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Original Article

Correlation between EOG and EEG in the detection of sleep onset

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Purpose: Bus driver sleepiness is a serious and urgent public safety issue. Manually analyzing electroencephalogram (EEG) changes to determine sleep onset latency, Maintenance of Wakefulness Test (MWT), is the gold standard for evaluating subject's ability to keep alert at twilight and in quiet situations. However, this test cannot be applied to drivers at work. Therefore, we attempted to develop an auto-program that analyzes sole electrooculogram (EOG) signals in a quasi-real-time manner, and sends out an immediate warning when sleepiness is detected.
Methods: Eighty-one bus drivers were recruited. Blink-type waves were characterized by pulse-type, high amplitude and high frequency (0.6–1.3Hz), and corresponded to fast eye closing and opening. Slow eye movement (SEM) was characterized by low frequency (0.2–0.6Hz), and corresponded to rolling, horizontal, bidirectional and conjugate eye movements. Sleep onset was determined by Blink index level lower than a certain threshold, concomitant with SEM index level higher than another threshold. These two thresholds were set progressively by corresponding MWT-determined sleep onset.
Results: Thresholds of these two indices were set at 79 and 985 from the data of 43 subjects. Sleep latency determined by EOG showed good agreement and sensitivity in comparison with MWT (91.2% and 93.3%, respectively). Following further verification with 38 subjects, agreement and sensitivity of sleep latency detected by EOG reached 88.3% and 93.6%, respectively.
Conclusion: This auto program computed sleep onset latency using indices of Blink and SEM. The results are in strong agreement with those of MWT. Our innovative EOG-based program has the potential to be applied to drivers and working individuals to warn of sleep onset in almost real time.

Keywords: Driver, slow eye movement, blink

INTRODUCTION

Bus driver sleepiness is a serious public safety issue. Electroencephalogram (EEG) changes are manually analyzed by well-trained technicians to determine sleep onset latency, making Maintenance of Wakefulness Test (MWT) the gold standard for evaluating subject's ability to keep alert at twilight and in quiet situations. However, this test is not

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able to be applied to drivers at work. Therefore, we attempted to develop an auto-program that analyzes sole electrooculogram (EOG) signals in a quasi-real-time manner, to immediately warn working individuals of sleepiness. The sleep onset latency determined by this program, based on thresholds of Blink index and slow eye movement (SEM) index, shows strong agreement with that determined by MWT.

During MWT, subjects are instructed to "stay quiet". However, this condition is not compatible with driving. In the present study, we focused on the correlations between EOG and EEG in two situations, lying quietly and performing some simple actions. Each subject completed 4 tests, divided into two types, standard MWT (2 tests) and non-standard MWT (2 tests) including actions (looking for an LED light and pushing a button). In previous studies, Fabbri et al. (2010) [1], Virkkala et al. (2007) [2], and Magossoa et al. (2006) [3] used SEM method to analyze two EOG channels to detect drowsiness. Estrada et al. (2006) [4] used SEM and rapid eye movement for automatic sleep stage classification. Häkkänen et al. (1999) [5] used Blink as an indicator of driver sleepiness.

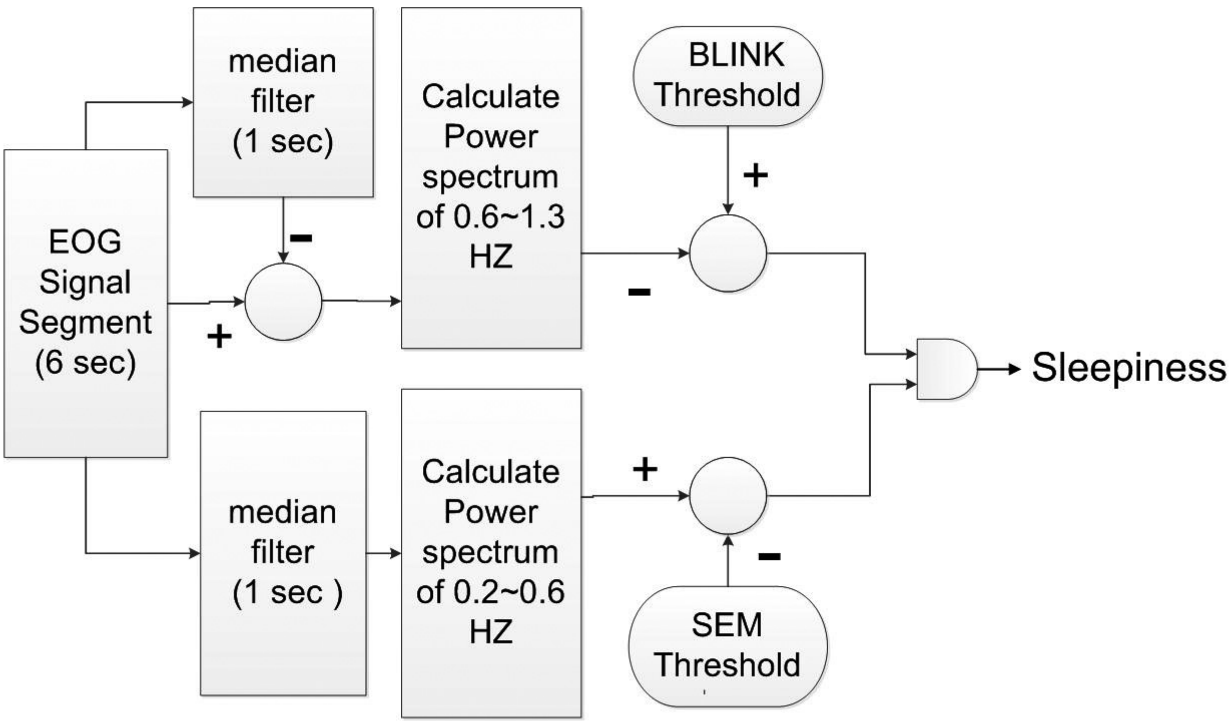
In this study, we attempted to simplify the EOG channels into one. Then, we investigated the correlations between EOG and EEG for different situations, i.e., staying quiet and performing some actions.

