Simultaneous Measurement of Heart Rate Variability and Blinking Duration to Predict Sleep Onset and Drowsiness in Drivers

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Abstract

Excessive sleepiness in drivers greatly increases the risk of traffic accidents. A compact, three-dimensional system for analyzing visual information from a face photograph using an infrared CCD camera was recently designed to monitor drivers. The present study aimed to examine whether temporal changes in autonomic activity as determined by spectral analysis of electrocardiogram heart rate variability (HRV) and blinking duration obtained with this camera system could predict sleep onset in a driving simulation. Ten healthy adults (mean age, 21.8 ± 0.64 years) were enrolled in the study. The subjects sat upright in the driver's seat while we performed standard polysomnography (PSG). HRV was assessed through a spectral analysis of RR intervals of the PSG electrocardiogram. Blinking duration was evaluated by an eyelid movement tracking system within the infrared CCD camera. Blinking duration was significantly prolonged during the 10 seconds before sleep onset compared with that during wakefulness (0.64 ± 0.13 vs. 0.34 ± 0.06 sec, p=0.0004). Subsequently, the high-frequency power of HRV was significantly greater at sleep onset (1201 ± 994.6 vs. 906.9 ± 766.2 ms^2, p=0.001). We conclude that simultaneous measurement of HRV and blinking duration can be utilized to predict sleep onset in an automobile driving simulation.

Keywords: Excessive sleepiness; Blinking duration; Heart rate variability; Sleep onset; Drowsiness; Driver

Abbreviations:

HRV: Heart Rate Variability; LF: Low-Frequency; HF: High-Frequency

Introduction

According to the National Police Agency Traffic Bureau, the numbers of traffic annual fatalities and injuries were approximately 5,000 and 850,000, respectively, in 2012 [1]. Sleepiness and a subsequent sleep onset in drivers are significant risk factors of road traffic fatalities/injuries. In addition, excessive daytime sleepiness was noted among 20-25% of general population in an epidemiologic study [2], and it was particularly prevalent in certain occupations as medical residents, shift workers, and transportation workers [3].

Various safe-driving systems have been developed and installed to prevent traffic accidents, including physiological monitoring for detecting the direction of driver facial movements [4]. As such, development of methodology to predict sleep onset by assessing the adaptive functional state of drivers is urgently needed to reduce the risk of traffic accidents.

Heart rate variability (HRV) is a non-invasive and reliable tool to quantify the autonomic activity in the sympathetic and parasympathetic modulation in humans [5]. The low-frequency (LF) component is a marker of sympathetic and parasympathetic modulation, while the high-frequency (HF) component is solely a marker of vagal modulation.

Sleep onset, typically with subsequent progression to deeper sleep, is associated with a shift to the augmented parasympathetic modulation [6,7]. Hence, circadian and sleep stage-specific effects on HRV are clinically relevant [8].

A compact, in-vehicle camera system was recently designed to monitor driver fatigue and loss of concentration. It is superior to the previous system in its ability to measure head position, gazing direction and eyelid closure through a three-dimentional system for analyzing visual information from a face photograph using an infrared CCD camera.

We investigated this new method, which simultaneously provides a blinking-related index with an infrared CCD camera and HRV parameters, both of which served as predictors of sleep onset in the driving simulation.

Materials and Methods

Ten healthy adults (mean age, 21.8 ± 0.64 years) were enrolled in this study. The study protocol was approved by the appropriate institutional review committee, and all subjects provided written consent of their participation after being informed about the details of the study purpose and methods.

Polysomnography

Standard polysomnography (PSG) [9] (ALICE3, Healthdyne Technologies, PA, USA.) was performed while subjects were in a relaxed sitting position on the driver's seat of a simulated automobile operation. The laboratory environment was dark and quiet during testing, and smoking, caffeinated beverages and physical/mental activities were prohibited during the 30 minutes prior to the PSG study.

Subjects avoided unusual exposure to bright light, noise, and conversation. Measurements were recorded from an electroencephalogram, electrooculogram, electromyogram, and electrocardiogram with a NASA lead. Sleep stage was evaluated by visual analysis according to Rechtschaffen and Kales [9]. Sleep onset was defined as the first three consecutive epochs of sleep stage 1, or the first epoch of sleep stages 2, 3, or 4, and REM sleep.

