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Estimation of Sleep Stage in the Falling Asleep Period Using a Lorenz Plot of ECG RR Intervals

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***Abstract*— The falling asleep period is the shift from the waking stage to sleep stages 1 and 2. Changes during the falling asleep period can be observed on electroencephalograms (EEGs). In this research, we developed a technique for estimating sleep stage at the falling asleep period without using EEGs. We performed a Lorenz plot (LP) using the intervals between heartbeats, known as electrocardiogram (ECG) RR intervals, of the falling asleep period, and confirmed that changes in the distribution on the LP occur according to changes in sleep stage. To evaluate the changes in these distributions, we projected the LP on y = x axis and y = −x axis, and analyzed the shifting of mean and standard deviation in each sleep stage. The results demonstrated that the distance from the coordinate origin to the mean of distribution became longer as sleep stage deepened, but the variations in the distribution of the LP stabilized. By quantitatively evaluating these phenomena, we proposed two indices of mean (*M* of LP) and ellipse area (*S* of LP) of the falling asleep period. Additionally, a multiple regression analysis was done to calculate sleep stage quantitatively, culminating in the derivation of the estimated equation of falling asleep period. Therefore, we could easily estimate the directionality of the sleep stage at the falling asleep period using a LP of ECG RR intervals.**

***Index Terms*—sleep, ECG RR intervals, Lorenz plot, falling asleep period.**

I. Introduction

MODERN society can be stressful, causing mental distress at the office and in daily life. Good sleep can provide comfort and relieve stress, and is becoming increasingly important in today's world.

As for good sleep, the quality of sleep is more important than the quantity, and the falling asleep period is important in obtaining good quality sleep. The present study focuses on the falling asleep period, a shift from the waking stage to sleep stages 1 and 2. Sleep stage 2 of falling asleep period is the stage judged by Rechtschaffen and Kales criteria [1], and is said to be the depth of sleep needed to obtain the sense of having slept. Until now, sleep state as a physiological index was obtained using the cumbersome electroencephalogram (EEG) method. Convenient measurement of falling asleep periods may assist in understanding varying instances of sleep, such as napping or falling asleep while operating a motor vehicle (drive dozing). Therefore, a simpler application is required for use in the field.

In the present study, the Lorenz plot (LP) of the intervals between heartbeats, known as electrocardiogram (ECG) RR intervals was used to estimate the falling asleep period from waking stage to sleep stage 2. Two indices of mean (*M* of LP) and ellipse area (*S* of LP) of falling asleep period were evaluated. Additionally, a multiple regression analysis was done to calculate sleep stage quantitatively, culminating in the derivation of the estimated equation of falling asleep period.

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II. Experimental Method

A. Subjects

Twenty healthy, non-medicated subjects (17 males, 3 females; college students; age: 21 – 23 yrs.) participated in the experiment.

All subjects obtained adequate sleep and performed the experiment without immoderate eating and drinking the previous night. In addition, subjects refrained from alcohol and caffeine ingestion and avoided napping or engaging in prolonged or strenuous exercise before the experiment. Informed, written consent was obtained from each subject prior to participation in the study.

B. Experimental Procedures

Each subject underwent experimental short-time sleep in a soundproof (below 35 dB), air-conditioned (temperature: 24 – 26 °C, humidity: 50 – 65%) room. As the experiment primarily focused on napping, subjects were awoken after 40 min.

III. Analysis Evaluation Method

Electroencephalograms were recorded on the central lobes and occipital lobes with reference to the opposite earlobe electrode according to the International 10-20 system. Four EEG channels were applied (C3/A2, C4/A1, O1/A2 and O2/A1).

EEGs and ECGs were recorded at a sampling frequency of 500 Hz, and noise was removed with high-pass (0.5 Hz), low-pass (30 Hz) and band-stop (57 – 63 Hz; for common mode noise) filters for EEGs, and high-pass (0.1 Hz), low-pass (120 Hz) and band-stop (57 – 63 Hz) filters for ECGs.

Afterward, the peak positions in the ECG (RR intervals) were detected by visual inspection and used to generate the LP. The LP of ECG RR intervals plotted the nth ECG RR interval (RRn) on the horizontal axis, and the n+1th ECG RR interval (RRn+1) on the vertical axis [2].

