A Study on Sleep Stage Estimation via Non-invasive Air Mattress Sensor

Takayuki Ishikawa[1],Hisanori Ando[1],Keita Kobayashi[1],
Emi Nishida[1],Kajiro Watanabe[1],Tetsuo Nakamura[2]

1 Hosei University, 3-7-2 Kajinocho Koganei Tokyo 184-8584, Japan
2 Jepico Corporation, 2-7-1 Nishi-sinjuku Sinjyuku Tokyo 163-0729, Japan
takayuki@wtnb.k.hosei.ac.jp

Abstract: In this study, a new automatic sleep stage judgment system was proposed using a non-invasive type air mattress sensor enabling the detection of three useful bio-signals: heartbeat rate, respiratory rate and other body movement. We found that fairly good correlations exist between these signals and the sleep stage. Based on this knowledge, we developed a novel sleep estimation method free from any stress.

Keywords: sleep stage, non-invasive, air mattress

1. INTRODUCTION

Today's Japanese society typifies the trend in the world's industrialized countries, in which people of old age are becoming more dominant in proportion to the population of the society. It is estimated that the ratio of people older than 65 years old in Japan will reach 22% by the year 2010. Therefore, the development of a domestic health-care system is anticipated to be of great importance.

Average people spend about one third of their time sleeping every day. Quality of sleep is thus critical for individual health. If a system can be devised to monitor the state of sleep daily at home through non-invasive and unrestrained procedures, it will enable the discovery of symptoms of insomnia at an early stage, thus helping to improve the quality of people's sleep and maintain people's health.

2. OBJECTIVE

The Rechtschaffen & Kales (R-K) method, well known as the international standard sleep stage estimation method, has several problems: primarily, it requires an expensive and sophisticated polygraph and induces physical and mental stress in examinees.

In our previous study, we showed that heartbeat and body movement data obtained by a non-invasive and unrestrained bio-measurement system can fairly estimate the sleep stage of the examinee[1, 2, 3].However the monitoring by the above system was inferior in accuracy when compared with the conventional R & K method, which uses the data given by brain-wave polygraph.

In order to improve the accuracy made by the estimation of the previous study, a new procedure to estimate the stage of sleep was presented here based on the bio-medical data obtained by the proposed system. Respiratory data was added to the above system for evaluation.

3. ASSUMPTIONS AND PROBLEM

For the simplicity of system development, we cite the following two assumptions

(A1) Examinees experienced six discrete sleep stages.

(A2) Examinees were normal; the average percentage spent in each sleep stage was that of normal sleepers.

Under the above assumptions, we consider the following problem.

(P1) Estimate the sleep stages from the heatbeat, respiration and body movement data.

For (A1), it is known that normal sleepers experience all of the sleep six stages in one night.
For (A2), the average percentages of each sleep stage are well known.

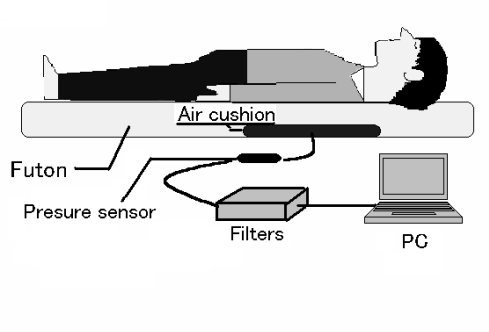


Fig. 1: Bio-measurement system

4. MEASUREMENT

Fig.1 shows the non-invasive and unrestrained bio-measurement system used in this study.

The measurement system consists of four units: an air mattress, a sensor, three filters and a PC. The system works as follows:
1) The examinee lies upon futon mattress under which an air mattress is laid.
2) The sensor in the air-mattress detects variations in pressure due to heartbeat, respiration and body motion. The value of the variation is transformed to electronic voltages through the condenser-microphone of the sensor.
3) The heartbeat, respiration and body motion signals are discriminated by the filters. These signals are introduced to a PC through an A/D converter.

Using the above instruments, data on heartbeat, respiratory movement and body movement are obtained. For comparison, the polygraph was also used. EEG (electroencephalogram), EMG (electromyogram), EOG (electrooculogram) and ECG (electrocardiogram) were measured by polygraph. Fig.2 shows the experimental system used a polygraph.

