

# DEVELOPMENT OF A SLEEP MONITORING SYSTEM WITH WEARABLE VITAL SENSOR FOR HOME USE

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Abstract: This paper describes a new sleep monitoring system for home use. The basic system consists of a wearable physiological sensor and PC software for analyzing sleep quality from user's wrist motion and heart rate variability. Different from a conventional sleep monitoring device used in a hospital, the sensor is so small and easy-to-use that a normal person can use it at home. This means that the system is useful for a sleep specialist who wants to check a patient's daily sleep pattern. The system can also be used for self-care. We have developed a wrist-watch-shaped physiological sensor that monitors user's wrist motion and pulse wave interval. We have also developed the algorithm for computing the quality of sleep from these physiological data on PC. Although sleep is a kind of brain activity and our sensor can not directly measure it, the output of our algorithm is close to medically evaluated sleep quality. We performed dozens of comparison experiments and found that its accuracy was about 73.5% on average. The value of the accuracy is enough for assessing a normal person's sleep quality.

## 1 INTRODUCTION

In recent years, many people have been suffering from sleep disorder caused by mental stress, irregular lifestyle or shift work. However, it is not easy to determine the quality of sleep because deep sleep is not always good sleep and shallow sleep is not always bad sleep. For example, it is natural that a person cannot sleep well because of jet lag. However, a person who is always sleepy in the daytime for a period exceeding one month might have a health problem. Therefore, it is important for a doctor to check a patient's sleep habits for several days in order to diagnose and cure his/her sleep disorder properly. Moreover, it is necessary for a person to check his/her own sleep habits and to change his/her lifestyle (self-care).

However, there is no good system to record and analyze daily sleep. For example, most medical sleep sensors, such as those employed for polysomnography (PSG), are for recording many kinds of physiological data (EEG, EMG, EOG and

so on) for only one or two nights, not for recording sleep habits with natural state in daily life. It is also too difficult for a normal person to handle PSG at home because it involves the use of many electrodes for measuring the physiological data. A doctor can attempt to learn a patient's sleep habits by interviewing him or her, but this is an inherently unreliable approach. A simple and easy-to-use sleep monitoring system that can be used in the home is strongly desired in order to get objective data on sleep habits.

In order to develop such a system, we have created a wrist-watch-shaped wearable physiological sensor that monitors user's wrist motion and pulse wave intervals (Pulse-to-Pulse Intervals: PPIs). The sensor can be made small and simple because wrist motion and pulse wave can be easily measured compared to the case of using PSG. We have also developed the algorithm for computing the quality of sleep from these physiological data. The algorithm can distinguish sleep stage (wake /REM /NREM [shallow /deep]) using the relationship between autonomic nervous activity and sleep stages.



dividing sleep stages are changed flexibly along with the dataset.

## 4 THE OVERVIEW OF THE SYSTEM

### 4.1 Wearable Physiological Sensor

Figure 2 shows our wearable physiological sensor. The size of the sensor is 50mm\*60mm\*13mm and the weight is only 35g. A rechargeable battery is used as an electrical power source. It is possible to measure physiological data for over 40 hours after full charge. The sensor incorporates a photoelectric pulse wave sensor and a 3-axis accelerometer. Besides, it has an external pulse wave sensor. Therefore, pulse waves can be measured on the user's wrist or on his/her finger, depending on his/her preference. The front panel serves as a wrist-watch displaying date and time, and as a sensor displaying time and the amount of activity. The sensor has only two buttons; namely, one is a light switch, and the other is a switch to start/end sensing.



Figure 2: Wearable physiological sensor.

The sensor measures pulse waves and accelerations on a user's wrist and stores the computed pulse-to-pulse intervals (PPIs) and the amount of activity in a flash memory (4MiB). Both analog and digital filters are used to remove the fluctuations of the amplitude and the basal line of pulse waveform, which makes PPIs more precise. As the size of the data measured in one night (7 hours) is 256 KiB, the sensor can store almost 2 weeks' data in the flash memory. The sampling rate of the pulse wave and 3-axis

accelerations is 64Hz. However, the resolution of the PPI is 0.1 ms by using linear interpolation to detect pulse peak.

