Sleep in the Cloud: On How to Use Available Heart Rate Monitors to Track Sleep and Improve Quality of Life

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Abstract

As the modern society accumulates sleep debt that jeopardizes health, performance and wellbeing, people become increasingly interested in self-assessment. We aim to enable sleep self-evaluation using available Heart Rate (HR) monitors, mobile and cloud technology.

Sleep was evaluated using a proprietary ECG-based validated sleep diagnostic software adapted to HR data obtained from HR monitor belts (HRMs) which are widely used to monitor HR during physical activity. Data were transmitted and stored on an iPhone, using a dedicated application. Two wireless communication channels are used for HRMs: (P1) Wearlink and (P2) ANT+. The stored information was uploaded to the cloud and automatically analyzed.

The functionality of an automated sleep monitoring and analysis, using HRMs, with either P1 or P2 transmission, iPhone, and cloud based SleepRate software analysis has been checked.

HR belts with ANT+ were the most suitable for recording HR during sleep. Millions of people own HRMs to assess their training. Now they can use the same device to evaluate and improve their sleep, thus improving their daytime physical and cognitive performance, wellbeing and overall health.

1. Introduction

As modern society accumulates sleep debt that jeopardizes health, performance and wellbeing [1], people become increasingly interested in self-assessment.

We aim to enable sleep self-evaluation using available HRMs in conjunction with mobile and cloud technology. In the present study, sleep analysis has been performed using a modification of our ECG-based validated sleep diagnostic software [2] based mainly on the RR interval (RRI) series. Thus, the widely used HRMs that provide this series are a good candidate to serve as an accurate monitoring device during sleep. However, there are some concerns regarding their usability as such: (1) HRMs are intended for use during physical activity when the conductivity between the electrodes and the body is high due to sweating, which does not necessarily occur during sleep. (2) The usability of smartphones as recording devices. (3) HRMs transmit the information wirelessly. Questions arise regarding the distance and relative position between the HRM and the recording device (note that there are mainly two communication protocols used for HRM: Wearlink and Ant+).

Thus we have tested the functionality of the automated sleep monitoring and analysis, using HRMs with both communication protocols, iPhone, and cloud based SleepRate software.

2. Methods

2.1. Study protocol

2.1.1. Test usability of widely available HRM for sleep evaluation. A multitude of HRM brands are available on the market. Essentially an HRM is a chest band made of plastic or fabric, which includes two imbedded electrodes and an electronic device that detects R peaks and transmits the RRI to a receiver/recording device. Two main communication protocols are widely used today: (P1) Wearlink, which uses analog communication at 5KHz and has a relatively short range of 50-100 cm, and (P2) ANT+ ,which uses digital communication at 2.5GHz and has medium range of about several meters.

The data were sent to and stored on an iPhone. To do this, the iPhone requires a receiver/transducer (dongle available on the market).

Thus in a first step to check the usability of HRMs during sleep we performed two sets of tests, one for each communication protocol. Users slept with either a Polar belt, an HRM with a P1 protocol that needs a dongle (60 Beat that attaches to the audio jack of an iPhone), or a Wahoo or Garmin belt, HRMs that use P2 and need a dongle that attaches to the charging slot of an iPhone. Users were instructed to have the belt very tight on the chest and to wet the area under the electrodes to make sure good skin/electrodes conductivity is achieved. For P1 the iPhone had to be kept in very close proximity to the user, while for P2 a more liberal distance to the mobile phone was permitted (2-3 meters). The transmitted information was stored on the iPhone during the night and uploaded to the cloud at the end of the night by means of a dedicated application we have developed for both P1 and P2. Automatic software analyzed the uploaded data and users were able to review their nightly results on a web application (www.mysleeprate.com).

2.1.2 Accuracy check of the R detection using the HRM and dongle system has been performed on several sleep recordings performed simultaneously with an ECG recorder (Embletta x30 by Embla) and HRMs with either P1 or P2.

2.1.3. Evaluation of the inconvenience caused by sleeping with a tight HRM was also performed by asking the users to specifically rate their experience.

The first 7 nights of each user in each set served to determine the usability/feasibility of the method. Users were allowed to continue recording additional nights. These additional nights allowed for the sleep parameters variability to be assessed across time.

