Estimation of Sleep Quality Based on Chaos Analysis of Heart Rate Variability

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Abstract— **In this paper, we propose an algorithm to estimate sleep quality based on heart rate variability using a chaos analysis. Recently it is focused that some people make a mistake or cause an accident due to lost of regular sleep and homeostasis so that a check system that can observe and evaluate their sleep in their daily life would be desired. Polysomnography (PSG) is however a only reliable system to diagnose sleep disorder and to evaluate its severity and therapeutic effect. An operator spends a lot of time for measuring data using PSG and the data has to be corrected by a medical doctor, that is hard work due to large data. Besides the Polysomnogram cannot be easily used in uncontrolled environment, because it measures brain waves, electromyogram, and so on. On the other hand a heart rate can be measured by a simple system such as a pressure sensor, an infrared sensor and so on. Therefore the estimation algorithm using only a heart rate is proposed in this paper so that people can check their sleep in their domestic site easily. The algorithm is developed by experimentally investigating the relationship between the largest Lyapunov exponent or correlation dimension and sleep qualities. The check system including the estimation algorithm could inform pattern and quality of his daily sleep to a user and then the user can previously arranges his life schedule and pays more attention based on this awareness of sleep results.**

I. INTRODUCTION

How can we refresh when we feel fatigue? Today, we often take a cup of coffee containing caffeine in order to awake ourselves or compensate shortage with various nutrients such as a vitamin compound. In the other ways, we drink alcohol in order to paralyze our tiredness, or receive massage in order to improve a blood circulation. These alternative deals however extend the limit of physical fatigue but never release the accumulated fatigue so that the fatigue could be dissipated only by sleep. The sleep is the very important physiology phenomenon for its life. However, many people live with an irregular life cycle affecting complex constrains from work environment and modern society so that they could not sleep enough and properly. That is why a collapse and a rhythm disorder of homeostasis can be seen in modern people. These symptoms lead tiredness, daytime sleepiness and a nap that can be critical factor of error and low efficiency of human work[2], [3].

There are many people who have any problem during sleep, but there are a few people who aware their problems among them, because the problems that occur during sleep are difficult to be recognized by oneself. Most patients often do not take care of it even if they feel tiredness or somnolence. A bottom-up approach is therefore important, where people can check their sleep qualities using a simple system in a domestic site and see a doctor for a precise check when they receive a negative information from it. If the system is also able to discover these sleep disorder in the early stage, we start curing it earlier in a hospital Nowadays, the research on sleep disorder is attracting researchers' interest, and the method for observing the sleep quality [5], [6], [7], [8] and curing system for some sleep disorders have been developed.

The International Classification of Sleep Disorders (ICSD) defines 88 sleep disorders. These sleep disorders are classified into four types 1) Dyssomnias, 2)Parasomnias, 3)Medical/Psychiatric Sleep Disorders, and 4)Sleep disorders under discussion.

The medical checking system of these sleep disorders is PSG shown in Fig.1, that is only an reliable system for it. The PSG has an electroencephalograph so that a shielded environment for its measurement is recommended. The PSG also measures an electromyogram (EMG), attaching electrodes at many parts of a subject body such as heart area, eyes, mentails, and legs. The PSG system estimates the sleep stages based on a lot of measured information explained above. It however gives a stress during monitoring to a subject due to many attached electrodes and the unusual environment. Furthermore, the PSG system is very expensive so that people could be diagnosed only at the medical center. We can not check our sleep in daily life using the PSG. In addition to these problems, there is no practical auto-detect program that can judge sleep stage automatically. The auto-detect program developed until now requires operator's corrections due to its low precision. This correction procedure is hard work because the measured data covers one night.

It is known that a heart rate changes in wide range during sleep [11][10] and that it has the relationship with sleep stages[9], [12] since the autonomic nerve system a significantly affects a heart rate. Especially, a large difference between REM(Rapid Eye Movement) sleep and NREM(Non-REM) sleep can be observed. Therefore we propose the method to estimate the sleep quality correctly only using a heart rate measured by a simple system with less stress in this paper

The relationship between sleep quality and heart rate is explained and the approach of our study is explained in the next section. In section three, a chaos analysis is explained and our previous work is introduced. In section four, the experimental results are shown and validity of our method is shown.