METHODS

Standard MWT measures a subject's ability to stay awake in a quiet, non-stimulating situation for 40 minutes. MWT can be used to measure the sleep onset time, i.e. the time (frame) during which a subject begins to enter sleep stage 1 for 3 epochs (one epoch is 30 sec) or sleep stage 2 for one epoch from awake.

Each exam consisted of four single tests performed at 9:00, 11:00, 13:00 and 15:00, respectively. Sleep onset was scored as the elapsed time from lights-out to the occurrence of three consecutive stage 1 epochs or one sleep stage 2 epoch for each test. Recordings were examined independently by a technician.

MWT recordings were acquired according to MWT protocol. The EOG active electrodes were placed 1 cm above the outer cantus of the left eye (E1), with the reference electrode



placed on the left mastoid (A1). We used KY device (developed by Professor Kuo, T. B. J.) to record one EEG channel and one EOG channel. The EOG traces were subsequently exported in European Data Format (EDF) for automatic sleep onset detection via computerized EOG analysis according to two indexes, Blink and SEM. SEM refers to low frequency (mainly 0.2–0.6 Hz), with rolling, horizontal, bidirectional and conjugate movements of the eyes. Blink waves are pulse-type signals of high frequency (mainly 0.6–1.3 Hz) that correspond to fast closing and opening movements of eyes. On Blink analysis, the blink wavelets were removed from EOG signal by filtering with a 1-sec median filter. EOG signal minus the filtered EOG signal resulted in blink wavelets in original EOG signal. The blink wavelets were processed by fast Fourier transfer (FFT) and calculated as the power spectrum of 0.6 to 1.3 Hz to obtain the index of Blink.

On SEM analysis, SEM wavelets were removed from EOG signal by filtering with a 1-sec median filter, followed by FFT processing. The power spectrum of 0.2 Hz to 0.6 Hz was calculated to obtain the index of SEM. There was sleep onset when Blink power was smaller than Blink threshold and SEM power was larger than SEM threshold.

RESULTS

Our aim was to match the sleep onset time with automatic detection of the standard time on MWT. We first set the result of a test as positive if sleep onset time was less than 40 minutes. A total of 172 test cases were assigned to four categories: TP (true positive), TN (true negative), FP (false positive) and FN (false negative). TP designates positive outcomes for both auto program and EEG, while TN designates negative outcomes for both auto program and EEG. FP and FN correspond to mismatches. Then, the performance of the program and each individual human scorer were evaluated in terms of the following indices:

Agreement = (TP + TN)/total number of tests × 100 %;

Sensitivity = TP/(TP + FN) × 100 %;

Selectivity = TP/(TP + FP) × 100 %;

A. Adjustment of SEM threshold

Tab 1. ***SEM THRESHOLD***

SEM Threshold	Agreement	Sensitivity	Selectivity
985.0	23.25%	100.00%	18.52%
2000.0	29.65%	100.00%	19.86%
5000.0	43.60%	66.67%	18.69%
15000.0	66.86%	20.00%	15.38%
25000.0	76.16%	13.33%	21.05%
30000.0	79.07%	10.00%	25.00%

The results are shown in Table I. For the best situation, agreement was 43.60%, sensitivity was 66.67% and selectivity was 18.69%.

