EOG AND ECG MINIMIZATION BASED ON REGRESSION ANALYSIS

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ABSTRACT:

A method based on regression analysis is presented that can be used for automatic minimization of EOG and ECG artifacts in the sleep EEG.

INTRODUCTION

It is known that the non-cortical activity gives a contribution to the EEG recordings. Electrooculogram (EOG), the electrocardiagram (ECG) and muscle activity (EMG) are the most important non-cortical sources.
For sleep analysis it is important to know the undisturbed EEG. Therefore, it is necessary to detected and/or reduce non-cortical sources on EEG. Additionally, the detection/removal methods must be fully automatic.
In the SIESTA project EOG, ECG as well as EEG are recorded. Therefore, it is self-evident to use these signals to reduce the influence of the EOG and the ECG. The EMG channel is not used, because the activity of different muscles is concerned. Therefore EOG and ECG signals are used for regression analysis, with the aim to reduce, at least, the linear and time-invariant part of the superposition.
Elbert et al. (1985) showed theoretically how the EOG influences the scalp potentials. Berg and Scherg (1994) assumed that the EOG source is a dipole. They applied a *multiple source eye correction (MSEC)* method. Based on that approach Ille et al. (1997) calculated a Spatial Filter matrix with Principle Component Analysis (PCA). Lagerlund et al. (1997) applied PCA for identifying different kinds of artifacts. The artifact components were identified by visual inspection of the principle components.

METHOD

Model:

It is assumed that the recorded EEG is a linear, time-invariant superposition of different sources.

$$EEG'(t) = EEG_{co}(t) + b_c \cdot ECG(t) + b_o * EOG(t) + u \qquad (1)$$

EEG' is the signal that can be recorded on the scalp, EEG_{co} is the cortical activity, ECG is the contribution from the heart and EOG is the contribution from the eyes. u considers the differences in the mean values; e.g. by an offset of the amplifier or the digitization, by different reference electrodes etc. The coefficients b are mainly determined by the geometry and the conductivity. During sleep it can be assumed that both are constant and do not vary in time. That means the system is time-invariant.
Linear means that every activity of any source is propagated without time delay and with constant attenuation. Furthermore it does mean that all frequencies are attenuated equally. For low frequencies (<1kHz) it can be assumed that the propagation time is negligible and capacitive effects can be omitted.

Estimation of the coefficients

We distinguish between channels whose influence should be eliminated

$$X_{TxNNE} = [ECG_{Tx1}\ EOG1_{Tx1}\ EOG2_{Tx1}]; \qquad (2)$$

and channels that should be corrected to obtain the 'true' EEG activity

$$Y_{TxNE} = [EEG(1)_{Tx1} \ldots EEG(NE)_{Tx1}]; \qquad (3)$$

All channels are concluded in S = [1 X Y]

$$S_{Tx(1+NE+NNE)} = [1_{Tx1}\ ECG_{Tx1}\ EOG1_{Tx1}\ EOG2_{Tx1}\ EEG(1)_{Tx1} \ldots EEG(NE)_{Tx1}] \qquad (4)$$

The mean value of each channel is summarized in the vector

$$\mu = mean(S) = E\{(S)\} = \mu = [T\ \Sigma X\ \Sigma Y]/T \qquad (5)$$

whereby $E\{.\}$ is the expectation operator and Σ is the summation operator for a column

We denote the 'true' (corrected) EEG

$$Y'_{TxNE} = [EEG(1)'_{Tx1} \ldots EEG(NE)'_{Tx1}]; \qquad (6)$$

The sum of the true activity and the additional non-EEG sources are recorded at the EEG electrodes

$$Y_{TxNE} = Y'_{TxNE} + X_{TxNNE} . b_{NNExNE} + 1_{Tx1} . u_{1xNE} \qquad (7)$$

whereby b are the coefficients (model coefficients) for correcting

$$b_{NNExNE} = (X^T_{NNExT} . X_{TxNNE})^{-1} . X^T_{NNExT} . Y_{TxNE} \qquad (8)$$

$$Y'_{TxNE} = Y_{TxNE} - X_{TxNNE} . b_{NNExNE} - 1_{Tx1} . u_{1xNE}$$
$$= S_{Tx(1+NE+NNE)} [-u^T_{1xNE} \mid -b^T_{NNExNE} \mid I_{NExNE}]^T \qquad (9)$$

