Investigation of Drowsiness while Driving Utilizing Analysis of Heart Rate Fluctuations

Gabriela Dorfman Furman[1], Armanda Baharav[2]

[1]Tel Aviv University, Tel Aviv, Israel, [2]HypnoCore, Yehud, Israel

Abstract

Sleepiness is a main causal factor for accidents and daytime malfunction. In this study we checked the feasibility of a new, ECG based method to detect the propensity to fall asleep while driving, using a passive Maintenance of Wakefulness Test (MWT) and an active Driving Simulation (DS) during increasing sleep deprivation conditions. Microsleeps (MS), and falling asleep (FA) events, were detected from electroencephalogram analysis. HRV was characterized using Time Domain analysis, Time Frequency Decomposition, Entropy, and Poincaré plots.

The first MS during MWT and DS represented a point for significant changes in all HRV measures. The first accident on DS occurred 2-7 minutes after the first MS.

There are clear HRV markers that indicate sleepiness in sleep deprived subjects. Provided some of these variables show the same trends in sleepy non sleep deprived subjects, a threshold should be defined as to imminent danger of a driver falling asleep at the wheel.

1. Introduction

The tendency to sleep during the course of daily life, when intending to stay awake, represents a major new public health threat because it contributes to traffic and work accidents [1]. The main consequence of sleep deprivation is sleepiness, a condition in which human beings are subjectively, behaviorally and physiologically affected [2-4]. Many investigations of wake-sleep transition have been made. However, the difference between intentional and unintentional sleep onset, specifically expressed by the intrusion of MS (brief periods of sleep) into wakefulness as detected in the electroencephalogram (EEG) needs further investigation.

Our goal was to characterize involuntary MS using HRV measures, and explore the possibility of detecting the propensity to fall asleep involuntarily, based on HRV. This detection should be based on comfortable, real-time, continuous monitoring of the Autonomic Nervous System (ANS) as derived from analysis of HRV and its correlation with Central Nervous System behavior during a state of drowsiness that leads to unintended falling asleep.

2. Methods

2.1. Study protocol

Ten subjects with driving experience, of both genders, aged between 18-50, volunteered for the study, under conditions of increasing sleep deprivation (34 hours). Prior to the sleep deprivation protocol, all subjects were screened for habitual sleep restriction using actigraphy [5], and for sleep disorders by performing a whole night sleep study. During the period of sleep debt accumulation, the volunteers performed on of two alternating tasks every two hours: active DS and passive MWT [6, 7]. EEG, EMG, EOG, ECG and audio-video were continuously monitored and recorded for analysis offline.

DS was performed in a driving environment created using a StiSim drive simulator on a monotonous 90 Km road. Subjects performed this task for approximately 75 minutes. Traffic accidents and faulty driving were automatically recorded by the simulator.

MWT consisted of up to 45 minutes of quiet passive sitting on a comfortable armchair while trying to maintain wakefulness. This task was interrupted if the subject slept for longer than a minute.

The ECG was analyzed to estimate and characterize the propensity to fall asleep by correlating it with FA and MS detected from EEG, EOG, EMG and video.

2.2. Data analysis

2.2.1. Visual inspection

Visual inspection of EEG, EOG and EMG signals and video-recording (considered gold standard) was used to identify the beginning and end of each MWT and DS test, and to detect MS and FA events. Accidents were automatically detected by the driving simulator; synchronous physiological signals were analyzed around the accident times. Alpha (8–13 Hz) and theta (4–7 Hz) waves from EEG were automatically detected and analyzed for estimating changes in the level of alertness.

MS were defined as 3-15 seconds of slow EEG activity (usually in the theta range) or alpha waves (usually seen when awake with closed eyes), FA were defined as more than 15 seconds of slow EEG activity.

Latency (time to first such event) and frequency of MS and latency of FA during MWT were analyzed in order to estimate the circadian effects that occur along with sleep deprivation effects.

MS latency and first accident latency (the time from beginning of experiment to first accident, due to MS), during DS tests represented a measure of functional vigilance during sleep deprivation.

2.2.2. ECG analysis

R waves were automatically detected from the ECG signal, and their occurrences as a function of time composed the RR interval series (RRI). HRV parameters preceding, during and after MS, FA and accidents. HRV was evaluated in the time domain (TD), time frequency domain (TFD) and using nonlinear analysis. For TFD the RRI was interpolated to equally spaced samples, and its time-frequency decomposition was performed using a continuous wavelet algorithm [8, 9]. Poincaré plots were used as an alternative description of short and long term correlation between heartbeats, from which nonlinear HRV indices were defined. RRI series was used to calculate Entropy measures of the RRI were also examined.

The correlation between MS and FA events and the accompanying behavior of HRV parameters was estimated.