Tab 2. ***BLNKING THRESHOLD***

Blink Threshold	Agreement	Sensitivity	Selectivity
9.0	76.16%	63.33%	38.78%
9.5	76.74%	70.00%	40.38%
13.0	73.26%	76.67%	37.10%
15.0	75.00%	90.00%	40.30%
17.0	76.16%	100.00%	42.25%
18.0	75.58%	100.00%	41.67%
79.0	49.42%	100.00%	25.64%

B. Adjustment of Blink threshold

The results are shown in Table II. For the best situation, agreement was 76.16%, sensitivity was 100.00% and selectivity was 42.25%.

C. Adjustment of both Blink and SEM

Tab 3. ***TWO THRESHOLDS***

Blink Threshold	*SEM Threshold*	*Agreement*	*Sensitivity*	*Selectivity*
79.0	935.0	91.28%	93.33%	68.29%
79.0	985.0	91.86%	93.33%	70.00%
84.0	935.0	91.86%	93.33%	65.12%
84.0	985.0	91.28%	93.33%	68.29%
84.0	1085.0	91.86%	90.00%	71.05%
89.0	985.0	90.70%	93.33%	66.67%
89.0	1085.0	91.86%	90.00%	71.05%

thresholds

From previous investigations, results obtained either by SEM or Blink do not show good agreement with those obtained by EEG. However, Table III shows that agreement reached 91.16% using both Blink and SEM. In this case, sensitivity was 93.33% and selectivity was 70.00%.

Tab 4. ***SUMMARY OF THE RESULTS OF THREE TYPES OF THRESHOLD ADJUSTMENTS***

Threshold types	*Agreement*	*Sensitivity*	*Selectivity*
Only SEM Threshold	43.60%	66.67%	18.69%
Only Blink Threshold	76.16%	100.00%	42.25%
Two Thresholds (with 43 subjects)	91.16%	93.33%	70.00%
Two Thresholds (with 81 subjects)	88.27%	93.55%	63.04%

From Table IV, the use of Blink and SEM together is a good approach to sleep onset detection.

The first four rows of Figure 1, respectively, show (i) EEG signal, (ii) EOG signal (iii) blink waves from EOG and (iv) SEM waves from EOG

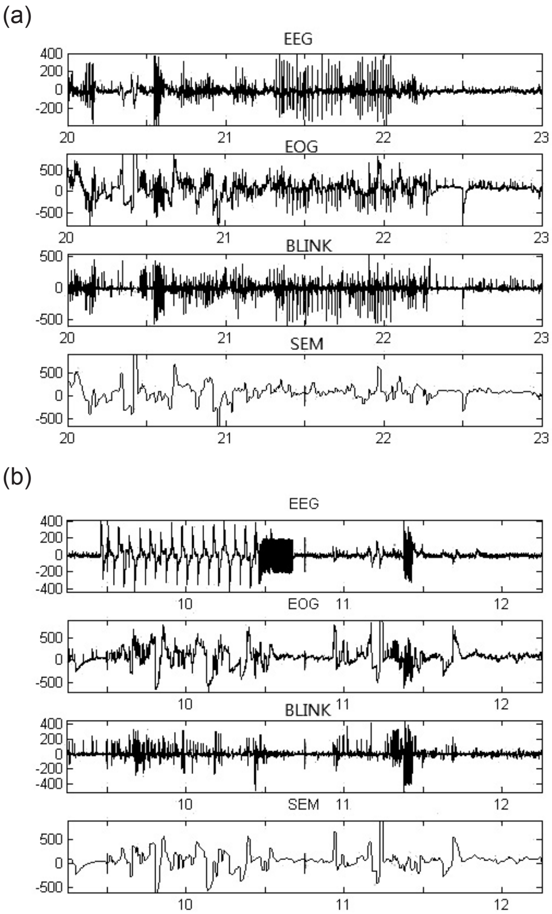


Figure.1. Examples of EEG and EOG signals: (a) first four rows, respectively, show (i) EEG signal, (ii) EOG signal (iii) Blink wave from EOG and (iv) SEM wave from EOG of subject

performing simple actions and falling asleep, (b) first four rows, respectively, show (i) EEG signal, (ii) EOG signal (iii) Blink wave from EOG and (iv) SEM wave from EOG of subject lying quiet and falling asleep.

from awake to sleeping while performing some actions. Figure 1(b) shows the waves under the condition of staying quiet. There are more spikes

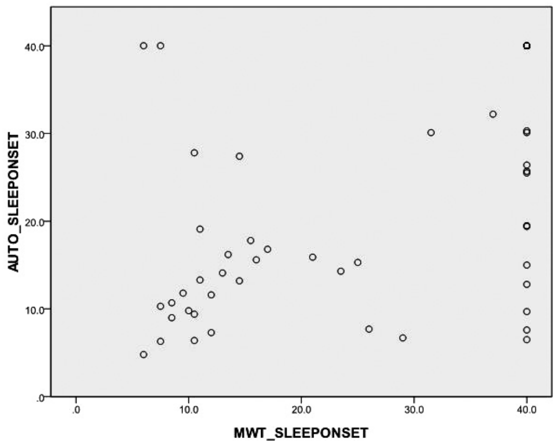


Figure.2. Auto program match to both standard and non-standard MWT (subjects = 43)

in the third row of Figure 1(a) than in Figure 1(b), indicating that the actions of subjects performed in 1(a) may influence Blink waves.