II. Sleep quality and heart rate variability

A nervephysiologic quality is changing meaningfully during his sleep, while a physical activity is very small. Generally, the sleep quality is classified into REM sleep and NREM sleep by electroencephalogram as shown in Fig. 2. Generally, a physical fatigue is healed in REM sleep, and then a brain has a rest in NREM sleep. Therefore we feel lack of sleep even if one of two sleep phases is missing. That is we can not recover enough even if we miss one of three requirements for a sound sleep: suitable sleep length, a deep sleep and a periodical sleep cycle of REM and NREM. The sleep quality should be estimated by some methods in order to evaluate these three items.

There are various studies on the sleep state estimation based on a heart rate information[11], [12], [13]. They infer a sleep state by estimating an activity of an autonomic nerve system by frequency analysis of a heart rate variability(HRV analysis), because they have a close relationship each other. In this method, a frequency spectrum from 0.15 to 0.40Hz of HRV is defined as a high frequency component "HF", and a frequency spectrum from 0.04 to 0.15Hz of HRV is defined as a low frequency component "LF". The HF component reflects the breathing activity with from two to seven seconds period that is controlled by an autonomic nerve system so that the HF component could become large when a parasympathetic nerve system becomes active and when the breathing activity becomes periodical. The power spectrum ratio of LF to HF in HRV can tell which nerve system is more active, a sympathetic nerve system or a parasympathetic nerve system. However, this method has lower reliability because LF is not stabile, which varies according to external stimuli. There is a study that proposes another frequency analysis for a sleep quality estimation[10], but it does not show stable results for various individuals and changes of one's conditions and environments.

Fig. 1. Example of PSG System

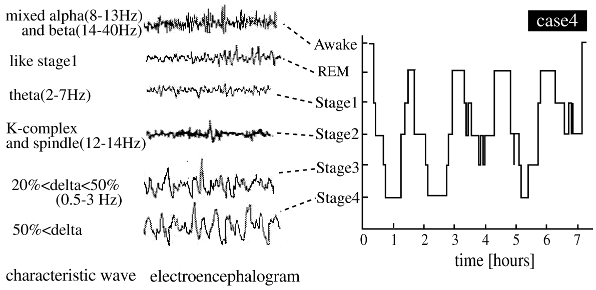

Fig. 2. Sleep stage defined by electroencephalogram

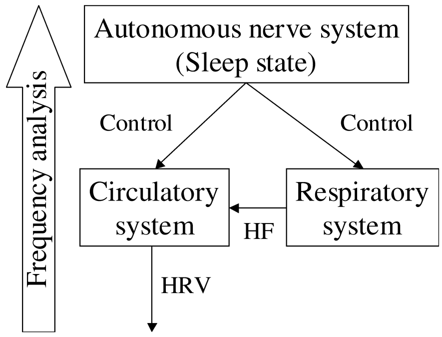

Fig. 3. Sleep stage defined by electroencephalogram

In these conventional approaches, a state of an autonomic nerve system is estimated based on a breathing periodical activity by sensing the HRV that is affected by the breathing activity as shown in Fig.3. A breathing activity and a heart are also controlled directly by an autonomic nerve system, and the HRV could reflect a state of an autonomic nerve system. However the affect directly from an autonomic nerve system is not evaluated and only HF excited by a periodical breathing activity is took into account. It is natural to focus on the direct affect from it for precise estimation of an state of an autonomic nerve system, if the heart activity could be evaluated as shown in Fig.4.

It is said that the HRV includes chaotic features and many researchers applying a chaos analysis to the HRV reported good results [15], [18], [19]. In this paper, we therefore propose another method with the chaos analysis to precisely estimate an autonomic nerve system based on HRV in order to infer a sleep quality. It evaluates chaotic properties in HRV so that a state of an autonomic nerve system could be directly and stably estimated based on

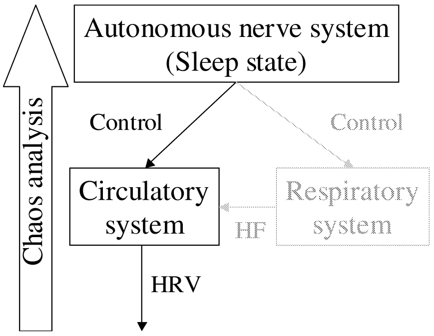

Fig. 4. Proposed approach for sleep quality estimation

HRV.

III. Chaos analysis of HRV

A. Takens embedding theorem

An internal dynamics of human system is very complicated and a heart rate or ECG is one of indices to prove that complexity of the system. The heart rate is affected by many factors: a physical activity, a breathing, a state of autonomic nerve system, an abnormal cardiac rhythms and an activity of organs so that it could not modeled.