X are the Non-EEG channels including a 1 column; *Y* denotes the EEG channels and S contains all channels; μ is the mean value vector over all channels and ' denotes the corrected or 'true' EEG; *NE* is number of EEG channels, *NNE*-1 is the number of Non-EEG channels; and b are the regression coefficients. *T* is the number of samples of the signal, superscripted ^{T} is the transpose operator, subscripted $_T$ denotes the number of elements of a vector (matrix.).

1) Calculation of the Covariance-matrix.

$$XCM = [1\ X\ Y]^T * [1\ X\ Y] = S^T * S =$$

$$XCM = \begin{bmatrix} T & \Sigma X & \Sigma Y \\ (\Sigma X)^T & X^T X & X^T Y \\ (\Sigma Y)^T & X^T Y & Y^T Y \end{bmatrix} \qquad (10)$$

The elements $(X^T . X)$ and $(X^T . Y)$ which are needed for calculating the regressions coefficients $b_{i,j}$ according to equation (5) are contained in the covariance-matrix XCM

The '1' column in S is considering the mean value μ. In CMX corresponds this additional row (and column) to the mean values of every channel. The really covariance *matrix* $E\{(S-\mu)^T.(S-\mu)\}$(without mean) is $E\{(S)^T.(S)\}-(\mu^T.\mu) = XCM/T - \mu^T.\mu$ reduced by 1 column and row of the mean. The covariance matrix can be easily calculated without an additional computation step for the mean value.

The covariance matrix *XCM* was calculated from whole night recordings; a simple artifact rejection method based on overflow check was applied; The EDF format gives a maximum and a minimum value for every channel (Kemp et al 1992) . The sample has been rejected if any channel excites the boundary.

Note: *XCM* can be also calculated for every sample (or segment) *i* and summed up. In this case the whole data set has not be loaded at once. The memory requirements are much lower.

2) Calculation of the b-coefficients (equation 5)
The regression coefficients b can be easily calculated from the elements of the covariance matrix.

$$[\mathrm{u}_{1xNE} \quad \mathrm{b}_{NNExNE}] = \left([1 \quad X]^T [1 \quad X]\right)^{-1} \left([1 \quad X]^T Y\right) \qquad (11)$$

3) Correcting the EEG Data (equation 6)
The EEG channels can by easily corrected by the following matrix multiplication

$$Y' = [1 \quad X \quad Y] * \begin{bmatrix} -\mathrm{u}_{1xNE} \\ -\mathrm{b}_{NNExNE} \\ I_{NExNE} \end{bmatrix} \qquad (12)$$

Data

The majority of the data was from the European Neurological Network (ENN) database. Additional recordings were from the Klinikum der Philipps-Universität Marburg / Schlafmedizinisches Labor (MARB) and at the Department of Psychiatry / University of Vienna (PSYV). All data were stored in the European Dataformat (EDF) for Biosignals (Kemp et al. 1992).

Data	Sleep Laboratory		Fs [Hz]	Length [s]	Overflow [s]
MR001S01	MARB	ENN Database	100	30780	187.580
MR001S03	MARB	ENN Database	100	30630	209.070
MR002S01	MARB	ENN Database	100	28241	567.860
MR003S01	MARB	ENN Database	100	33744	7900.030
MR003S03	MARB	ENN Database	100	28760	776.440
MR004S01	MARB	ENN Database	100	26870	224.500
MR005S01	MARB	ENN Database	100	28800	203.530
SIE00001	MARB		100	29595	1604.960
D0000000	PSYV		256	20880	(*)

Table 1: Overview of the Data. The MR* records were provided from the European Neurological Network (ENN). Only channels with same sampling rate as the EEG channel were evaluated; Fs gives the corresponding sampling rate. Length is the total recording time and overflow gives the time where in any channel an overflow occurred. (*) indicates that no (reliable) overflow check was possible.

