32nd Annual International Conference of the IEEE EMBS
Buenos Aires, Argentina, August 31 - September 4, 2010

Relationship between Heart Rate Variability using Lorenz Plot and Sleep Level

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Abstract— **In the present study, we propose a new technique for estimating depth of sleep over the whole night using electrocardiogram (ECG) RR intervals (RRIs). We produced a Lorenz plot (LP) using the RRIs recorded during all-night sleep and confirmed that changes in distribution on the LP occur based on changes in sleep stage. To evaluate the changes in these distributions, RRIs are projected a LP on a y = x axis, y = −x axis, and analyzed the shifting of the mean (center C) and standard deviation (area S) for each sleep stage. Analysis interval time was 60 seconds, shifting every second, and we compared heart rate variability (HRV) and sleep level. Center C showed progress toward light sleep levels and area S showed the transition phases toward deep sleep. A concordance rate of 60.1% between the estimated values and actual transitional sleep level was obtained for all-night sleep. Therefore, transitional sleep level can be evaluated based on HRV using the LP.**

I. Introduction

JAPAN has become a 24-h society as its economy continues to grow. Within such a society, the number of people who work in jobs requiring day-and-night shift work increases. According to the Comprehensive Survey of Working Conditions in Japan, these individuals account for 18% of all workers. In general, there is no doubt about the importance of sleep, but sleep classification is currently based on brain waves (electroencephalogram: EEG), and assessment requires the subject to wear numerous electrodes. This makes sleep measurement in daily life very impractical.

In order to devise a practical means for evaluating sleep, various studies have been conducted on the use of other indexes. For example, we have used an infrared-type motion sensor to noninvasively measure the features of body movement during all-night sleep and to estimate sleep depth [1]. However, it is not possible to evaluate sleep in real time using this approach. We thus focused on the RR intervals (RRIs) on the electrocardiogram (ECG) as an instant and noninvasive method [2].

Sleep is deeply linked to RRIs by the autonomic nervous system, and can change markedly within a few seconds. In addition, the study of heart rate variability (HRV) has clearly shown that it can be used as a substitute index for sleep. It is known that all-night sleep is affected by automatic nervous system (ANS) switching, and this can change markedly within a few seconds.

For investigating ANS activity, frequency analysis methods, such as fast Fourier transformation (FFT), have been widely adopted. This method requires long durations of time to analyze heart rate, but shorter spans are necessary for real-time analysis. To identify changes more rapidly, we proposed a method using evaluation indexes based on Lorenz plot (LP). On the LP, the nth RRI is plotted on the x axis and the n+1th RRI is plotted on the y axis [3]. The proposed method also has the advantage of being able to show changes visually (Fig. 1) [4]. To analyze visual changes quantitatively, they are subsequently calculated as evaluation indexes, and RRIs are projected on the LP as y = x axis, y = −x axis. The distribution is considered to be an ellipse constructed by the lines of the long and short axes. The long axis refers to standard deviation (sigma(x)), which is calculated from the coordinate origin, and the short axis also refers to standard deviation (sigma(−x)). The area of the ellipse and the origin-to-center distance are calculated as the evaluation indexes center C and area S [5],[6].

In the present study, the relationship between sleep based on EEG and evaluation indexes from the LP during all-night sleep was examined. Sleep transitions were found to be related to the stability of evaluation indexes from the LP. We also defined the thresholds of stability using evaluation indexes and calculated estimation values. We weighted the estimation values from ECG against the measurement values from EEG, and found that the method using the LP has the potential to estimate the depth of sleep in real time.

II. Experimental Method

A. Subjects and Experimental Procedures

Seven healthy subjects (male: 6, female: 1) between 18 and 24 years of age participated in the present study. All subjects had regular sleep-wake habits, and none were taking any medications. They were asked to strictly avoid alcohol and caffeine, napping and engaging in prolonged and strenuous exercise during the daytime.

The experiment was carried out in a sound-proof (less than 35 dB) and air-conditioned (temperature: 24–26°C; humidity: 50–65%) room. The study for all-night sleep lasted 420 min (from 00:00 to 07:00).