However a chaos analysis can evaluate the complexity and predictive uncertainty of a chaotic system. F. Takens proposed an embedding theorem to reconstruct the time delay coordinate system from one-dimensional measured data of a complex system [16]. According to the embedding theorem, a time series can be converted into a state space with more than "m" dimensions and "τ" time delay shown in eq.(1).

$$v(t) = (y(t), y(t+\tau), \ldots y(t+(m-1)\tau)), \qquad (1)$$

where $y(t)$ is an observed time series and $v(t)$ is a state space vector with m dimensions. Lyapunov spectrum could be a calculability of a system's future behavior: future indetermination. The correlation dimension is a number of variables required to express the target system that could be an index of system complexity.

B. Parameter settings

The dimensions, time delay for the reconstruction and the number of data for analysis should be fixed for the chaos analysis. The correlation index was saturated at five-dimension space in our previous works, when the number of the dimensions increases. Therefore the embedding dimension for the reconstruction is fixed at five. The delay time τ was determined when the first local minimum point of autocorrelation function are found. The local minimum point is around three in various data [21], [11] and then it is fixed to three in this paper. About the data length used for the analysis, it is empirically fixed at 300 R-R intervals that is corresponding about to five minutes, because analysis results become the same when more than 240 data are used for chaos analysis.

In addition, five minutes for measurement is reasonable comparing with the international standard of the HRV analysis, that recommends more than five minutes for observation of HRV.

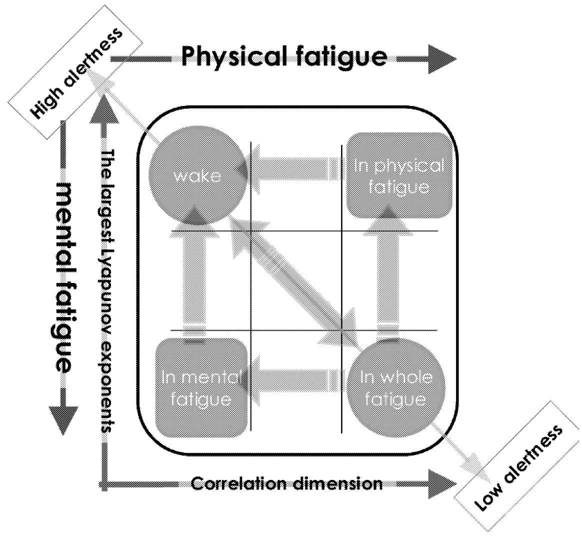

Fig. 5. Map to Estimate Alertness and Tiredness by Chaos Analysis[11]

These parameters are used for calculating the correlation dimension and the largest Lyapunov exponent after an attractor reconstruction in our study.

C. Two-dimensional map of chaos indices

From our previous experiments, we derived relationship between physical states: awake and fatigue, and chaos indices: the largest Lyapunov exponent and correlation dimension by matching subjects questionnaires about three items: an awake level, a physical fatigue level, and a mental fatigue level. The consistent relationship is obtained and qualitatively shown in a two-dimension map shown in Fig.5.

We found a close positive relationship between the correlation dimension and the physical fatigue and a close negative relationship between the largest Lyapunov exponent and the mental fatigue. Besides, we found a diagonal axis in the map can be corresponding to the awake level

People will feel sleepy when the correlation dimension becomes relatively big, and when the largest Lyapunov exponents becomes relatively small.

In the same way, we apply the chaos analysis to the state estimation of the autonomic nerve system during sleep and analyze the results on the two-dimensional map.

IV. Experiments

A. Experimental settings

We measured the precise sleep quality by using the PSG. The PSG system collects several kinds of data: electroencephalogram(C4A1, C3A2, O2A1, O1A2), eye movement(electro-oculogram:EOG) and Electromyography(EMG) of Chin and leg parts. This measured state is used for comparison with the inferred result of the proposed method.