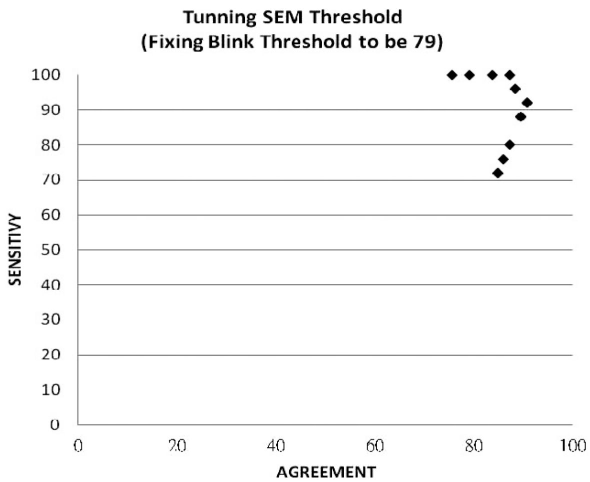


Figure.3. Sensitivity versus agreement of two-threshold method. Tuning of SEM threshold under the condition of Blink threshold fixed at 79.

Figure 2 shows the agreement between the results of two-threshold method and the results of MWT (subjects = 43).

Figure 3 shows the agreement and sensitivity of two-threshold method in tuning SEM threshold under the condition of Blink threshold set at 79.

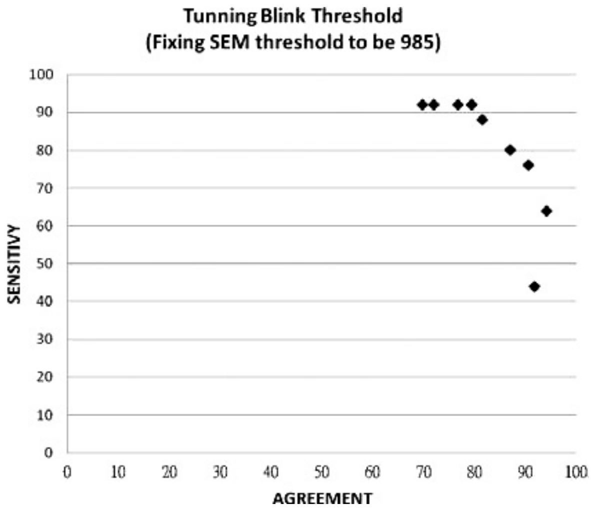


Figure.4. Sensitivity versus agreement of two-threshold method. Tuning of the Blink power threshold under the condition of SEM power threshold set at 985

Figure 4 shows the values of agreement and of sensitivity of two-threshold method in tuning the Blink threshold under the condition of SEM threshold fixed at 985. Figures 3 and 4 together show the best values for agreement and sensitivity, 91.2% and 93.3%, respectively.

This result is the same as that shown in

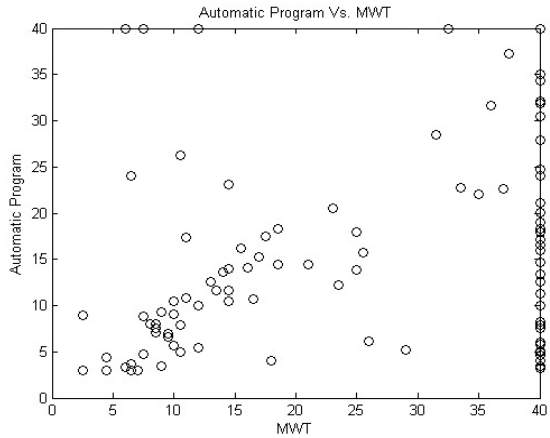


Figure.5. Comparison between two-threshold method and MWT (subjects = 81).

Tables III and IV. Applying the parameters of two-threshold method to 81 subjects, the values of agreement and sensitivity reached 88.3% and 93.5%, respectively. The sleep onset time correlations between auto program and MWT are shown in Figure 5.

CONCLUSION

From Tables I- IV, SEM with one EOG channel was not in good agreement with the results of EEG. Similarly, the results of Blink threshold tests showed poor agreement. However, there was a strong correlation between EOG (one EOG channel) and EEG. Agreement reached 91.16% and sensitivity reached 93.33% using the combination two-threshold method (Blink and SEM). This correlation was strong no matter if the subjects performed simple actions or stayed quiet. The two-threshold method has the potential to be used for sleep detection.

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