2.2. Sleep analysis

Sleep evaluation was performed using a validated ECG-based sleep diagnostic software [2] adapted to fit RRI series provided accurately by some HRMs. The algorithm uncovers sleep architecture, including wakefulness, light sleep, slow wave sleep (SWS or deep sleep) [3], Rapid Eye Movement (REM) sleep [4], arousals (autonomic and correlated to cortical events) and awakenings. Based on the above, the software provides clinically understandable variables as follows: total sleep time, sleep efficiency, sleep latency and the percentage of time the user was in each sleep stage.

Three additional indexes of practical value have been defined and are provided to the interested user: Sleep Quality Index (SQI), Stress Index (SI), and Continuity Index (CI).

SQI: SQI summarizes the general architecture of the sleep during any given night and it integrates several important measures: total sleep time, sleep efficiency (the percentage of time one was asleep out of the time one intended to sleep), the relative amounts of REM sleep and of SWS. Thus, a user with sleep parameters within recommended/normal sex/age values for variables that are integrated within SQI [5] will get an SQI around 100. Divergence in any of these parameters will result in a correlated reduced SQI.

SI: The sympatho-vagal balance represented by the Low Frequency to the High Frequency range power content ratio of HR variability spectrum is a recognized measure of stress, with higher autonomic balance levels indicating higher stress [6]. Thus, we use the average LF/HF ratio during different sleep/wake states to define a sleep time SI. Thus a high autonomic balance during sleep indicating an increase sympathetic activity, points towards a relatively higher stress.

CI: CI is intended to define the continuity of the sleep. It equals 100 when the sleep is not fragmented at all. It decreases with the increase in sleep fragmentation, i.e. when either the number of awakenings and/or the arousals index (the number of arousals per hour of sleep) increase. Note however, that since our analysis is based on HR variability, the arousals we detect are subcortical arousals and the arousal frequency of cortical-gold standard events may differ from the frequency of cortical arousals [7].

3. Results

3.1. Usability/feasibility test

3.1.1 Communication Body-HRM-iPhone: 20 users with mean age 39±10 years performed sleep recordings with the system for a total of 135 nights with P1, and 22 users of similar ages (42±11 years) completed 145 nights with P2. The prerequisite to return meaningful results was defined as at least two hours of good quality HR recordings. Good recording was defined as having good quality of HR recording for more than 80% of the time.

Only 79% of nights met the threshold to get a report in the P1 group, while more than 98% of the nights in the P2 group. Good recordings, above 80% of the night, were at 36% of the nights in P1 and 83% of the nights in P2.

One user in the P1 group was unable to receive any sleep information in any of his six nights trial due to interference in the communication between the HRM and the iPhone in his given environment.

3.1.2 R detection: The simultaneous recordings of belt and Embletta showed high correlation between the corresponding RRI signals. The sleep analysis showed good similarity, as can be seen in the example in Figure 1.

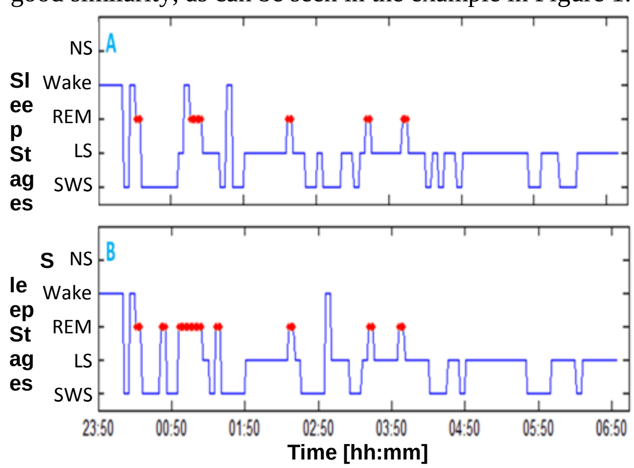

Figure 1: An example of sleep analysis calculated from RRI signal recorded by (A) Embletta, (B) HRM. Stages appear as slow wave sleep (SWS), light sleep (LS), REM sleep, Wake and not scored (NS).

3.1.3. It appears that subject were able to sleep with the belts for many night. Only 20% of the users reported that sleeping with the belt bothered them a lot.