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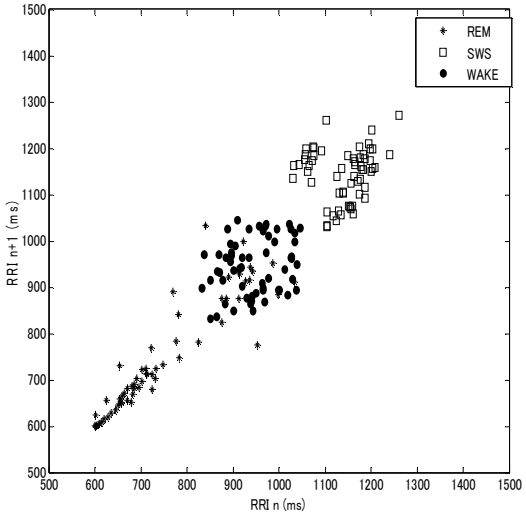

Fig. 1. Transition of LP: The nth RRI is plotted on the horizontal axis and the n+1th RRI is plotted on the vertical axis. The LP is initially located on lower left with large variation and shifts to the upper right with decreasing variation as time progresses. Filled circles indicate the LP in the waking stage for 60 s. Open squares indicate the LP for slow wave sleep (stage 3 or 4) for 60 s. Asterisks indicate the LP for REM stage for 60 s.

B. Experimental Device

Electrodes were attached to all subjects based on the ten-twenty method (derivations: C3-A2, C4-A1, O1-A2, O2-A1), and EEG signals were high-pass filtered at 0.5 Hz, low-pass filtered at 30 Hz, and band-stop filtered at 57–63 Hz for common-mode noise. HRV was measured using standard bipolar leads with ECG. EOG was measured at the electrode positions on the upper-right of the right eye and lower-left of the left eye. Electromyogram (EMG) was measured at the mentalis muscle. Biological signals were measured at a sampling frequency of 500 Hz. ECG wave type conversion was performed using Vital Tracer (Kissei Comtec) software. Automatic nervous activity was analyzed by MaP1060 (Nihonsanteku).

III. Analysis Evaluation Method

Sleep stages were judged manually from polysomnography recordings based on the Rechtschaffen and Kales criteria [7]. In addition, we used nine levels of sleep depth, 0 to 8, and Rapid Eye Movement (REM) [8]. EEG signals, EOG and EMG were manually judged every 60 s by three investigators according to the criteria shown in Table I.

Heart rates during sleep were measured by ECG signals. RRIs were detected and used to generate a LP. The LP was plotted with the nth RRI (RRI n) on the horizontal axis and the n+1th RRI (RRI n+1) on the vertical axis. The LP was divided into RRIs using the evaluation indexes center C and area S (Fig. 2).

From the y = x axis, center C and standard deviation (sigma(x)) of the distance from the coordinate origin are calculated. Similarly, from the y = −x axis, standard deviation (sigma (−x)) of the distance from the coordinate origin is calculated. Area S, the area of the ellipse showing variations in the LP, is $S = \pi \times \text{sigma}(x) \times \text{sigma}(-x)$ [5],[6]. RRIs between the period of n-60 and n were calculated and plotted on the LP. Plotting was performed for every second of data to calculate center C and area S throughout the experiment. Analytical data processing was performed using MATLAB software (Math Works).

TABLE I
COMPARISON OF SLEEP STAGE AND 9 SLEEP LEVELS + REM

Sleep stage	Nine sleep levels + REM	Determination method	Physical level
Waking	0	α wave>50%	Awake
1	1	α wave≤50%	Drowsiness, very light sleep
	2	θ wave	
	3	Hump	
2	4	K-complex	
	5	Spindle	Light sleep
	6	δ wave<20%	Moderately deep sleep
3	7	20%≤δ wave<50%	
4	8	δ wave≥50%	Very deep sleep
REM	REM	Low-voltage waves + rapid eye movement	High sleep, dreaming

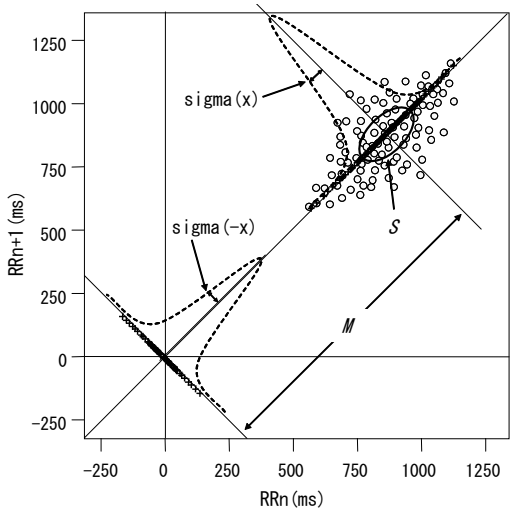

Fig. 2. Evaluation method of LP for 60 s: C is the mean of the distance from the coordinate origin to the distribution center. S is the area of the ellipse determined by $S = \pi \times \text{sigma}(x) \times \text{sigma}(-x)$. Sigma(x) refers to the standard deviation of the LP data projected on the y = x line. Sigma(−x) refers to the standard deviation of the LP data projected on the y = −x line.

