzed in this study. Recordings were visually scored according to a standard [7] by two experienced sleep technologists. Automatic analysis is based only on EOG Left (slightly lateral and 1 cm up from the outer canthus), referenced to the left mastoid M1 (EOG L-M1).

III. METHODS

The analysis, based on overlapping 2 s segments, was carried out in 0.5 s intervals resulting in 75% overlap. The analysis involved four steps: A) detection of QRS peaks from a single EOG channel, B) estimation of power spectrum of EOG with and without the data part during the possible QRS peaks, C) calculation of mean frequency, and D) evaluation using a simple sleep classifier based on mean frequency of EOG L-M1.

A. QRS peak detection

Two second EOG L-M1 segments were filtered with a 2nd order Butterworth infinite impulse response (IIR) filter. Zero phase 10-30 Hz filtering was obtained using the second filtering on reversed filtered signal.

From the filtered signals, the absolute maximum value was used as an estimate of the first QRS peak in each segment. The second highest peak outside the 65 ms window of the first peak was used as an estimate of the second QRS peak. If the distance was at least 665 ms from the first peak (heart rate <90 bpm) it was also considered as a possible QRS peak. If the second peak was accepted, the third highest
peak was also evaluated similarly.

New spectral estimates of EOG were used only when at least two peaks were detected. Fig. 1 and 2 visualize the QRS detection in a case with some and a case with no QRS artifacts during SWS and SREM.

**B. Estimation**

We used a least square (LS) representation of Discrete Fourier Transform (DFT) to evaluate the power spectrum from 0.5 to 30 Hz. Spectrum $P$ of $y$ can be evaluated using (1) and (2) where $f$ is from 0.5 to 30 Hz in 0.5 Hz steps and $t$ is from 0 to 1995 ms in 5 ms steps and $w$ is the Hann window.

$$A = \begin{bmatrix}
\exp(i2\pi f_0) & \cdots & \exp(i2\pi f_m t_0) \\
\vdots & \ddots & \vdots \\
\exp(i2\pi f_n) & \cdots & \exp(i2\pi f_m t_n)
\end{bmatrix}$$

(1)

$$P = \left( A^T A \right)^{-1} A(w)$$

(2)

Using detected possible QRS peaks, a modified matrix $B$ was created for each 2 s segment by removing 5 rows (25 ms) around each QRS peak. A modified spectrum $P_m$ was then obtained by (3).

$$P_m = \left( B^T B \right)^{-1} B(w_m)$$

(3)

**C. Calculation of mean frequency**

Mean frequencies were evaluated for both spectrum estimation methods from 0.5 to 30 Hz by (4-5).

$$M = \frac{\sum f P(f)}{\sum P(f)}$$

(4)

$$M_m = \frac{\sum f P_m(f)}{\sum P_m(f)}$$

(5)

**D. Sleep detection**

Wakefulness and sleep were separated in 30 s epochs using mean frequency of EOG L-M1. When the percentage of 2 s segments with a mean frequency below the fixed threshold during the 30 s epoch was above the set threshold then the epoch was labeled as sleep and otherwise as awake. This automatic detection was compared to the standard visual scoring based on EEG, EOG and submental EMG [7].

**E. Statistical analysis**

Agreement and Cohen’s Kappa [8] were used to evaluate the sleep detection. Leave-one-out cross validation was done by calculating the agreement for each subject by training the system using data from the rest of subjects.

The Wilcoxon Signed Ranks Test was used for testing the variation in Cohen’s Kappa between the two methods.

**IV. RESULTS**

On average, 60% of segments had at least two possible QRS peaks. In Fig. 3 mean frequency without QRS is shown as a function of mean frequency with QRS peak.
The average agreement for binary wakefulness, sleep classification without QRS removal was 89% with Cohen’s Kappa of 0.44. This was obtained with an average mean frequency of less than 9.3 Hz in more than 86% of segments in each 30 s epoch. The improvement in Cohen’s Kappa was significant (p=0.002).

Classification results with mean frequencies during different sleep stages are shown in Table I. Individual results for all subjects are shown in Table II.