The amount of activity is calculated as the number that the scalar of the 3-axis acceleration is larger than 0.01 G, which is the same as Actigram (Cole, 1992).

The stored PPIs and amount of activity data are sent to PC via USB.

We evaluated the performance. Firstly, the correlation coefficient between the amount of activity counted by the sensor worn on the left forearm and that measured by an actigraph (Micromini-Motionlogger Actigraph, Ambulatory Monitoring Inc.) worn on the right forearm during sleep was 0.95 (average of 3 healthy subjects). Figure 3 shows an example of the result.

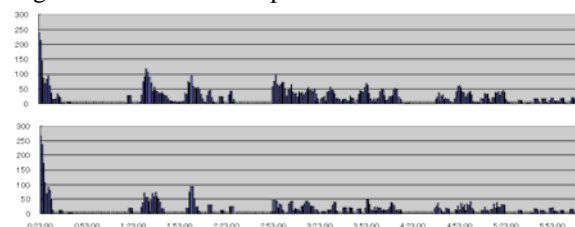
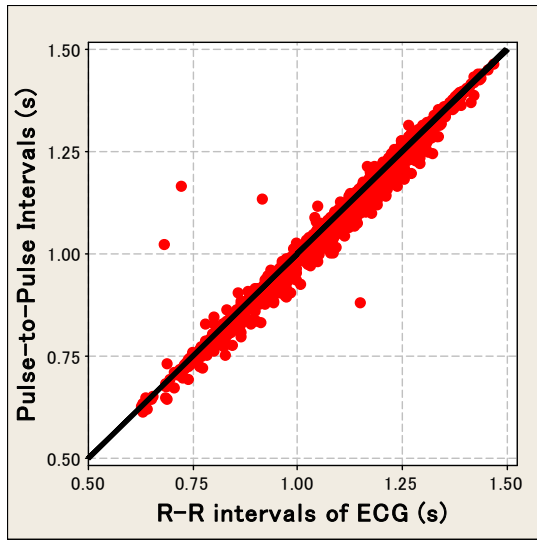


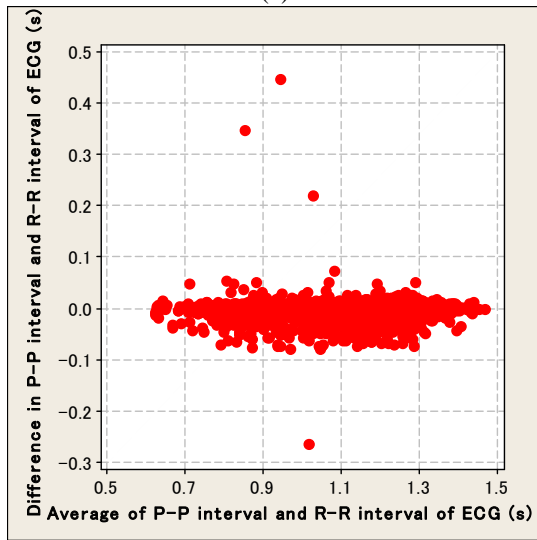
Figure 3: Actigram during sleep. Upper graph shows the result measured by Actigraph and lower graph shows that measured by our sensor.

Besides, the correlation coefficient between the PPIs computed by the pulse wave measured by the sensor and the R-R intervals computed by a simultaneously measured electrocardiogram during sleep was evaluated. Single-channel ECG was measured by CM5 lead using PSG (Polymate AP1124, TEAC Corporation, sampling rate: 1 kHz) simultaneously with the PPI measured by our sensor. R-R intervals were computed using commercially available R-R interval analysis software for the PSG (NoruPro Light Systems, Japan). The correlation coefficient is 0.96 (average of 3 healthy subjects). Figure 4(a) shows the correlation plot, and (b) shows the Bland & Altman plot between R-R intervals of ECG and PPIs.

These values are accurate enough to use the sensor as a medical device.



