Early Detection of Falling Asleep at the Wheel: A Heart Rate Variability Approach

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Abstract

In this study we check the feasibility of a new ECG-based approach to detect drivers' propensity to fall asleep at the wheel. Ten healthy volunteers, under conditions of increasing sleep deprivation (up to 34 hours), were asked to alternately undergo a Maintenance of Wakefulness Test or a Driving Simulation test every 2 hours while ECG, EEG, EMG, eye movement and video were recorded. Results from 59 falling asleep (FA) events tracked from the first 5 volunteers during MWT provide promising trends: Heart Rate Variability in the VLF range decreases consistently and significantly minutes before FA events. The sympatho-vagal balance is very low compared to baseline wake values for about 5 minutes before the events. The mean HR and overall RR variability decrease during FA events by 2.2 SD and 2.9 SD below regional means. These changes found during MWT suggest that ECG derived parameters in the time and time-frequency domains may provide a useful tool for monitoring drivers' drowsiness and preventing traffic accidents.

1. Introduction

The National Sleep Foundation's 2007 report on drowsy driving finds fatigued driving to be under-recognized and underreported [1]. Drivers are not aware of their propensity to fall asleep at the wheel. Traffic safety can be achieved by making sure the driver is aware of his imminent falling asleep at the wheel and preventing him from going on, threatening safety on the road and putting his own life in danger.

Methods of early detection may be based on continuous monitoring of several physiological parameters, such as EEG, eye movements, pupillary reaction, muscular tone and behavior [2-4].

The functional and anatomical congruity of the autonomic cardio-respiratory regulation and sleep-wake control have allowed us to use Heart Rate Variability (HRV) in the time and time-frequency domains to look into the process of normal sleep onset (SO) and sleep at night [5,6]. The same physiologic basis allows us to further develop HRV analysis techniques to look into real time change patterns preceding falling asleep (FA) at the wheel and under sleep deprivation conditions.

We aim to detect early the propensity to fall asleep at the wheel using parameters based on HRV.

2. Methods

2.1. Study protocol

Ten normal subjects aged 22-40 of both sexes, volunteered for the study. They gave informed consent and were screened for background diseases and sleep disorders. The study was approved by the local ethics committee. For 7 days prior to the study volunteers were instructed to sleep at least 7 hours per day, and their wake-sleep schedule was checked using actigraphy to ensure lack of prior sleep debt. They underwent a standard in-lab polysomnographic sleep study to rule out any intrinsic sleep disorder. Two hours after waking up in the morning, subjects started a protocol of sleep deprivation for the subsequent 34 hours. During this time of sleep debt accumulation, they had to perform two alternating tasks at two hour intervals: Maintenance of Wakefulness Test (MWT) and Driving Simulation (DS). During the entire testing time they remained connected to EEG, EMG, EOG, and ECG with continuous audio-video recording. Between tests all volunteers were escorted by a technician to prevent unwanted sleep episodes. A sleep expert detected SO events (in real time and offline). The recorded data was analyzed off line. All recorded signals, except the ECG served to identify and register FA events. The ECG was analyzed to estimate and characterize the propensity to fall asleep.

MWT is a standard procedure of sitting in dim light and quiet conditions for up to 45 minutes after being instructed to remain awake without any kind of arousing measures [7]. The procedure is interrupted earlier if the subject develops more than 2 minutes of sleep as

determined by standard electrographic criteria [8]. SO is defined as the first of two consecutive NREM stage 1 epochs of 30 seconds, or the first 30 second period of any other sleep stage. All FA events which resulted in at least 12 seconds of sleep as determined by EEG were analyzed.

DS was performed using the *STISIM Drive* (Systems Technology) simulator on a simulated monotonous 90 Km road for approximately 75-90 minutes. Traffic accidents and faulty driving were automatically recorded by the simulator.

2.2. Data analysis

R waves were automatically detected from the ECG signal, and their occurrences as a function of time composed the RR interval series (RRI). RRI was interpolated to equally spaced samples, and its time-frequency decomposition (TFD) was performed by a continuous wavelet algorithm [9,10]. This algorithm was especially developed to deal with non-stationary signals. It uses narrow time windows to estimate fluctuations of high frequencies and wider windows for lower frequencies, thus achieving optimal time resolution for each frequency band. The power in 3 standard frequency bands was calculated: Very Low Frequency (VLF – 0.008-0.04Hz) representing vasomotor regulation, Low Frequency (LF – 0.04-0.15Hz) which includes both sympathetic and parasympathetic modulation of the sinus node, High Frequency (HF – 0.15-0.5Hz) representing mainly parasympathetic influence [11], and the LF/HF ratio representing the sympatho-vagal balance [12, 13]. The three minutes before the FA reference point were used as a regional baseline for each subject. The amplitudes and powers of all signals were calculated relative to that regional baseline. Finally, since RRI showed marked changes in its variability before and after FA, we also calculated the amplitude of the change in units of baseline standard deviations (SD).