Heart rate variability

Spectral analysis of HRV (Memcalc/Win, GMS Co., Tokyo, Japan) was performed using RR intervals from the electrocardiogram. Low-frequency (LF; 0.04-0.15 Hz) and high-frequency (HF; 0.15-0.40 Hz) power were calculated by integrating the power spectral density in defined frequency bands. The HF component and LF/HF ratio were used as indices of parasympathetic and sympathetic activity, respectively [5].

Measurement of eyelid movement

An eyelid movement tracking system (Anti Sleep, Smart Eye, Göteborg, Sweden) comprising an infrared CCD camera with a single lens and image processing function was used to obtain facial information, such as head position, gaze direction, and eyelid closure in the driving simulation.

The system required a one-time calibration using special checkerboard at the beginning of the measurement, which enabled measurements in the longitudinal direction. Blinking duration was derived by measuring the time from the time of one eyelid closure to the next eyelid closure.

Data analysis

Data are presented as means ± SD, and were analyzed by the paired t-test. All analyses were performed using the Statview statistical software package (SAS Institute, Inc.; Cary, NC, USA). A P value of <0.05 was considered statistically significant.

Results and Discussion

Blinking duration tended to increase during the transitional period from wakefulness to sleep, with a significantly longer blinking duration during the 10 seconds immediately before sleep onset relative to that during wakefulness (0.64 ± 0.13 vs. 0.34 ± 0.06 sec, p=0.0004; Figure 1a).
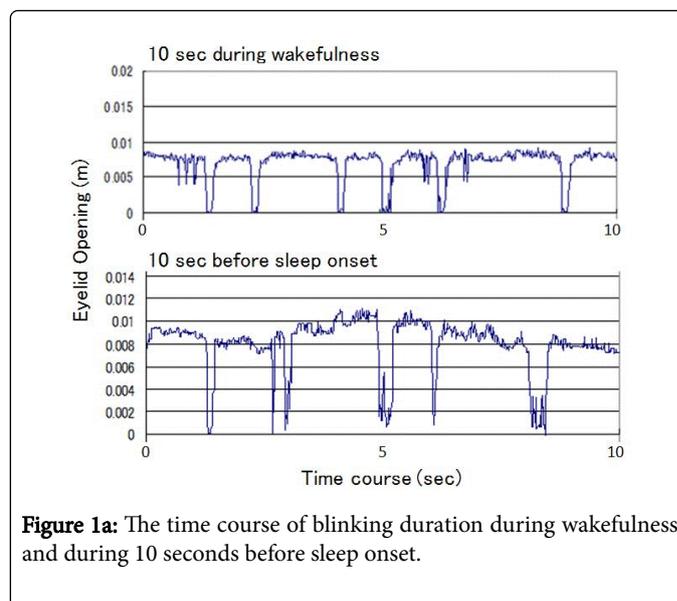
Figure 1a: The time course of blinking duration during wakefulness and during 10 seconds before sleep onset.

We observed no significant differences in eye position, head position, and gazing direction before and after sleep onset. Furthermore, prolonged blinking preceded an increase in HF components in all participants. HF levels increased significantly at sleep onset compared with that during wakefulness (1201 ± 994.6 vs. 906.9 ± 766.2 ms^2, p=0.001; Figure 1b), whereas LF/HF increased during wakefulness.
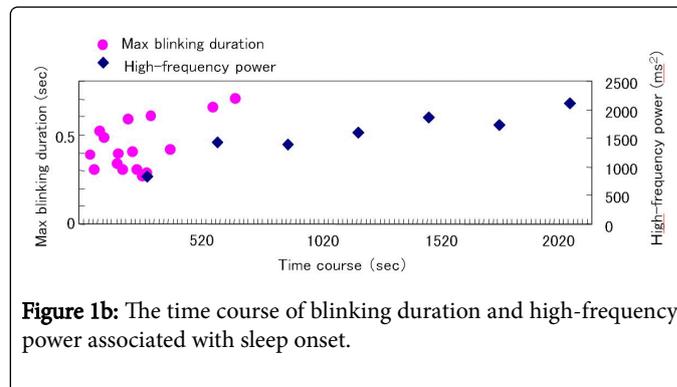
Figure 1b: The time course of blinking duration and high-frequency power associated with sleep onset.