IV. RESULTS

A. Relationship between sleep level and LP center C

A time series graph of sleep level and center C is shown in Figure 3. Center C shows waves with the highest peak at 315 min. Center C repeatedly decreases after stabilizing for fixed times. When sleep level shifts to deeper levels, variations in center C become smaller. Conversely, variations become larger when sleep level shifts to lighter levels. In the case of continuously deep levels of sleep, variations remain small.

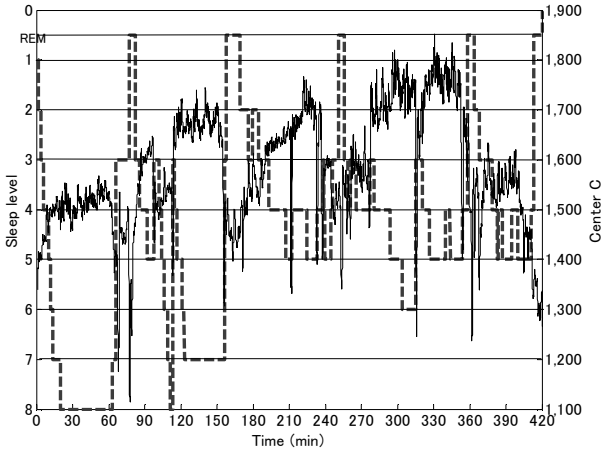

Fig. 3. Comparison between sleep level and center C: Sleep level (solid line) was classified into nine phases (0–8 + REM). Center C (dashed line) was calculated as the standard deviation (sigma(x)) of the distance from origin to center.

B. Relationship between sleep level and LP ellipse area S

A time series graph of sleep level and area S is shown in Figure 4. Variations in area S are small from 0 to 20, 90 to 100 and 190 to 210 min. However, from 15 to 50, 110 to 160 and 210 to 230 min, variations are significantly larger. After 210 min, the fluctuations in area S become large. Sharp fluctuations account for the highest amplitude at around 315 min. When sleep level shifts to deeper levels, variations and fluctuations become smaller; conversely, when sleep levels shift to lighter levels, variations and values in area S are marked. In addition, the changes are particularly evident during REM. After 230 min, comparatively large values are seen.

C. Comparison between sleep level and evaluation indexes

Results suggest that there are three characteristic relationships between evaluation indexes (center C, area S) from the LP and sleep level transitions. When sleep level deepens, both center C and area S stabilize. When sleep level lightens, evaluation values do not stabilize. In addition, when sleep levels are steady, center C stabilizes even though area S fluctuates. Therefore, the two evaluation values are linked to sleep level transitions. Based on these three patterns, it may be possible to estimate the transition between sleep levels using LP values. "Steadiness" and "unsteadiness" were defined visually based on abstract representations.

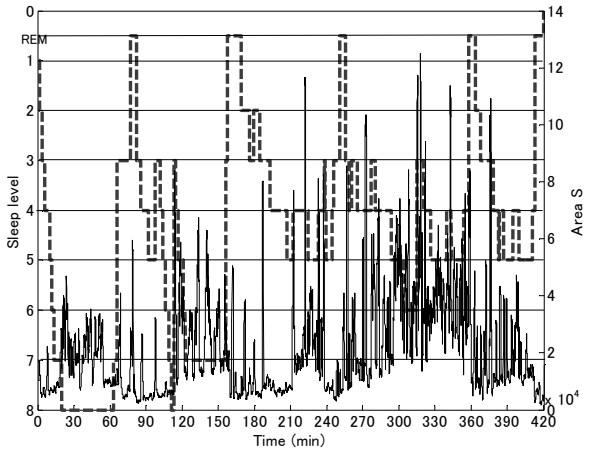

Fig. 4. Comparison between sleep level and area S: Sleep level (sold line) was classified into nine phases (0–8 + REM). Area S (dashed line) was calculated using: $S = \pi \times \text{sigma}(x) \times \text{sigma}(-x)$.

D. Definition of threshold index

As a measure of stability of evaluation indexes, standard deviation (SD) can be used, and for quantitative evaluation, threshold indexes are defined. SD of center C and area S was measured for 1 min. Values of center C and area S were adjusted in order to set numerical data for RRIs, allowing sleep levels to be judged every minute, and center C and area S were measured every second, with SD determined every minute.

Threshold indexes were determined as stability. SD of evaluation indexes for 3 min after the beginning of the experiment were regarded as standard values (SV). Threshold index C (threshold index for SD of center C) and threshold index S (threshold index for SD of area S) were obtained by multiplying SV by coefficient K. With regard to coefficient K, it is applied to multiple numbers, which are 1 to 5 and 1/2 to 1/5. In addition, area S is defined by two threshold values because fluctuations in area S were larger than those for center C. Threshold value S1 is multiplied by coefficient K, and threshold value S2 is calculated by multiplying S1 by 1/2. For these calculations, we computed estimated values that indicated the transition between sleep levels using an algorithm (Fig. 5).