3. Results

This study consists of 3 main steps: (1) searching for ECG-based variables that change significantly with FA; (2) determining a pattern of the changes occurring during the time interval before FA; (3) defining possible thresholds for early detection of FA in different subjects.

3.1. Time domain

Figure 1 shows a representative example of HRV changes in the time domain. The variability of the RRI displays a significant decrease during FA, while the mean RRI increases (i.e. a slower, less variable HR during FA).

3.2. Time frequency decomposition

A sample analysis of the time-frequency decomposition of RRI is shown in figure 2. The analysis of TFD presents the following pattern around FA event:

1. VLF: power starts to decrease slowly and consistently approximately 5 minutes before an FA.
2. LF: a prominent increase in comparison with mean baseline values begins shortly prior to an FA (less than 60 seconds).
3. HF: there is a steep increase in variability seconds before an FA.
4. LF/HF: shows very low values minutes before an FA and significant increase in variability during an FA.

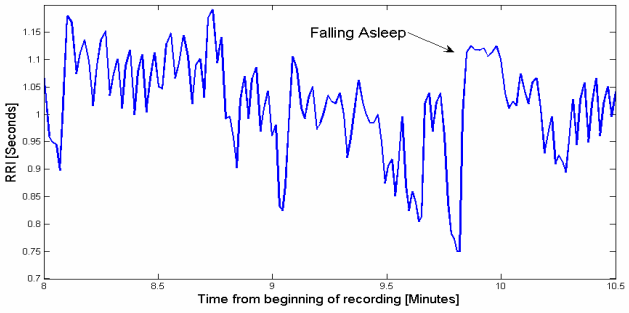


Figure 1 shows an example of the first FA event in one subject: RRI as a function of time during an MWT.

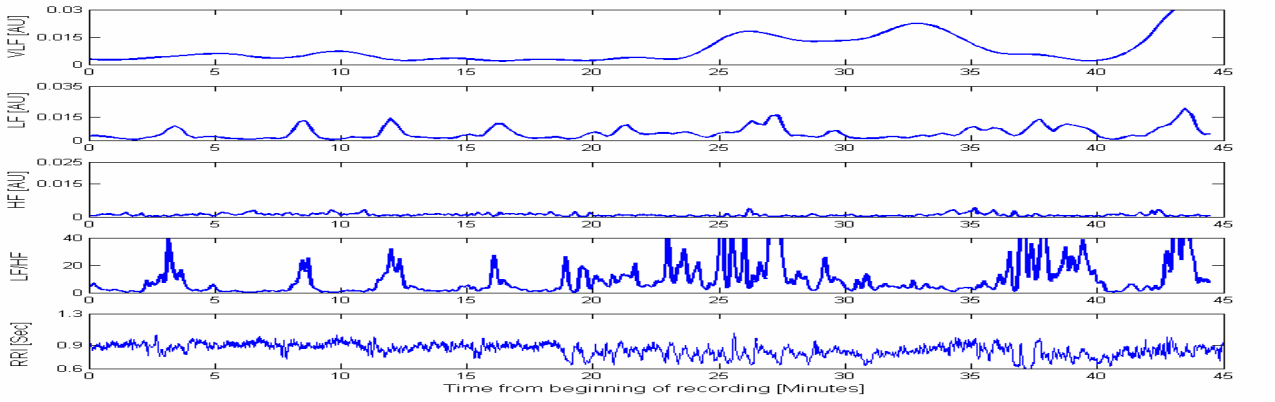
A summary of the results in all subjects is shown in table 1. The general pattern observed during FA events is a decrease in mean RRI variability of more than 2.9 SD from its regional baseline mean value. At the same time, the mean RRI value increases by more than 2 SD.

Table 1: Mean±SD of HRV variables for FA events for all subjects during MWT. (a) Mean RRI and RRI Variability calculated for all FA events for all subjects (N=59). The first column displays the results for the 3 minutes prior to FA event, the second column relates to the duration of the microsleep period. (b) VLF, LF and Balance calculated for first FA event of MWT (N=24). The first column displays the results for the minutes prior to FA event, the second column relates to the period starting from the first FA.