The present study found that changes in HF and blinking duration were significantly associated with sleep onset. Our findings suggest that the combination of prolonged blinking duration and increased HF provides us with the critical information needed to assess the adaptive functional state of drivers (Figure 2).

Autonomic activity can be evaluated by an analysis of HRV, which varies during different sleep stages, showing predominantly parasympathetic activation of the heart during non-REM sleep and increased sympathetic activity during REM sleep [5-8]. Whiletime responsiveness of HRV is not instantaneous enough to detect sleep onset, that of blinking is approximately 1 to 5 seconds, and thus measurement of blinking duration may reliably predict sleepiness in a driver. Electrooculograms have been widely used to measure blinking duration in driving simulations in the past, but this technique requires the subject to have multiple electrodes attached to their face [10]. In addition, simple video cameras which monitor blinking may also lack the accuracy necessary to detect drowsiness [11].
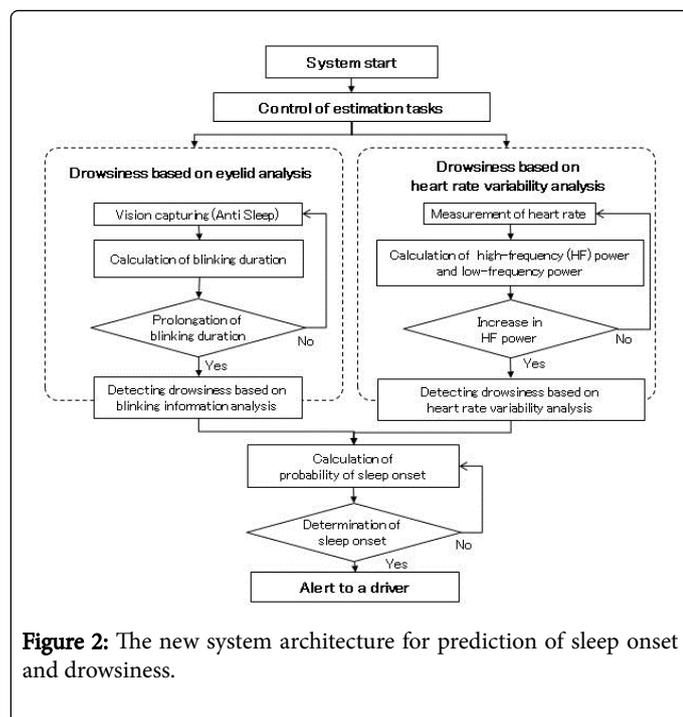
Figure 2: The new system architecture for prediction of sleep onset and drowsiness.

However, an eyelid movement tracking system comprising an infrared CCD camera was recently designed for real-time three-dimensional measurement of eyelid closure in a person sitting in the driver's seat, and demonstrates sufficient accuracy and reliability. Our results suggest that simultaneous recording of both HRV and blinking duration with a CCD camera could help detect sleep onset in young healthy subjects.

Blinking habits vary from person to person, and given the instability in blinking recognition due to head movements before sleep onset and eye size, the device must be improved to allow for optimal image recognition. Diagnostic imaging of blinking in simulator experiments and actual driving experiments, in addition to practical validation of the physiological index, will be important to provide valuable information for increasing the accuracy of sleep detection. In the future, threshold values should be established for the HF components of HRV and blinking time in order to accurately detect sleepiness in a large-sized subject group.

Conclusion

We introduce a new system of estimating sleep onset based on temporal changes in HF components of HRV and blinking duration.

Time-series observations of HF components of HRV and blinking duration provide new insight into sleep onset and daytime sleep. Application of this practical approach would help significantly to prevent accidents caused by drivers falling asleep.

Acknowledgements

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