3. Results

3.1. Sleep deprivation and circadian influence on MWT and DS

We used a multitude of variables calculated from the RRI series in order to evaluate drowsiness: average RRI median; average RRI peak to peak (p-p); average RRI entropy; average RRI p-p of median; average Poincaré SD1; average Poincaré SD2. For each subject, the values of all variables calculated were normalized to the personal average of any given variable before the first MS.

The latency and frequency of MS and FA as a function of time provided a measure of sleepiness accumulated with increasing sleep deprivation. The circadian modulation was estimated by dividing the results into 8 time bins corresponding to 8 sets (two consecutive tasks MWT/DS) of tests. The results were summarized, and some of them are described in figures 1-5.

Another interesting phenomenon is shown in Figure 2, where the B4MS and the AFMS graphs intersect in the late afternoon hours. This circadian time is known as the "forbidden zone" when the chance of falling asleep is low [10].

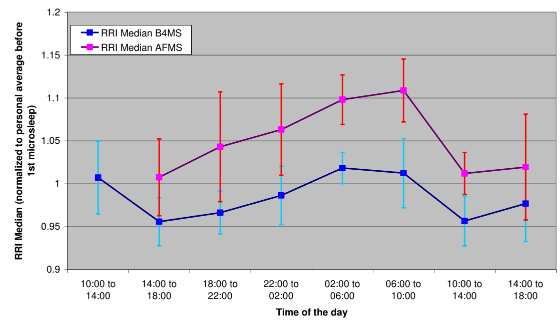

Figure 1. MWT: average RRI median before first microsleep (B4MS) (lower graph) and after (AFMS) (upper graph), normalized to personal average before the first MS. Note that the RRI median is lower after the first MS and this difference is larger during night time.

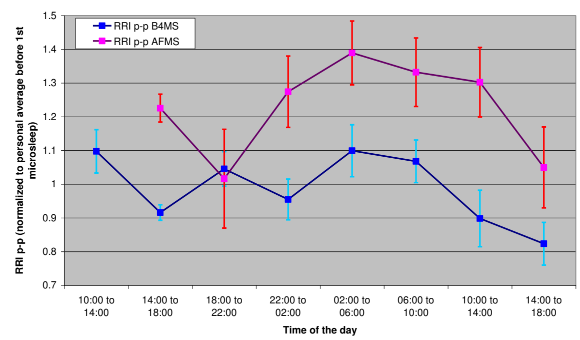

Figure 2. MWT: peak to peak average B4MS (lower graph) and AFMS (upper graph).

These results display both the influences of the circadian cycle and sleep deprivation impact on the time domain parameters. While sleep deprivation causes an increase in the calculated values, the circadian modulation is notable by the relative decrease in the same parameters during the second day of the experiment when circadian alertness is at play and overcomes some of the influence of the sleep debt.

Non linear parameters obtained from entropy showed similar behavior.

Identical trends in calculated parameters were found in the active DS task when compared to the passive MWT. All calculated values after the first MS were generally higher than before, and there was a peak during the late-night hours, or early morning hours of the second day. There were however some differences. For example, the peak in the parameters' value in MWT was shifted from

02:00-06:00 time period to 06:00-10:00 in DS (see for example graph SD2 during MWT compared with SD2 during DS test) and there were no MS events detected in 14:00-18:00 time period of the first day and 18:00-22:00 time period in DS tests. An example is presented in Figure 3.

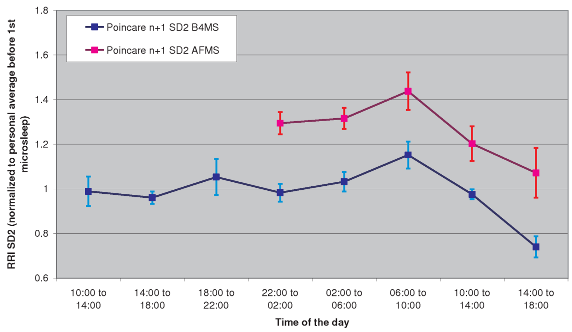

Figure 3. DS: average Poincaré B4MS (lower graph) and AFMS (upper graph). The differentiation between the two states is higher than for MWT and significant as represented by the small error bars.

The TFD of the RRI series also uncovered differences in variables when they were compared before and after the first MS. Each of the frequency components (VLF for ranges<0.04 Hz; LF between 0.04-0.15Hz and HF between 0.15-0.5 Hz) was allocated a different moving window: VLF -180 sec; LF -120 sec; HF - 30 sec. All windows were advanced by 1 sec steps. The median values of the windows were extracted. The LF/ HF was filtered in the same manner, with a window length of 120 sec. Examples of RRI and calculated parameters during MWT and DS in an individual subject appear in figure 4.