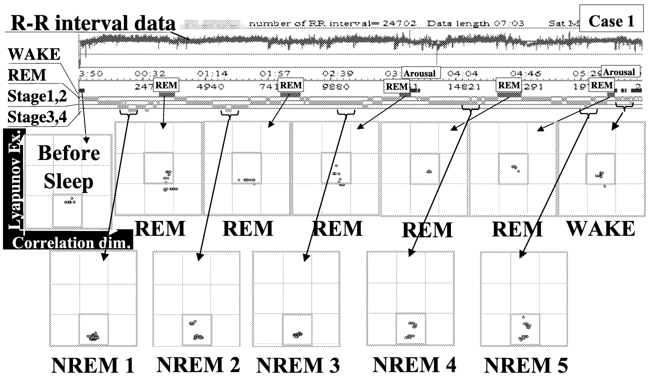

Fig. 6. Change of chaos indices for one night

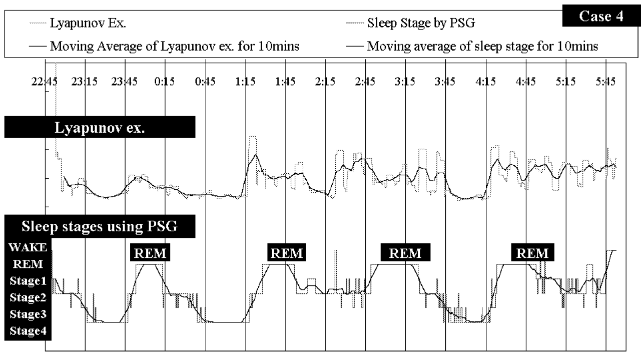

Fig. 7. Comparison of sleep stage with largest Lyapunov exponent in time series

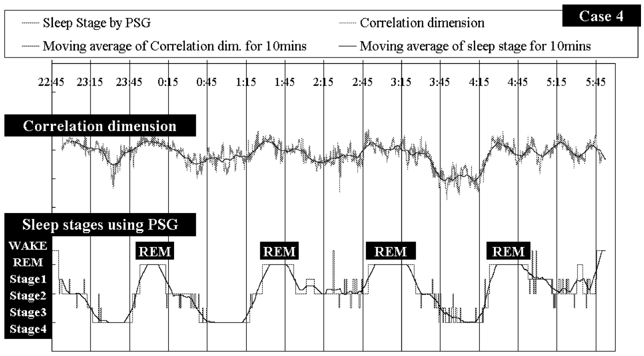

Fig. 8. Comparison of sleep stage with correlation dimension in time series

In this experiment we got data from nine subjects: five twenties-year-old subjects(Cases 1-5), two forties-year old subjects(Case 6 and 7) and two sixties-year old subjects(Case 8 and 9). The precise information is listed on the table I.

Our experiments are composed of two stages. Firstly, the chaos indices at sleep state are plodded on the two-dimensional map that has the largest Lyapunov exponent as a vertical axis and the correlation dimension as a horizontal axis in order to investigate positions and variance of their distributions. Secondly, we consider the relationship between the chaos indices and the sleep states estimated by the PSG. and evaluate correlation between chaos indices and sleep stages by the correlation coefficient.

B. Evaluation on two-dimensional map

The R-R intervals measured at one night about six hours are shown in upper graph of Fig. 6 and the sleep stages estimated by the PSG are shown under the graph. Figure 6 shows an example extracted from the nine subjects' data. This estimated sleep stage is also corrected manually. The distribution of the chaos indices are shown dividedly based on the sleep stages estimated by the PSG. The upper maps show the distribution in REM phase and the lower maps show one in NREM phase.

We found that the location of the distributions in REM and NREM phase apparently differ, and the variances are almost same, comparing the upper maps with the lower maps. The position of REM sleep is the center of the map, and the position of NREM sleep is the lower center of the map, that is under the REM part. The similar results were obtained when nine subjects are investigated.

From these experiment results, The REM sleep and NREM sleep can be distinguished by checking the largest Lyapunov exponent.

C. Correlation of chaos indices and sleep stages

We focus on the correlation of the chaos indices calculated by the proposed algorithm and the sleep stages estimated by the PSG in time series. An example of the experimental results is shown in Figs. 7 and 8.

A gray line and a black line in the upper graph of Fig. 7 are the largest Lyapunov exponent and its moving average for ten minutes, respectively. A gray line like a square wave and a black line in the lower graph of Fig.7 are the sleep stages from the PSG and its moving average, respectively. In the same way, a gray line and a black line in the upper graph of Fig. 8 are inverse of the correlation dimension and its moving average for ten minutes, respectively. The lower graph are the same as the lower graph of Fig.7. This is a normal case, where the sleep starts with NREM and finishes at a shallow sleep after NREM via four periodical REM-NREM cycles. The transitions of the largest Lyapunov exponent, the correlation dimension and the sleep stage from the PSG is not continuous and some local peaks like a noise can be observed. Therefore the moving average is applied to the chaos indices and the sleep stages from the PSG, which does not prevent the algorithm from evaluating the sleep quality: sleep length, sleep depth and a periodical sleep cycle of REM and NREM.

