The association between the subjective quality of sleep and the phase of a 90-minute periodic signal for the wake-up support system

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Abstract: In this paper, we discuss the association between the phase of a 90-minute periodic signal (90-MPS) and the subjective quality of sleep in sleep experiments of multi-subjects using sensors for the wake-up support system. When 90-MPS is extracted from the sensor data using Fast Fourier Transform (FFT) and filtering, the change in period appears as a phase shift of 90-MPS. Therefore, it is necessary to focus on the phase of extracted 90-MPS and analyze the association between that and subjective quality. The sympathetic nervous system index that has data with a clear 90-minute period from the sensor data during sleep was selected using FFT. Furthermore, a 90-MPS is extracted by using the filter, and the association between the phase of 90-MPS at the wake-up time and quality of sleep using the Oguri-Shirakawa-Azumi sleep inventory, middle-aged and aged version (OSA-MA) was analyzed. When quality of sleep was the highest, the distribution was centered on phase III of 90-MPS at four categories excluding refreshing (OSA-MA 4) among the five categories of OSA-MA. It has been confirmed that the highest quality of sleep can be obtained when the waking up phase is III.

Key Words: 90-minute periodic signal, phase, subjective quality of sleep, OSA-MA, Fast Fourier Transform, sleep experiment, multi-subjects, sensor, wake-up support system

1. Introduction
It has been recognized that quality of sleep is an important factor for maintaining health, and expectations for deep sleep or pleasant sleep is increasing nowadays [1–4]. Low quality sleep does not give the body enough rest and interferes with activities during the day and directly affects underlying disease, such as high blood pressure, obesity, and diabetes [5–7]. Research and development of applications are in progress for pleasant wake-up [8–10]. Furthermore, researches on satisfaction of sleep have been
studied. Among them, studies on predicting wake-up time using data measured during sleep are in progress [11].

In the sleep experiment, the subjective quality of the subject has been often evaluated using the Oguri-Shirakawa-Azumi sleep inventory, middle-aged and aged version (OSA-MA) [12–16]. The OSA-MA is a questionnaire designed for self-reported sleep quality at night on the next morning [12]. This questionnaire consists of 16 components, each of which was graded as four levels (1–4 score), and are divided into five categories: sleepiness on rising (OSA-MA 1), initiation and maintenance of sleep (OSA-MA 2), frequent dreaming (OSA-MA 3), refreshing (OSA-MA 4), and sleep length (OSA-MA 5). A higher score indicates better sleep quality. The reliability and reproducibility of OSA-MA have been confirmed by others [12].

Rapid eye movement (REM) sleep is distinguishable by rapid movement of the eyes, accompanied with low muscle tone throughout the body, and the propensity of the sleeper to dream vividly. REM and non-REM sleep alternate within one sleep cycle, which lasts about 90 minutes in adult humans [17–19]. A method of measuring an electroencephalogram (EEG) during sleep is often used to create hypnograms necessary for judging REM sleep [20–22]. However, if a sensor for measuring EEG during sleep is attached, it may be inconvenient for the bed, which may affect the evaluation of quality. An evaluation method that does not affect quality of sleep is needed.

Many researchers have reported an analysis of various factors related to sleep and proposed a sleep monitoring system for high sleep quality [23–29]. The tossing and turning play a role in adjusting humidity and temperature inside a bed [28]. Moreover, those are also reported to be conditions that affect quality of sleep [23, 25]. For instance, it has been commercialized that smart mattresses and mattress pads adjust the temperature automatically [26]. In addition, it is important to track human vital signs of breathing and heart rates during sleep because it can help to assess the general physical health of a person [24]. Internet of things (IoT)-based unobtrusive sleep monitoring pillow that monitors breathing patterns and overall qualification of sleep was proposed [27]. Furthermore, a study was conducted to visualize the relation between changes in the autonomic nervous system (ANS) and quality during sleep [29]. There is a conventional method of showing the relation between the parasympathetic nerve activity (PNA) index high frequency (HF) and the sympathetic nerve activity (SNA) index low frequency (LF)/HF using heart rate data [30–32]. The relation among HF, LF/HF, and quality of sleep has been studied [33–35]. However, there are few studies that predict the wake-up time using evaluation of the association between sleep quality and the ANS. The ANS can be assessed using frequency analysis of heart rate data during sleep [29]. When the sleep satisfaction level is high, it is presumed that the PNA index such as HF representing the relaxation component rises. On the other hand, when the sleep satisfaction level is low, it is presumed that the SNA index such as LF/HF representing the stress component rises.

If the sleep cycle is simply repeated at 90 minutes, the quality of sleep should always be high when awakening occurs in multiples of 90 minutes from bedtime. However, it is difficult to determine the exact wake-up time at the moment of high quality of sleep because the length of sleep cycle varies from approximately 60 min to 150 min even within a night. When 90-minute periodic signal (90-MPS) is extracted from the selected sensor data using Fast Fourier Transform (FFT), filtering, and inverse FFT (iFFT), the change in period appears as a phase shift of 90-MPS. Therefore, it is necessary to focus on the phase of extracted 90-MPS and to analyze the association between that and subjective sleep quality. The association between the phase of 90-MPS and subjective quality of sleep was reported in sleep experiments of one subject. When a subject wakes up at a specific phase of 90-MPS, it has been confirmed that the highest quality of sleep can be obtained [36]. In this paper, we discuss the association between the phase of a 90-MPS and the subjective quality of sleep in sleep experiments of multi-subjects using sensors for the wake-up support system. First, using frequency analysis with FFT, we select a parameter that has data with a clear 90-minute period from the non-contact sensor data during sleep. Then, a 90-MPS is extracted by using the filter, and the association between quality of sleep evaluated using OSA-MA and the phase of a 90-MPS at a wake-up time is analyzed.
2. Experiment and analysis