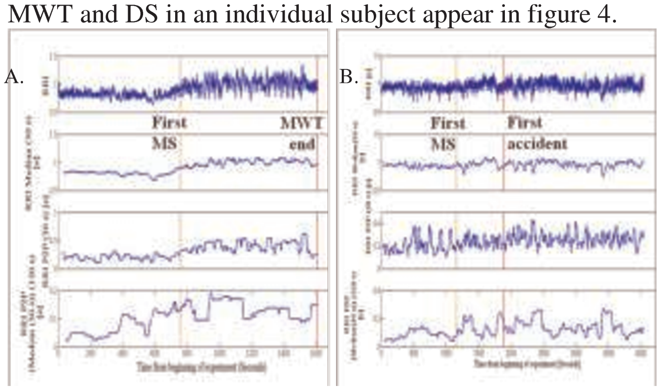

Figure 4. From top to bottom graphs of RRI; RRI median (representing the RRI mean-line); RRI peak to peak (p-p) (representing the RRI variability), and peak to peak of the median; during A. MWT and in B. DS. Left line shows time of first MS, right line shows in A. end of MWT, in B. time of first accident.

The clearest difference between before and after first MS was found in the TFD as presented in figure 5.

The sleep deprivation setting created a large number of MS events also during active tasks.

Sleepiness as expressed by MS intrusion within wakefulness, showed dependence on 2 main variables, time awake and circadian cycle, as shown in figure 6.

DS results indicated that there was on average, a time interval of 2-7 minutes between the first MS and the first accident.

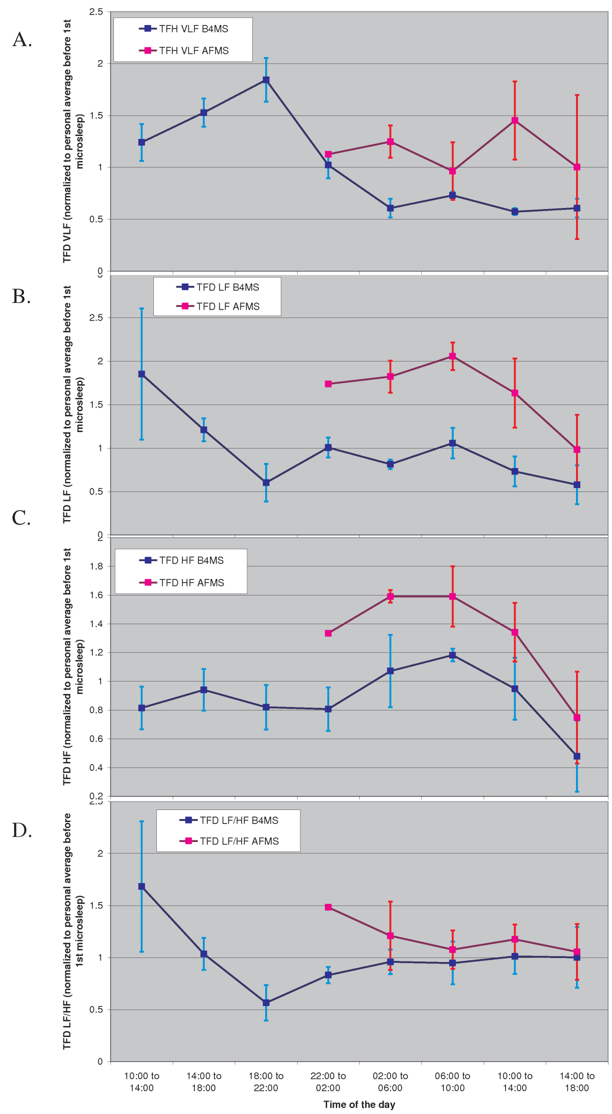

Figure 5. DS: (a) VLF, (b) LF, (c) HF, (d) LF/HF. All normalized to personal average before the first MS. Note the small error bars for (very precise results) and the large ones AFMS (imprecise results) as time advances. The differentiation in LF/HF B4MS and AFMS diminishes with time and sleep deprivation. B4MS and AFMS have clearly different values between 02:00-06:00 and 10:00-14:00 of the second day.