(a)



(b)

Figure 4: Correlation plot (a) and Bland & Altman plot (b) between R-R intervals of ECG and PPIs.

## 4.2 PC Software

Figure 5 shows the flow of the algorithm for computing sleep stages from the data of PPIs and the amount of activity.

We employ Cole's algorithm for wake/sleep identification from the amount of activity data (Cole, 1992). This algorithm cannot determine wake/sleep in real time, but its accuracy is about 90%. At the same time, the indices of autonomic nervous activity are derived from frequency analysis of the variability of PPIs. Firstly, sampled PPIs' dataset in a minute is interpolated at even intervals by cubic spline interpolation by the minute. Next, Fast

Fourier Transformation (FFT) is executed for the even-interval PPIs to get the frequency spectrum. In the frequency domain, the integral value of the power from 0.04Hz to 0.15Hz is called LF (low frequency), which shows both sympathetic and parasympathetic nervous activities. The integral value of the power from 0.15Hz to 0.4Hz is called HF (high frequency), which shows parasympathetic nervous activity. Therefore, we can get the balance of sympathetic and parasympathetic nervous activity, which is related to sleep stages as we mentioned above. In order to classify the sleep stages from the dataset of LF and HF values, the k-means clustering method is adopted. Firstly, REM/NREM sleep is divided from 2-hour data set, and then, shallow/deep sleep is divided from its NREM dataset.

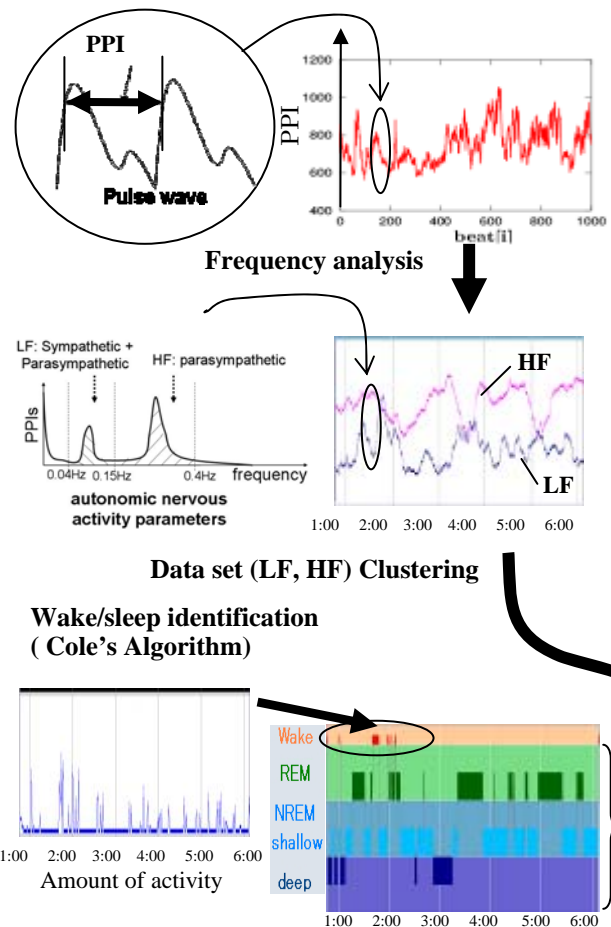


Figure 5: Algorithm for computing sleep stages.

We developed sleep analysis software on Windows XP/Vista using this algorithm. The program was coded and compiled by Visual Basic Ver.6 (Microsoft Corp.).

Figure 6 and 7 are the picture image of the software. Figure 6 is one night's data, which shows pulse rate, variability of pulse rate, LF and HF trends, amount of activity and the simplified hypnogram. Figure 7 is a summary of a 2-week hypnogram showing sleep habits. This is the most useful function for sleep care, which cannot be implemented in the conventional sleep monitoring systems.



Figure 6: Result of one night's data.