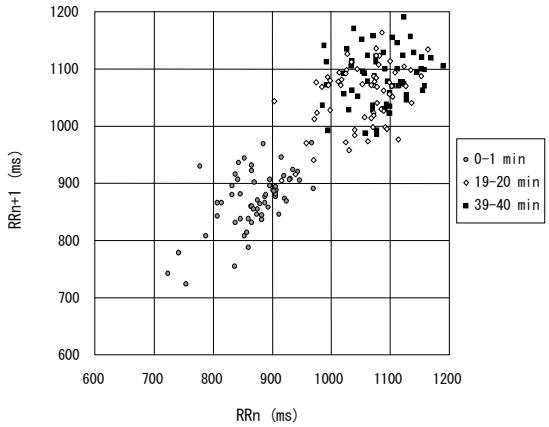

Fig. 1. Transition of LP (one of eight subjects who attained sleep stage 2): The nth ECG RR intervals on the horizontal axis and the n+1th ECG RR intervals on the vertical axis. LP is located lower left at first with large variation and shifts to upper right as time progresses with decreasing variation. Filled circles indicate the LP of waking stage for 1 min (0–1 min). Open diamonds indicate the LP of sleep stage 1 for 1 min (19–20 min). Filled squares indicate the LP of sleep stage 2 for 1 min (39–40 min).

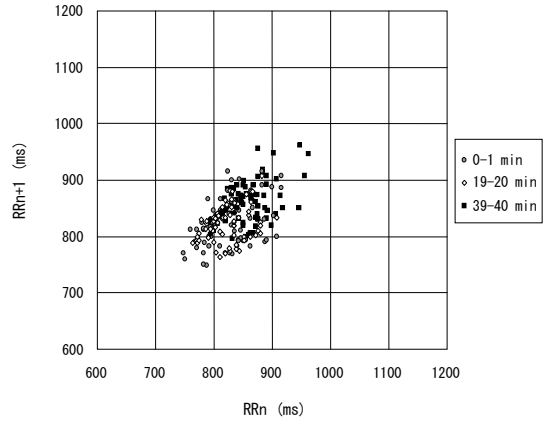

Fig. 2. Transition of LP (one of eight subjects who did not attain sleep stage 2): The LP is centrally distributed with little variation.

To evaluate falling asleep period in detail, sleep stage was judged manually by an EEG specialist using the Rechtschaffen and Kales criteria with 30 sec epochs.

The LP generated by dividing 40 min of data into 1 min sections (0–1, 19–20, 39–40) for one of eight subjects who attained sleep stage 2 is shown in Figure 1, and indicates a shift to the upper right and a decrease in variation as the sleep state deepens. Changes in the ECG RR intervals can therefore be visualized using the LP. The LP for each 1 min section (0–1, 19–20, 39–40) for one of eight subjects who did not attain sleep stage 2 is shown in Figure 2, and indicates a central distribution with little variation. The difference in the quality of sleep is indicated by the dissimilar center positions and the changes in variation shown in Figures 1 and 2.

In order to more easily analyze changes in sleep state, we propose a new evaluation index using LP of ECG RR intervals. The use of the LP provides some advantages in the evaluation of ECG RR intervals, including ease of use and real-time detection of heart rate variation. Additionally, the visual characteristics of the ECG RR intervals are easily understood and noise elimination of the ECG signal is simple. For these reasons, it is possible to visually analyze changes in sleep state in real time, through the LP of ECG RR intervals [3].

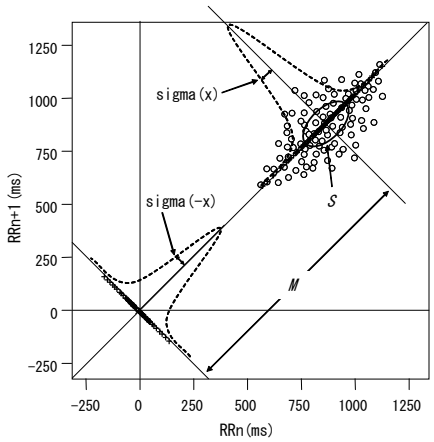

Fig. 3. Evaluation method of the LP for 1 min: *M* is the mean of the distance from the coordinate origin of the LP data projected to the y = x line. Ellipse area *S* is determined by $S = \pi \times \text{sigma}(x) \times \text{sigma}(-x)$. The sigma(x) value is the standard deviation of the LP data projected to the y = x line. The sigma(−x) value is the standard deviation of the LP data projected to the y = −x line.