<table>
<thead>
<tr>
<th>Sleep stage</th>
<th>Wake</th>
<th>Sleep</th>
<th>Mean freq. (Hz)</th>
<th>Wake</th>
<th>Sleep</th>
<th>Mean freq. (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MT</td>
<td>200</td>
<td>356</td>
<td>6.4</td>
<td>253</td>
<td>303</td>
<td>6.5</td>
</tr>
<tr>
<td>Wake</td>
<td>718</td>
<td>475</td>
<td>8.1</td>
<td>763</td>
<td>430</td>
<td>8.1</td>
</tr>
<tr>
<td>SREM</td>
<td>160</td>
<td>2615</td>
<td>4.8</td>
<td>108</td>
<td>2667</td>
<td>4.9</td>
</tr>
<tr>
<td>S1</td>
<td>359</td>
<td>1245</td>
<td>5.9</td>
<td>349</td>
<td>1255</td>
<td>5.9</td>
</tr>
<tr>
<td>S2</td>
<td>282</td>
<td>6653</td>
<td>4.4</td>
<td>270</td>
<td>6575</td>
<td>4.5</td>
</tr>
<tr>
<td>S3</td>
<td>17</td>
<td>847</td>
<td>3.1</td>
<td>16</td>
<td>848</td>
<td>3.4</td>
</tr>
<tr>
<td>S4</td>
<td>3</td>
<td>898</td>
<td>2.5</td>
<td>3</td>
<td>898</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Table I: Total number of epochs classified as wake, sleep and mean frequency in different sleep stages using mean frequency without and with QRS removal.

V. DISCUSSION

The number of ECG elimination methods for single channel analysis when no ECG reference signal is available is limited [2, 3]. In this study the ECG artifact part of an EOG channel was left out of the least square (LS) estimation of mean frequency. This improved the results of automatic sleep detection. In contrast to, for instance, the subtraction method the effects of QRS false positives can be assumed to be small.

Fig. 2. Two examples of QRS peak detection during SREM with a two second segment showing some QRS peaks (top) and no QRS peaks (bottom): a) raw EOG Left-M1 signal b) absolute filtered 10-30 Hz with peaks c) original signal with 25 ms (5 samples) removed around these peaks indicated by a circle.

Fig. 3. Mean frequency without QRS is shown as a function of mean frequency with QRS peak. For clarity only every 60th point is plotted.
TABLE II
SUBJECT NO, SLEEP EFFICIENCY, PERCENTAGE OF SEGMENTS WITH ATLEAST TWO QRS PEAKS, AGREEMENT AND COHEN’S KAPPA FOR AUTOMATIC WAKEFULNESS AND SLEEP BINARY CLASSIFICATION BASED ON MEAN FREQUENCY WITHOUT AND WITH QRS REMOVAL.

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>No. Sleep eff.</th>
<th>QRS Agreement</th>
<th>CK</th>
<th>With QRS removal</th>
<th>Agreement</th>
<th>CK</th>
</tr>
</thead>
<tbody>
<tr>
<td>216</td>
<td>89% 84%</td>
<td>79.5%</td>
<td>0.37 85.5% 0.48</td>
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<td></td>
<td></td>
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<tr>
<td>261</td>
<td>94% 61%</td>
<td>90.4%</td>
<td>0.52 89.8% 0.51</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>169</td>
<td>84% 49%</td>
<td>82.5%</td>
<td>0.51 82.4% 0.52</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>194</td>
<td>85% 74%</td>
<td>93.2%</td>
<td>0.67 93.6% 0.72</td>
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<tr>
<td>82</td>
<td>79% 55%</td>
<td>86.0%</td>
<td>0.57 86.5% 0.60</td>
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<tr>
<td>262</td>
<td>94% 64%</td>
<td>94.4%</td>
<td>0.29 94.5% 0.30</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>213</td>
<td>96% 60%</td>
<td>97.1%</td>
<td>0.56 97.0% 0.59</td>
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<td></td>
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<tr>
<td>131</td>
<td>84% 34%</td>
<td>86.9%</td>
<td>0.41 88.0% 0.49</td>
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<tr>
<td>31</td>
<td>81% 51%</td>
<td>87.2%</td>
<td>0.49 89.3% 0.60</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>91% 63%</td>
<td>92.9%</td>
<td>0.59 94.7% 0.71</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>181</td>
<td>81% 79%</td>
<td>79.9%</td>
<td>0.53 82.8% 0.58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>196</td>
<td>98% 66%</td>
<td>97.5%</td>
<td>0.18 97.6% 0.35</td>
<td></td>
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<td></td>
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<tr>
<td>24</td>
<td>84% 53%</td>
<td>86.6%</td>
<td>0.23 87.1% 0.27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>195</td>
<td>96% 50%</td>
<td>94.7%</td>
<td>0.24 94.9% 0.36</td>
<td></td>
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</tr>
</tbody>
</table>

VI. CONCLUSION

Simple exclusion of possible QRS artifacts from single channel EOG improved the automatic wakefulness and sleep detection based on the mean frequency of EOG L-M1. Use of disposable EOG electrodes enables self-applicable methods for the ambulatory monitoring of wakefulness and sleep in shift work and in screening studies of sleep disorders.

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REFERENCES