(a)	Before FA	During FA
Mean RRI (seconds)	0.89±0.05	0.97±0.09
Mean RRI Variability (seconds)	0.24±0.04	0.06±0.03

(b)	Before FA	From 1st FA
VLF (normalized)	0.74±0.11	0.21±0.02
LF (normalized)	0.19±0.14	0.58±0.20
Balance LF/HF	3±2	20±18

(a)



(b)

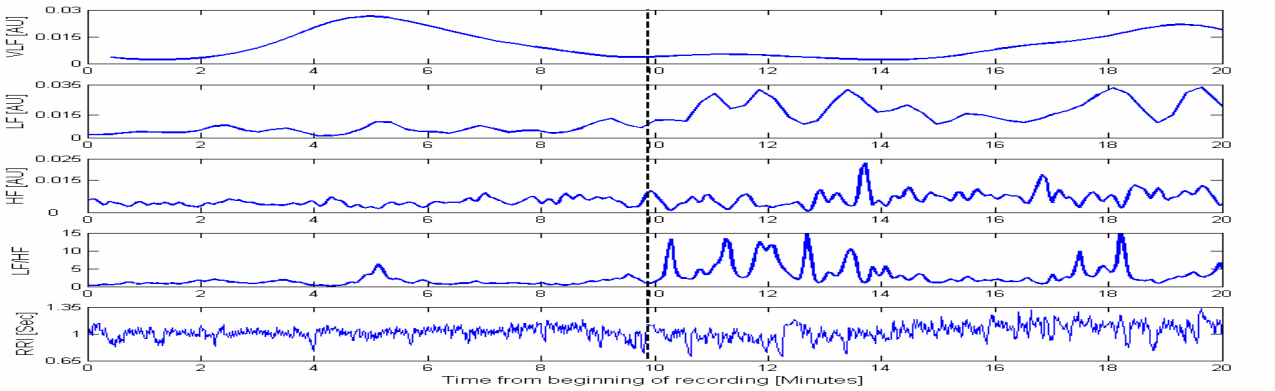


Figure 2: Sample readings for a single patient during an MWT. The first four plots show spectral variables as a function of time, the last plot represents the RRI. (a) MWT with no FA events. (b) MWT with FA events. The dashed line marks the first FA event. Note the power drop in VLF band and the power surge in LF band that occur around minute 10. Also note the increased HF variability after the first FA. The LF/HF ratio is low and stable before the first FA and increases significantly with ongoing variability thereafter. RRI variability increases after the first FA.

The accumulation of sleep debt causes an increase in sleep need with a growing and uncontrollable drive to fall asleep. The sleep drive increases as a function of time awake. The circadian sleep wake cycle plays an additional role during our experiments: the propensity to fall asleep during evening hours is minimal and is greatest during early afternoon and at the end of the night. The number of SO and the sleep latencies during consecutive MWTs along the experiment is consistent with this normal physiologic behavior. Figure 3 presents sleep latency measured during the tests as a function of time awake. Sleep latency tends to decrease (increased propensity to fall asleep) as the time awake increases (sleep debt accumulates). Note that the propensity to fall asleep during evening hours is minimal and it is greatest during early afternoon and at the end of the night.

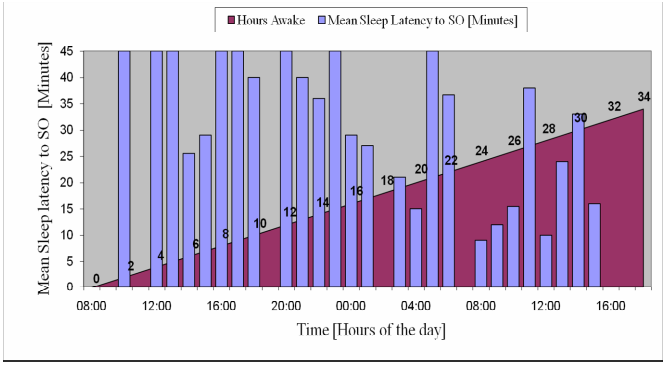


Figure 3: The dark grey represents accumulating hours of sleep deprivation starting from the morning after a regular night sleep in-lab. The bars represent the mean sleep latency (mins) to SO during MWT.

4. Discussion and conclusions

Changes in the autonomic regulation of the cardiovascular function occur in preparation for normal sleep and also when a person faces different tasks. We look into these changes through the window of HRV, with a special focus on falling asleep at the wheel. Sleep deprivation was employed as a mean to increase the propensity to fall asleep. MWT and Driving Simulation represented the test task to allow us to quantify physiologic changes before, during and after an unwanted event of microsleep. We found that a gradual and sustained decrease in VLF preceded FA events by minutes. These changes are regular and recur consistently during MWT and represent most probably a depletion of humoral factors that promote wakefulness. The behavior of the LF/HF represents a low sympatho-vagal balance before FA as a sign of the relaxation taking over. After the FA there is a surge in this balance signifying an increased stress aimed to overcome the drowsiness. The very significant RRI changes with decreased variability and lower heart rate during FA events confirm the autonomic changes discussed previously: during a microsleep there is a decrease in sympathetic drive with increased vagal activity.

We can find a threshold in HRV parameters to predict FA during MWT. These events lack the stress of a driver's simulation FA event and certainly the motivation to stay alive while driving a vehicle in the real world. Thus the present work represents the first step on the way to early detection of falling asleep while driving.

Acknowledgements

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