Correlation analysis is applied in order to evaluate the relationship between these indices and sleep stages. The correlation diagram of the largest Lyapunov exponents and the sleep stage is shown in Fig. 9, and the correlation diagram of the correlation dimension and the sleep stage is shown in Fig. 10.

For correlation analysis, we assume that the sleep states including the wake state: "NREM #4, #3, #2, #1, REM and WAKE" could be located linearly with even interval and they are numbered from one to six. The correlation

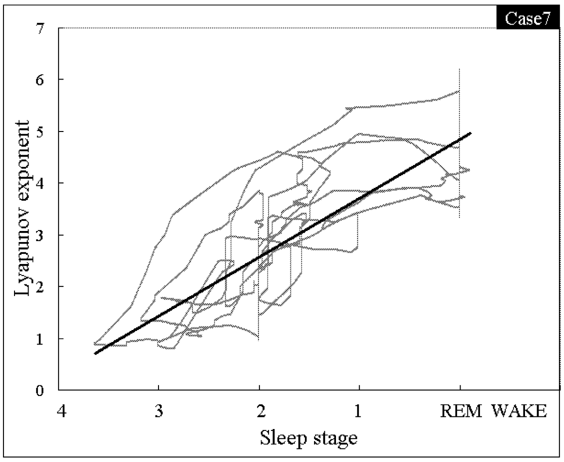

Fig. 9. Correlation map between the largest Lyapunov exponent and sleep stage

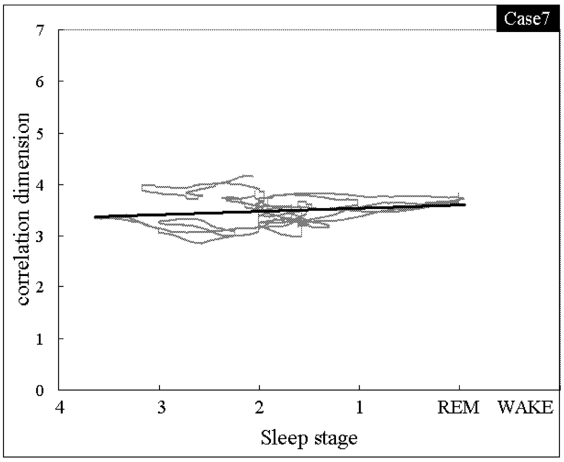

Fig. 10. Correlation map between the correlation dimension and sleep stage

coefficients are calculated for nine persons' data for one night. The number of R-R intervals for one night is about 20,000. The coefficients are shown in Table I

From these results, we found the largest Lyapunov exponent has close relationship with the sleep stages. The P-values are 0.0001 or less in all of these correlation analysis results. Therefore, the sleep stage of human could be inferred from the large Lyapunov exponent.

On the other hand, we cannot find consistent results about correlation dimensions. Some people has a positive relation and others has a negative relation.

V. Conclusion

In this paper we propose the estimation method of the sleep stage using chaos analysis of the HRV, focusing on the close relationship between the Lyapunov exponent and the sleep stage. We found that the relationship between the Lyapunov exponent and the sleep stage experimentally, using the PSG. The proposed method can estimate the sleep stage with simple system component without the large system such as the PSG. Besides it could estimate not only the sleep stage but also sleep quality by checking the depth of sleep, the number of sleep cycle, and its period.

This algorithm can be embedded into a portable system so that we could check our sleep after wake-up in a domestic site and could rearrange our work schedule according to the sleep result. We also pay more attention if we could know that a sound sleep is missing in the quality aspect not in the time aspect.

TABLE I
Correlation coefficient between chaos indices and sleep stage from PSG

Case	Age	Gender	Correlation coefficient		Sampling points
			Lyapunov ex.	Correlation dimensions	
1	22	f	0.675	0.455	24500
2	22	f	0.707	-0.603	22600
3	20	f	0.583	0.620	26000
4	20	f	0.726	0.747	22300
5	21	f	0.740	-0.438	26000
6	21	f	0.597	0.377	20341
7	20	f	0.829	0.193	26319
8	21	f	0.722	0.207	26473
9	21	f	0.460	0.326	30901
10	42	m	0.408	-0.441	19500
11	42	m	0.707	-0.266	22000
12	65	m	0.771	-0.438	21000
13	65	m	0.567	-0.339	22000

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