Based on the above results it was found that HRMs using Wearlink communication are not robust enough to serve as a device for sleep evaluation. On the other hand HRMs using ANT+ were found to be more robust and less susceptible to communication interference, thus allowing a higher adherence to nightly usage. ANT+ HRM technology is thus suitable to be used for sleep recordings and evaluation based on HR variability analysis.

3.2. Sleep analysis results

Fifteen users of P2 had 7 or more good recordings (more than 80% of the recording had good RRI signal), for a total of 366 good nights. The following results refer to these nights. The sleep analysis based on the RRI series obtained from HRM provides detection of sleep architecture, awakenings, autonomic arousals, and stress for each tested night. We provide a review of some sleep evaluation as expressed by the three indices previously defined above: SQI, SI and CI.

The SQI is based on most important sleep related measures. Figure 2A shows an example of the SQI of a single user during a period of one month. The value fluctuates from day to day. Although the SQI depends on the total sleep time and thus will correlate with it, the SQI provides additional information regarding different sleep stages duration, that does not correlate with the user's time in bed, as can be seen in Figure 2. Note the time spent in bed is the only quantified parameter one can measure without any additional devices. Thus the HRM based sleep analysis provides additional insight into a

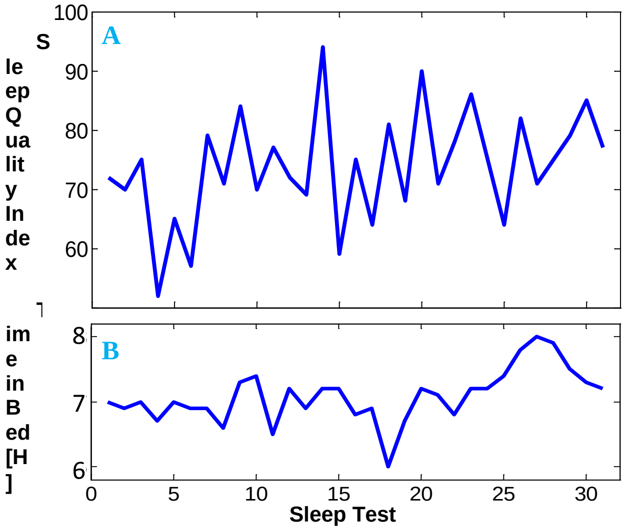

Figure 2: (A) An example of SQI of a user as a function of the sleep test (SQI values range between 0 and 100). (B) The corresponding time in bed for the same tests.

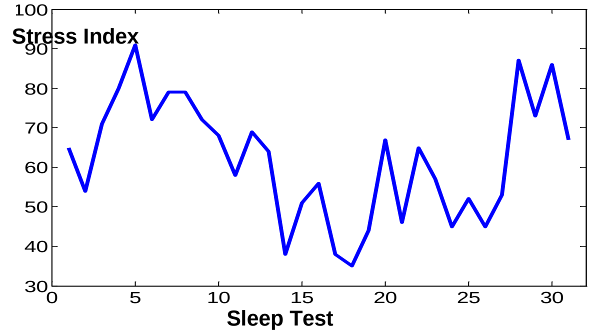

Figure 3: An example of SI of a user as a function of the sleep test (SI values range between 0 and 100). Note the fluctuation in the user's SI during the month.

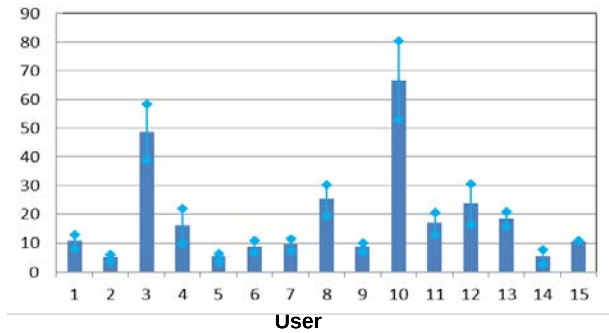

Figure 4: Average SI and standard deviation for each of the 15 users.

person's sleep. This insight can be related to daytime function that is highly dependent on sleep time and quality.