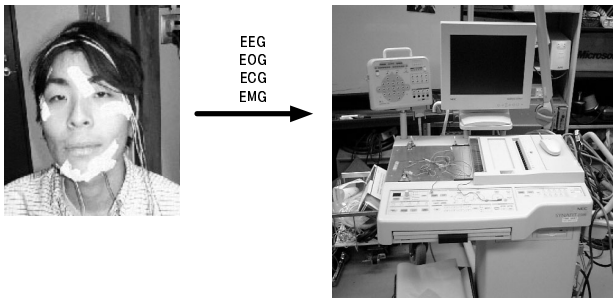


Fig. 2: Experimental system used a polygraph

5. DATA ANALYSIS

For analysis of the examinee's sleep, the heartbeat and respiration signals were used. Differences in the heart rate and standard deviation of the heart rate were calculated.

The standard deviation thus obtained was presumed to represent the degree of the body movement. The absolute value of differences in the respiration rate was also calculated. The values of these two differentials and the deviation were treated by BPF in the range of 0.0074 to 0.038Hz.

5.1 Correlation between bio-medical data and the stage of sleep

First, the data obtained from polygraph was analyzed by the computer soft-ware Sleep Sign to determine the sleep stage. The sleep stage data thus obtained were used to calculate the correlation coefficients with bio-medical data given by the present study.

Fig.3(a) shows the correlation map between the sleep stage and the absolute value of differences in heart rate obtained from the non-invasive and unrestrained bio-measurement system. Fig.3(b) shows the correlation map between the sleep stage and the respiration rate. Fig.3(c) shows the correlation between the sleep stage and the body movement.

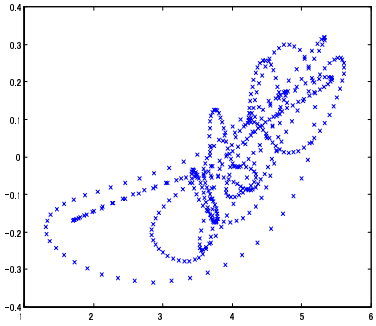
The correlation coefficients between the sleep stage and each bio-medical data were as follows:

Differentials of heartbeat rate:	0.7269
Differentials of respiration rate:	0.6901
Body movement rate:	0.5895

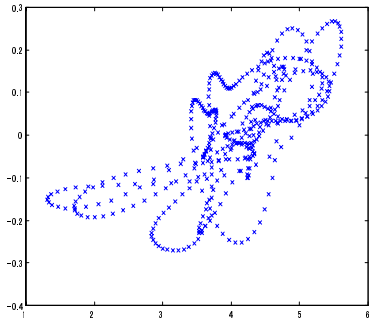
Normally, it is judged that a strong correlation exists if the correlation coefficient is higher than 0.5 in bio-medical data[4]. Therefore, it is proper to use the present bio-medical data for sleep stage estimation.

5.2 Estimation of the sleep stage by the proposed method

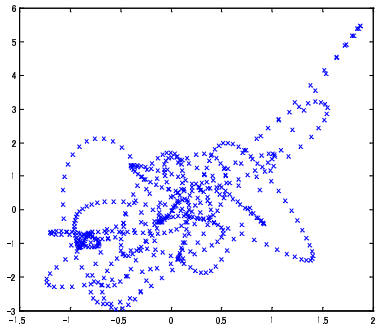
As stated in 5.1 each bio-medical datum, i.e. heart rate, respiration rate, and body movement, correlates fairly well with the stage of sleep. Based upon these correlations, the sleep stage was estimated using the value of differences of both heartbeat rate and respiration rate, body movement (standard deviation of the heart rate) with the following values of the ratio for each sleep stage:



(a)Heartbeat



(b)Respiration



(c)Body movement

Fig. 3: Correlation diagram

Wakefulness	0.101
REM Sleep	0.159
Sleep Stage 1	0.130
Sleep Stage 2	0.467
Sleep Stage 3	0.088
Sleep Stage 4	0.055

Using these values, the sleep stage based on heart rate, respiration rate and body movement was estimated at intervals of one minute. Then, the overall sleep stage was estimated by taking the average of the sleep stage from these three data.