The evaluation method using the LP of ECG RR intervals is shown in Figure 3. Data of the LP for 1 min are projected to the y = x axis and y = −x axis.

From the y = x axis, mean (*M*) and standard deviation (sigma(x)) of the distance from the coordinate origin are calculated. Similarly, from the y = −x axis, the standard deviation (sigma(−x)) of the distance from the coordinate origin is calculated. Ellipse area (*S*) showing the variation of the LP is $S = \pi \times \text{sigma}(x) \times \text{sigma}(-x)$ [4], [5].

By evaluating the relationship between sleep stage, LP mean *M* and LP ellipse area *S*, we developed a method to estimate sleep stage.

IV. Results

A. Relationship between sleep stage and LP mean M

The change in the sleep stage and LP mean *M* of one of eight subjects who attained sleep stage 2 is shown in Figure 4. The waking stage (sleep stage 0) continued for a few minutes, followed by a sudden change to a deep sleep stage. LP mean *M* rose from the onset of measurement and stabilized by the transition from sleep stage 1 to sleep stage 2. Conversely, subjects who did not attain sleep stage 2 showed no remarkable change in LP mean *M*. The LP mean *M* was calculated every minute, and the mean value at 3 min post start of the experiment was used as a reference point. All subjects were at the waking stage for 3 min after beginning the experiment, and measurements were normalized using the mean value from this period.

Data from eight subjects who attained sleep stage 2 and eight subjects who only attained sleep stage 1 were divided into three sections: waking stage, sleep stage 1, and sleep

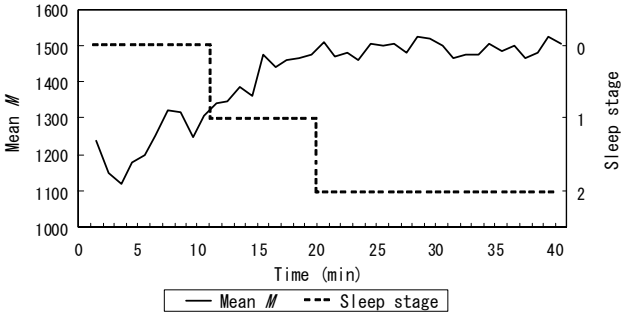

Fig. 4. Transition of sleep stage and LP mean *M* (one of eight subjects who attained sleep stage 2): As the level of sleep deepens, the center of the distribution rises and gradually becomes stable.

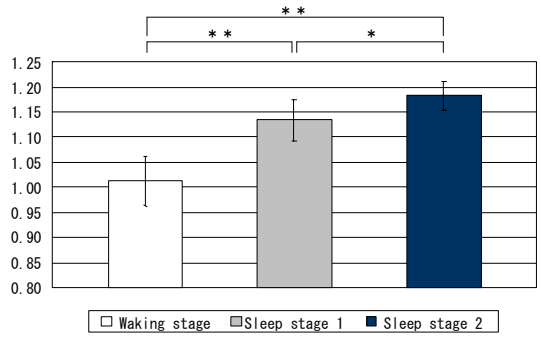

Fig. 5. Mean and standard deviation of LP mean *M* (eight subjects who attained sleep stage 2): Significant difference (p<0.01) was seen between the waking stage and sleep stage 1 and between the waking stage and sleep stage 2, and significant difference (p<0.05) was seen between sleep stage 1 and sleep stage 2.

TABLE I
MEAN AND STANDARD DEVIATION OF LP MEAN *M*

		Waking stage	Sleep stage 1	Sleep stage 2
LP mean *M* Mean (*SD*)	Attained sleep stage 2	1.01 (0.05)	1.13 (0.04)	1.18 (0.03)
	Sleep stage 2 not attained	1.01 (0.04)	1.11 (0.04)	

stage 2. The mean and the standard deviation of LP mean *M* of each sleep stage were calculated (Table I). Data from four subjects that failed to sleep during the experiment were excluded.