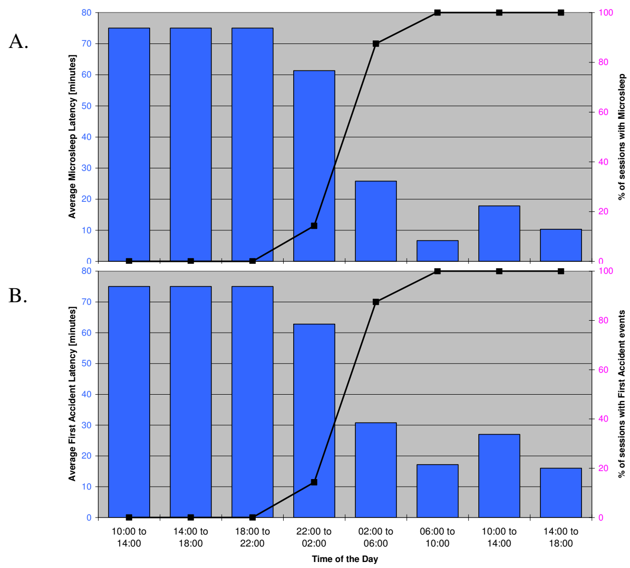

Figure 6. (a) The average MS latency (minutes) measured during the DS tests for each time period. Where no MS occurred a default value of 75 minutes was used (the approximate duration of the DS test). The dark line shows the percentage of subjects who experienced aMS. (b) The average latency to the first accident in the DS test (minutes). A default value of 75 minutes was used when no accident occurred, The dark line shows the percentage of people that experienced an accident due to a MS. Note that the MS or accident begin from night hours, but once they start the latencies drop quickly as sleep deprivation increases. The number of subjects experiencing MS or accidents also sharply increase during night hours.

4. Summary and discussion

The present study is the first to evaluate cardiovascular changes in relation to microsleeps and involuntary falling asleep in a sleep deprivation setting. Our results indicate a very clear change in autonomic function after the first MS, during both passive and active tasks, as viewed through HRV analysis. The time domain analysis deals with short term changes in Heart Rate, mainly accelerations due to "autonomic arousals"**.** Thus we might speculate that the changes in these variables after the first MS indicates an exhaustion of the arousal drive due to a higher level of stress/sympathetic activity triggered by the MS event and the need to overcome increasing drowsiness. Time-frequency domain analysis findings support similar conclusions. LF component is higher after the first microsleep indicating an increased level of sympathetic tone. This change is preceded by a gradual decrease in VLF and LF before the first MS. However this gradual decrease does not allow to predict the exact timing of the first MS during MWT or a first accident during DS. There is a delay of minutes between the first MS and the first accident on DS, as presented in the results section. Thus the detection of a first "microsleep" would be a suitable barrier to stop a drowsy driver from continuing on a dangerous path by driving while the chance for an accident due to inattention is imminent. This conclusion is reached under conditions of severe sleep deprivation. It remains to study whether the same threshold may be used under real life chronic sleep deprivation or sleepiness with no sleep restriction at all. Real life danger while driving on roads induces a motivation that may overcome some of the MS events. Thus maybe the physiological changes in real life condition are subtle and should be further investigated

References

[1] Dement W, Mitler M. It's time to wake up to the importance of sleep disorders. JAMA: the journal of the American Medical Association;269(12):1548.

[2] Babkoff H, Caspy T, Mikulincer M. Subjective sleepiness ratings: the effects of sleep deprivation, circadian rhythmicity and cognitive performance. Sleep (New York, NY)1991;14(6):534-9.

[3] Pilcher J, Huffcutt A. Effects of sleep deprivation on performance: a meta-analysis. Sleep1996;19(4):318.

[4] Forest G, Godbout R. Effects of sleep deprivation on performance and EEG spectral analysis in young adults. Brain and cognition;43(1-3):195.

[5] Morgenthaler T, Alessi C, Friedman L, Owens J, Kapur V, Boehlecke B, et al. Practice parameters for the use of actigraphy in the assessment of sleep and sleep disorders: an update for 2007. Sleep2007 Apr 1;30(4):519-29.

[6] Reed M, Green P. Comparison of driving performance on-road and in a low-cost simulator using a concurrent telephone dialling task. Ergonomics1999;42(8):1015-37.

[7] Mitler M, Gujavarty K, Browman C. Maintenance of wakefulness test: a polysomnographic technique for evaluation treatment efficacy in patients with excessive somnolence. Electroencephalography and clinical neurophysiology1982;53(6):658.

[8] Keselbrener L, Akselrod S. Selective discrete Fourier transform algorithm for time-frequency analysis: method and application on simulated and cardiovascular signals. IEEE Trans Biomed Eng1996 Aug;43(8):789-802.

[9] Toledo E, Gurevitz O, Hod H, Eldar M, Akselrod S. Wavelet analysis of instantaneous heart rate: a study of autonomic control during thrombolysis. Am J Physiol Regul Integr Comp Physiol2003 Apr;284(4):R1079-91.

[10] Lavie P. Ultrashort sleep-waking schedule. III. 'Gates' and 'Forbidden zones' for sleep. Electroencephalography and clinical neurophysiology1986;63(5):414-25.

Address for correspondence.

Gabriela Dorfman Furman
Ha'Tzionut 40 Rehovot
gabidf@post.tau.ac.il