E. Investigation of concordance rate with sleep level

As mentioned above, we classified three patterns using the algorithm: estimation 3, sleep level shifted from light to deep; estimation 2, transition was steady; and estimation 1, sleep shifted from deep to light.

In order to examine the properties of these patterns, we calculated a measurement index by comparing sleep level for 2 min: measurement 3, sleep level steadily increased; measurement 2, sleep level did not change; and measurement 1, sleep level steadily decreased.

The mean concordance rate between measurement index and estimation index was 60.1% (SD = ±5.9) in all subjects.

The mean coefficient K for SV of center C to determine threshold values was 3.3 and 1/3.7 for SV of area S.

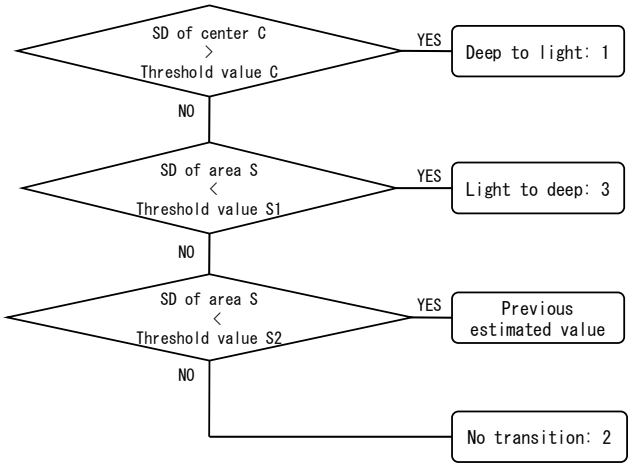

Fig.5. Algorithm for determining sleep levels using a LP: If the SD of C is larger than threshold C, sleep level was considered to have shifted from deep to light. If the SD of area S is larger than threshold S1, sleep level was considered to have shifted from light to deep. Finally, if the SD of area S is larger than threshold S2 (threshold S1 < threshold S2), the value was assumed to be the same as 1 min earlier.

TABLE II
CONCORDANCE RATE OF TRANSITIONS

	Subjects								
	A	B	C	D	E	F	G	Mean	
Factor of center C	3	2	4	3	5	2	4	3.3	
Factor of area S	1/3	1/4	1/5	1/4	1/3	1/3	1/4	1/3.7	SD
Concordance rate (%)	64.1	50.1	63.8	55.6	57.4	69.8	60.1	60.1	5.9

V. Discussion

In the present study, as a simple method for analyzing HRV during all-night sleep, the distribution of points on a LP was regarded as an ellipse. To quantitatively determine the changes in distribution on the LP, center C and area S were calculated as evaluation indexes. On comparison between sleep level and evaluation indexes, the stability of evaluation indexes was related to sleep stage transition.

In order to estimate the transition between sleep levels using the LP indexes, we needed to define stability. Estimation indexes were calculated using an algorithm based on threshold indexes. The concordance rate for estimation and measurement indexes was 60.1%. There has been substantial research into estimating the sleep quality using heart rate. The previously obtained concordance rate was about 60%, which is comparable to that obtained in our study. This suggests that it is possible to predict sleep transitions based on sleep cycles. The reason why the proposed method defined standard values for 3 min after the start was that all subjects were in the waking stage for the first 3 min, and a mean value could indicate a change from wakefulness.

The present study aimed to estimate sleep depth in real time, and thus RRIs (from n-60 to n) were calculated with the LP every second. However, sleep level epochs are assigned in 1-min increments. To align the data, SD values for center C and area S are calculated, but the obtained evaluation indexes from the previous 60 s would lead to a time-oriented gap, thereby reducing concordance rate. A previous study considered RRI fluctuation over a fixed period. Therefore, it may be necessary to investigate a method to eliminate such gaps. With regard to all-night sleep, it is known that the appearance rate of REM increases in the latter stages of sleep (as time passes), and the occurrence of sleep levels vary. This suggests that dividing all-night sleep into two halves in order to consider sleep level changes would decrease the concordance rate after 240 min.

VI. Conclusion

In the present study, RRIs of the heartbeat were evaluated using a LP, and the relationship between evaluated indexes (center C, area S and sleep level) was investigated. The features of fluctuations related to transitions in sleep level were thus obtained. Using these features, few found that it is possible to estimate changes in sleep level using the proposed method. Moreover, ultradian rhythms in the sleep cycle occur approximately every 90 min, and clearly delineated sleep cycles would help improve the accuracy of estimation. The present study defines threshold values in more detail, and considers the changes in occurrence of sleep level over time.

VII. Acknowledgements

This research was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (C), 22500415, 2010.

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