The four tracks in Fig.4 show estimations by use of the data on heartbeat, respiration, body movement and overall data, respectively.

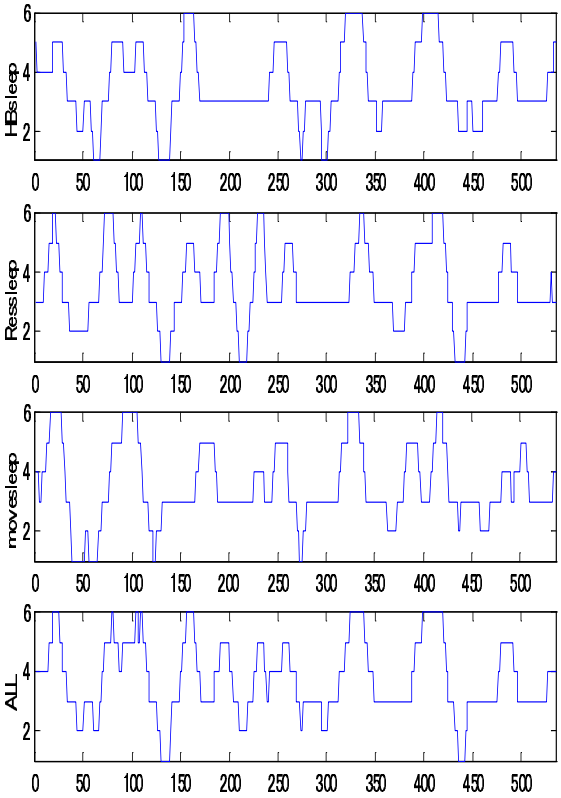


Fig. 4: Estimation of the stage of sleep

6. DISCUSSION

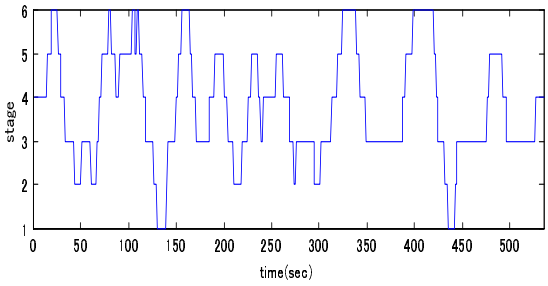
In order to investigate the accuracy of the estimation of the sleep stage by the present study, the results were compared with the estimation made by the international standard, the R & K method coded as Sleep Sign in the computer.

Fig.5 compares the estimation of the sleep stage made by the proposed method with the estimation by R&K.

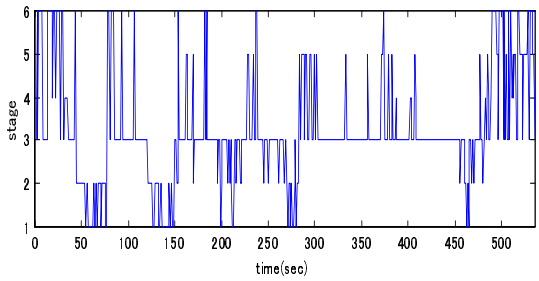
As for PSS (Percentage of Sleep Stage) the error is less than 10%. As far as the sleep index is concerned, the proposed method estimates the transition between each stage of sleep with an accuracy of 90% or above compared with the conventional method. Therefore, the proposed method can be used to evaluate the quality of a person's sleep.

7. CONCLUSIONS

The R & K method, which is the international standard for sleep stage estimation, requires the examinee to sleep with electrodes attached to his head or face. Such a



(a)Estimation by proposed method



(b)Estimation by Sleep Sign

Fig. 5: Comparison of sleep stage estimations

system is unsuitable for daily use. A non-invasive and unrestrained method is proposed in this study. With less than 10% error, it provides reliable accuracy for the purpose of a domestic health care system.

In the present study, data on the PSS from normal sleepers were used. Since standard data for infants and the elderly can be obtained, the proposed system can be applied to estimate the sleep stage of individuals from these higher risk groups.

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