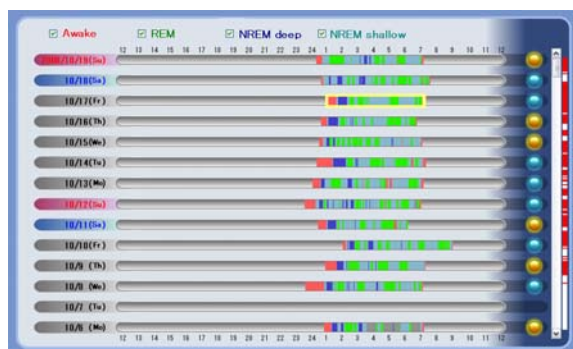


Figure 7: Result of summary of a 2-week hypnogram.

## 5 VALIDATION OF THE SLEEP ESTIMATION

Correlation between the sleep stage estimated by the proposed method using our wearable physiological sensor and the sleep stage estimated using PSG by sleep specialists was evaluated. EEG, EOG, chin EMG, ECG, respiration and SpO<sub>2</sub> by PSG (Polymate AP1000, TEAC Corporation, Sampling rate: 250Hz), the pulse wave and acceleration by our sensor was recorded simultaneously in a night (8 hours). The test was held in two cities (Showa University East Hospital, Tokyo, Japan and The Institute for Science of Labour, Kawasaki, Japan). 45 normal healthy subjects (30 males and 15 females, 19-72 years old) are measured. All subjects had informed consent.

The sleep stages of PSG were distinguished manually by sleep specialists (doctor, clinical laboratory technologist, or sleep researcher) who belong to those cite based on Rechtschaffen & Kales method (Rechtschaffen, 1968) by the minute. Our sensor also estimated the sleep stages also by the minute.

We defined coincidence ratio as an evaluation function to compare the estimation result by our sensor with the result by PSG.

The coincidence ratio is defined as a correlation coefficient of moving average of sleep stages (20-minutes time window) between the stages estimated by this method and those from PSG. Table 1 shows the result of the comparison.

Table 1: Result of the comparison.

	coincidence ratio				
	SWS	REM	NREM	WAKE	ALL
average	0.740	0.712	0.697	0.799	<b>0.735</b>
SD	0.079	0.067	0.080	0.100	<b>0.052</b>

Figure 8 shows an example of the estimation results.

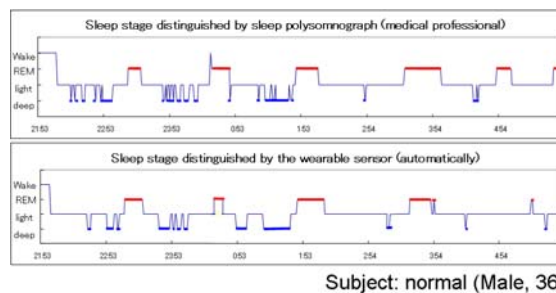


Figure 8: an example of the estimation results. (upper: sleep stage distinguished by medical professionals using PSG, lower: sleep stage distinguished automatically by the sensor)

## 6 DISCUSSIONS

“ Beat-to-beat” pulse interval detection is necessary to obtain autonomic nervous activity. Our algorithm has enough ability to get “beat-to-beat” pulse intervals. However, this algorithm is applicable for healthy subjects, except for cardiac disease, peripheral blood circulation disorder. The coincidence ratio of our sleep stage estimating algorithm is 0.735. Although it is a rather low value, PSG results also varied depending on the examiner (variance is about 20%), and therefore it seems to be acceptable for home healthcare use. However, it is also applicable for healthy subjects, except for autonomic nerve disorder, cardiac disease.

## 7 CONCLUSION

Measurement of sleep habits is a promising new medical field. However, there are no systems suitable for it. This is because current sleep monitoring systems cannot satisfy the needs for accurate analysis of sleep and convenience in use. In order to provide a solution, we developed a small and easy-to-use sensor device. We also developed an algorithm for analyzing sleep stages. We confirmed sufficient accuracy in the detection of PPIs by comparison with R-R Intervals by ECG, and that in the estimation of the sleep stage by comparison with the result of PSG. The software can display the sleep data of one night and the summary of a 2-week hypnogram. This function is useful not only for a doctor analyzing a patient's sleep habits, but also for a user analyzing his/her sleep.

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