The mean and standard deviation of LP mean *M* of eight subjects who attained sleep stage 2 are shown in Figure 5. One-way analysis of variance (ANOVA) showed a significant difference (p<0.01) between the waking stage and sleep stage 1, between sleep stage 1 and sleep stage 2, and between the waking stage and sleep stage 2. Multiple comparisons were also made between each sleep stage resulting in a significant difference (p<0.01) between the waking stage and sleep stage 1 and between the waking stage and sleep stage 2, and significant difference (p<0.05) between sleep stage 1 and sleep stage 2.

The mean and the standard deviation of LP mean *M* were also calculated from the eight subjects who only attained sleep stage 1 (Table I). Here, one-way ANOVA showed a significant difference (p<0.05) between the waking stage and sleep stage 1.

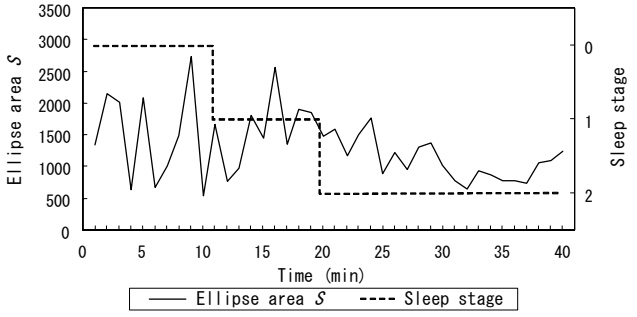

Fig. 6. Transition of sleep stage and LP ellipse area *S* (one of eight subjects who attained sleep stage 2): Area under the curve decreases as sleep stage deepens.

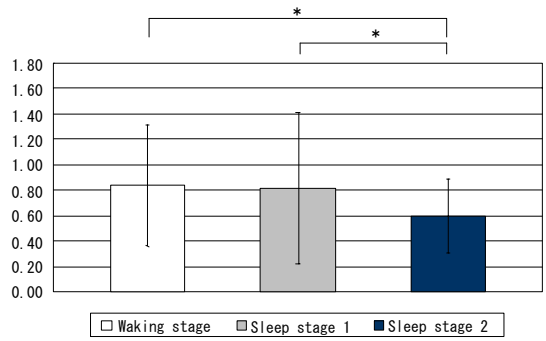

Fig. 7. Mean and standard deviation of LP ellipse area *S* (eight subjects who attained sleep stage 2): Significant difference was not seen between the waking stage and sleep stage 1. Significant difference (p<0.05) was found between the waking stage and sleep stage 1, and between sleep stage 1 and sleep stage 2.

TABLE II
MEAN AND STANDARD DEVIATION OF LP ELLIPSE AREA *S*

		Waking stage	Sleep stage 1	Sleep stage 2
LP ellipse area *S* Mean (*SD*)	Attained sleep stage 2	0.84 (0.48)	0.82 (0.59)	0.59 (0.29)
	Sleep stage 2 not attained	1.00 (0.45)	0.95 (0.52)	

B. Relationship between sleep stage and LP ellipse area S

The change in sleep stage and LP ellipse area *S* of one of eight subjects who attained sleep stage 2 is shown in Figure 6. Large variations in LP ellipse area *S* are seen during the waking stage (sleep stage 0), but gradually decrease as the sleep state deepens. In contrast, subjects who only attained sleep stage 1 showed little change in LP ellipse area *S*. In addition to the analysis of LP mean *M*, mean of LP ellipse area *S* 3 min after the start of the experiment was used as a reference point, and LP ellipse area *S* was determined every minute. Data were divided into three sections: the waking stage, sleep stage 1, and sleep stage 2, and the mean and standard deviation of LP ellipse area *S* of each sleep stage were calculated (Table II).

The mean and the standard deviation of LP ellipse area *S* of eight subjects who attained sleep stage 2 are shown in Figure 7. A significant difference (p<0.05) was found between the waking stage and sleep stage 1, between sleep stage 1 and sleep stage2, and between the waking stage and sleep stage 2 using one-way ANOVA.