RESULTS

$E\{(S-\mu)^T.(S-\mu)\}$	ECG [mV]	EEG 1 C3-A2 [µV]	EEG 2 Cz-O2 [µV]	EOG 1 [µV]	EOG 2 [µV]
ECG [mV]	0.071	0.035	-0.024	-0.034	-0.055
EEG 1 C3-A2 [µV]		30.640	7.062	1.771	0.231
EEG 2 Cz-O2 [µV]			19.402	1.367	0.591
EOG 1 [µV]				3.220	-0.209
EOG 2 [µV]					4.679

Table 2: Upper triangular elements of the covariance matrix of ECG, EEG and EOG of recording MR001S03.EDF; the diagonal Elements are the variance (total power) of every channel. The other elements are the covariance between the corresponding channels indicated in the first row and column.

MR001S01	μ	EOG 1	EOG 2	EKG
EEG 1 C3-A2	0.4885	0.8384	0.2146	0.8420
EEG 2 CZ-O2	0.0926	-0.4687	-0.1535	0.4805

MR001S03	μ	EOG 1	EOG 2	EKG
EEG 1 C3-A2	0.4310	0.5643	0.0844	0.8312
EEG 2 CZ-O2	0.2442	0.4338	0.1455	-0.0160

MR002S02	μ	EOG 1	EOG 2	EKG
EEG 1 C3-A2	4.4536	0.2240	-0.3101	-0.6696
EEG 2 CZ-O2	4.6858	0.2410	0.0302	-0.9151

MR003S01	μ	EOG 1	EOG 2	EKG
EEG 1 C3-A2	7.9051	0.0256	0.4079	1.8968
EEG 2 CZ-O2	-5.6354	-0.0578	-0.3120	0.9694

MR003S03	μ	EOG 1	EOG 2	EKG
EEG 1 C3-A2	0.2709	0.0863	-0.1035	1.1525
EEG 2 CZ-O2	-0.1053	0.0293	0.2389	-0.0371

MR004S01	μ	EOG 1	EOG 2	EKG
EEG 1 C3-A2	0.3846	0.2124	0.6922	0.4342
EEG 2 CZ-O2	0.1748	-0.4034	0.0070	-0.5025

MR005S01	μ	EKG
C3A2	-11.2421	0.0702
C4A1	1.0923	-0.0373
A1A2	-15.6756	0.1151

SIE00001	μ	EOGlinks-A2	EOGrechts-A2	EKG
EEG 1 C3-A2	-0.0274	0.0755	-0.0905	0.0275
EEG 2 CZ-O2	-0.5508	0.0986	0.0528	-0.2641

D0000000	μ	AG1	AG2	EKG
FP2	24.6910	0.3501	0.2707	-0.0075
A2	3.6706	0.0708	0.1109	-0.0789
C4	1.5568	0.2236	0.1913	-0.0279
O2	3.0593	0.0933	0.0844	-0.0501
FP1	-1.7518	0.3157	0.1433	0.0760
P3	1.1814	0.3008	0.2482	-0.0252
C3	2.8961	0.1488	0.0413	0.0649
O1	27.7612	0.0285	-0.0301	0.0323
FZ	2.7986	0.2997	0.2144	-0.0041
CZ	2.0966	0.2574	0.1911	-0.0187
PZ	2.7482	0.1790	0.1434	-0.0287
F3	2.8166	0.2613	0.0966	0.0648

Table 3: Regression coefficients $b_{i,j}$ for correcting the EEG channels for all data sets. In the upper left corner of every table is denoted the recording name, the first column and row depict the labels (as in the EDF-header information), of the EEG channels and the non-EEG channels, respectively. μ denotes the constant coefficient in equation (1).