The SI is aimed to test the stress level of a sleeping person. The relative disconnection from the environment during sleep allows assessing a stress index that represents the basic stress level, better than any other baseline evaluation during wakefulness. There are not known normal levels for SI during sleep. Thus, each user serves as his own reference, in which the nightly stress level is compared to his/hers other nights' measurements. An example of nightly variations in SI is given in Figure 3. In this example one can easily see that the SI varies between the days, with more stressed periods around day 5 and toward the end of the tested period.

Though SI presents nightly fluctuations, a striking tendency emerges from looking into a few tens of users across more than a week each: there is a baseline value for each user that is relatively constant, see Figure 4. It seems that different subjects have different SI baselines. Note that though the example in Figure 3 shows user #10 which shows the highest SI, the same fluctuation pattern appears for all subjects at all baseline levels.

CI represents another aspect of good night sleep, and it is independent of macro sleep architecture, which relates to the relative durations of different sleep stages during the night. This means that even if a person has a sufficient sleep time including all sleep stages, he might have an unrefreshing sleep due to high fragmentation resulting from a high frequency of arousals. High fragmentation may sometimes correlate with sleep disorders such as Obstructive Sleep Apnea or Periodic Leg Movements [7]. We found that CI does not vary much from night to night, see figure 5. The standard deviation is about 7% of the average CI value for each subject. The highest relative standard deviation was found for subject #8 who had a very low continuity, a mean CI of 38, with values ranging from 18 to 52. This subject had a decreased CI during all tested nights.

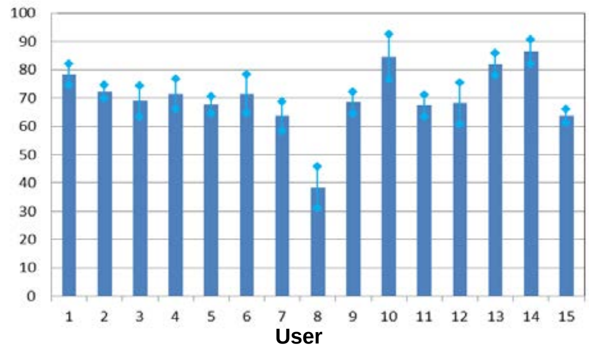

Figure 5: Average CI and standard deviation for each of the 15 users. Note the low standard deviation for most users, and the very low CI value of user #8.

Although CI cannot point to a specific sleep related disease, it may indicate a sleep abnormality and that additional specific work up is needed. However, one should keep in mind that since CI is mainly based on autonomic awakenings and arousals as expressed by accelerations in the HR, it might be that an extremely high variability in the users' HR may appear as low CI.

We have presented here the results based only on nights with good quality recordings. The influence of suboptimal quality of recordings on different sleep parameters is obviously of great interest. As expected, the SQI was found to be sensitive to gaps in recordings, and its reliability decreases with the increase in the duration of such gaps. We found that the SI and CI produce reasonable values even for large portions of unacceptable signal. The obtained values of SI, CI are close to the user’s normal baseline, even if the signal has very large intervals of unacceptable signal.

4. Conclusions

The use of popular fitness belts that are HRMs, in conjunction with ANT+ communication protocol, can represent an effective sensing device for HR during sleep. The raw data obtained can be stored on an iPhone for an entire night and uploaded to the cloud, were a dedicated software performs automated analysis of a person's sleep. This sequence proves to be an effective method for sleep self-evaluation in the comfort of one's own bed.

Sleep assessment based on HR variability analysis provides sleep architecture [3,4] well correlated with gold standard sleep tests [2] and not merely sleep-wake patterns as obtained by using accelerometer based devices. In addition, HR variability analysis represents a window into the autonomic function, thus allowing getting information about the stress level of a sleeping subject.

Although our Stress Index currently lacks the reference normal values, even in its limited version, in which the subject serves as his own reference, users can gain valuable information just by tracking the fluctuations SI across different nights and correlating with daily activities, events or mood.

Moreover, due to the availability of HRMs and their proven value for sleep assessment, large scale sleep data analysis becomes possible and normal values can be derived for SI or other sleep related autonomic variables based on HR variability analysis.

This simple and readily available sleep evaluation method allows millions of people who have their HR belts for training to use them to evaluate and improve their sleep, thus improving their health, daytime wellbeing and performance.

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