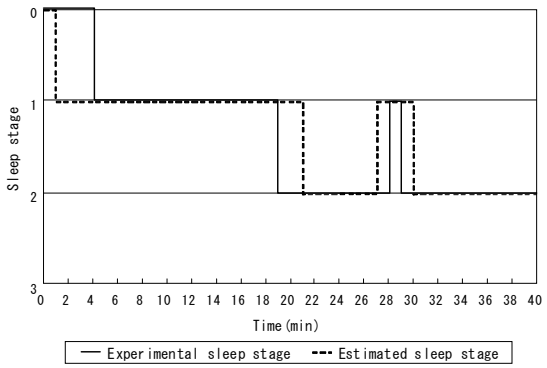

Fig. 8. Experimentally determined sleep stage (solid line) and estimated sleep stage using multiple regression equation (dashed line).

Multiple comparisons were, again, made between each sleep stage, and showed a significant difference (p<0.05) between the waking stage and sleep stage 2 and between sleep stage 1 and sleep stage 2; however, no significant difference was seen between the waking stage and sleep stage 1. The mean and standard deviation of LP ellipse area S of eight subjects who only attained sleep stage 1 were also calculated and one-way ANOVA of the data showed no significant difference between the waking stage and sleep stage 1 (Table II).

C. Derivation of estimated equation of sleep stage by multiple regression analysis

An estimated equation of sleep stage was derived based on the relationship of sleep stage, LP mean M and LP ellipse area S as ascertained from experimental results. Multiple regression analysis was performed using LP mean M and LP ellipse area S, for the eight subjects who attained sleep stage 2, as objective variables and sleep level as an explanatory variable, and resulted in the following multiple regression equation:

$$y = 4.908(x1) - 0.270(x2) - 4.031 \quad (1)$$

Here, $x1$ represented LP normalized mean M, $x2$ represented LP normalized ellipse area S, the multiple correlation coefficient was 0.661, and the squared multiple correlation coefficient adjusted for degrees of freedom was 0.434. No collinearity between $x1$ and $x2$ was found, and using the multiple regression equation resulted in a significant relation of 0.1% between sleep stage and y.

D. Estimation of sleep stage using multiple regression equation

Estimation of sleep stage in a new subject (male; college student; age: 21 yrs.) was performed using LP mean M and LP ellipse area S of ECG RR intervals. The changes in sleep stage obtained from experimentation (solid line) and estimation by the multiple regression equation (dashed line) are shown in Figure 8. Calculated changes in sleep stage during the falling asleep period effectively estimated the experimentally determined shift between the waking stage, sleep stage 1, and sleep stage 2.

V. DISCUSSION

This research demonstrated that the change in sleep stage can be estimated using the LP of the change in ECG RR intervals during the falling asleep period. Significant differences in mean values of LP were found between the waking stage and sleep stage 1, between the waking stage and sleep stage 2, and between sleep stage 1 and sleep stage 2. At the LP ellipse area that represented nonlinear characteristics of ECG RR intervals, significant differences were also seen between the waking stage and sleep stage 2 and between sleep stage 1 and sleep stage 2; however, no significant difference was found in the ellipse area between the waking stage and sleep stage 1. Therefore, detection of sleep stage 2 could be possible using an ellipse area index. The result of ellipse area S showing attainment of sleep stage 2 more definitively clarified that sleep stage 2 was a physiological different state from waking stage and sleep stage 1. In addition, quantifying changes in sleep stage was made possible by derivation of the estimated equation of the falling asleep period using multiple regression analysis of the LP mean M and LP ellipse area S. The accuracy of the estimated equation increased with the addition of ellipse area S as an explanatory variable of the multiple regression analysis when sleep stage of the falling asleep period was estimated.

VI. CONCLUSION

The present study investigated a simpler method for estimating the sleep stage within the falling asleep period. Sleep stage was ascertained from two indices of mean (M) on the y = x axis of LP and ellipse area (S), the extension of distribution of LP. The change of LP mean M indicates a shift from the waking stage to sleep stage 1 and sleep stage 2, and the LP ellipse area S is a more precise determination of a shift to sleep stage 2. Furthermore, the sleep stage of the falling asleep period was calculated as a regression formula using multiple regression analysis, and when used in conjunction with the LP of ECG RR intervals, the formula effectively estimated the sleep stage of falling asleep period.

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