The corrected EEG for recording MR001S03 can be calculated according to equation (6) as follows.

EEG(1)' = EEG(1) - 0.4310 - EOG1 * 0.5643 - EOG2 * 0.0844 - ECG * 0.8312

In Table 2 can be seen that the coefficients are different for different EEG channels. E.g. in recording MR001S03 can be clearly seen how, that the ECG influence to EEG 1 (C3-A2) is much bigger (0.8312) than to channel EEG2 (-0.0160). Furthermore can also be seen that EOG1 has a much bigger influence than EOG2.

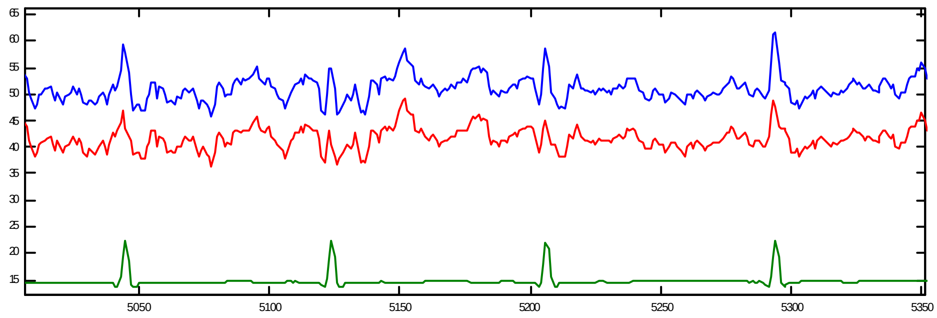

Figure 1: The channel "EEG1 C3-A2" of the recording MR003S01.EDF is shown. The first line shows the original EEG in [µV]. The second line is the corrected EEG1' and the third line shows the recorded ECG [3mV / unit]. The time axis is drawn in sample units; 5050 corresponds to sample 475550 from the beginning of the recording. The sampling rate was 100Hz.

Figure 1 gives an example for ECG reduction. A segment of recording MR003S01 was taken and the recorded EEG1 was corrected using the ECG channel.

*EEG(1)' = EEG(1) + 1.8968 * ECG*

In the first signal it can bee seen that the QRS-complex of the ECG contributes to the EEG signal. After reduction of the ECG (second line) the QRS-complex in the EEG is attenuated.

DISCUSSION

As can be seen in Table 2, the covariance e.g. between EEG1 and EOG1 is 1.771µV²; that are 1.771/30.640 = 5.8% of the variance in EEG1 and can hardly be ignored. Furthermore many regression coefficients in Table 3 are much larger than zero. That means that the recorded signals are correlated. This correlation should be considered in the further analysis. A side-effect of the applied method is the covariance matrix obtained. This covariance matrix might be interesting for further analysis.

It was shown in figure 1 that the ECG component can be reduced, but is still present. One reason for the incomplete ECG removal might be that only one (spatial) component of the ECG was considered. That might also happen with the EOG channels. Because of the imperfect elimination of the EOG and ECG the term "minimization" is suggested.

A limitation is that not all (spatial) components of the non-cortical sources are recorded. Components that are orthogonal to the recorded channels cannot be removed. The next step is, that not only the recorded EOG channels (against the reference electrode) are regressed but also some additionally transformed channels. E.g. EOG1-Fp1 and EOG2-Fp2 might be a good measure for the vertical activity of left and right eye, respectively.

The introduced regression method can be fully automated. Initially, the covariance matrix has to be computed. Secondly, the regression coefficients b are calculated. Finally, the correction of the EEG signal can be done by applying a matrix multiplication to the recorded channels corresponding to spatial filtering. No visual inspection is needed with the reported method.

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