2.1 Experimental environment

Sleep experiments for 4 nights per person were conducted on healthy 11 males and 8 females in their 20s. Participants in the study did not have an underlying disease and did not have a sleep disorder. Although there are individual differences, their sleeping time was more than 7 hours. On the day of the experiment, they did not take a nap to avoid disturbing their sleep at night, and they did not consume alcohol or caffeine from 18:00. These experiments were conducted in a sleep laboratory equipped with sensors as shown in Fig. 1. The sleep experiment was conducted for 76 nights, but only 61 nights of data were used for analysis because of data loss by sensors failure. The experiments were done after getting approval by the ethics review committee of Yamagata University. Sensors to be used in this experiment were selected by referring to parameters reported to be related to sleep evaluation in previous works [23–29], for example, thermometers, hygrometers, and a barometer sensors to measure changes in temperature and humidity inside and outside the bed [23, 25, 26, 28]; a vibration sensor to measure heart rate and respiration rate [24]; an accelerometer to monitor the motion of head on a pillow [27]. The home server stores data collected from sensors and performs data analysis such as FFT, iFFT, filtering calculation, and evaluation of the association between the phase of 90-MPS and level of OSA-MA.

Thermometers, hygrometers and a barometer sensor installed in/outside the bed were sent to file server via wireless microcomputer units (MCUs). An accelerometer and a vibration sensor which was used to obtain the heart rate and respiration rate are installed under the pillow, and under the mattress, respectively. The following information was recorded in 1 minute intervals during sleep: acceleration, temperature, humidity, atmospheric pressure, and vital signs such as heart rate and respiration. Table I describes the obtained 11 parameters. In addition, after the subject woke-up, a questionnaire was completed regarding his/her subjective quality of sleep using the OSA-MA evaluation [12–16]. Evaluation factors are divided into five categories: OSA-MA 1, OSA-MA 2, OSA-MA 3, OSA-MA 4, and OSA-MA 5. A higher score indicates better sleep quality.

The HF and LF were calculated from the heart rate in this experiment because the correlation be-
Table I. Descriptions of sensor parameters.

| No. | Parameter | Sensor          | Position       |
|-----|-----------|-----------------|----------------|
| 1   | Max_X    | Accelerometer   | Under the pillow |
| 2   | Max_Y    |                 |                |
| 3   | Max_Z    | Wireless MCU 1  | Outside the bed |
| 4   | Temperature 1 |           |                |
| 5   | Humidity 1 |                 |                |
| 6   | Atmosphere |                 |                |
| 7   | Temperature 2 |           |                |
| 8   | Humidity 2 | Wireless MCU 2  | Inside the bed |
| 9   | Heart rate | Vibration sensor | Under the mattress |
| 10  | Respiration rate | |                |
| 11  | State     |                 |                |

tween ANS and quality of sleep was reported in previous studies [29, 36]. HF and LF components from vital sign measurements such as electrocardiogram are often used as relaxation or stress evaluation parameters for the ANS. HF which has a range of 0.15–0.4 Hz is used as a PNA evaluation parameter because the HF power spectral density (PSD) increases when the parasympathetic nervous system is active. On the other hand, LF has a range of 0.04–0.15 Hz. The LF PSD increases when both the SNA and the PNA are active. Therefore LF/HF is used as a SNA evaluation parameter. These parameters are used in the conventional HF-LF/HF scatter plot model, a method for the evaluation of biological stress [29–32].

2.2 Selecting of parameter with 90-MPS
We select a parameter that has data with a clear 90-minute period from the 10 parameters of sensor data and 2 parameters of calculation during sleep. The State parameter which measures the bedtime and wake-up time was excluded from the FFT analysis. Figure 2 shows the frequency analysis of 12 parameters with FFT. The horizontal axis represents the frequency (mHz) and the vertical axis represents the min-max normalization of PSD. In FFT, the PSD refers to the frequency content of parameter data. The red dotted box indicates the 90-MPS content. It can be seen that the higher the PSD in the red dotted box gets, the higher the 90-MPS content becomes. The environmental parameters such as temperature, humidity, and atmosphere showed a low PSD of the 90-MPS. Changes in environmental parameters and those in the 90-MPS of sleep are considered to be less related. In addition, the Accelerometer parameter, which monitors the movement of the head during sleep, also showed a low PSD of the 90-MPS. The respiration rate, heart rate, and LF/HF showed higher PSD of the 90-MPS than the HF. Specifically, the LF/HF contains the most 90-MPS content among the 12 parameters. Therefore, LF/HF is selected as a parameter to examine the association between the subjective quality of sleep and the phase of a 90-MPS.

Table II. Classification into 3 levels for each category.

| Subjective quality of sleep | OSA-MA 1 | OSA-MA 2 | OSA-MA 3 | OSA-MA 4 | OSA-MA 5 |
|-----------------------------|---------|---------|---------|---------|---------|
| Maximum                     | 65.0    | 59.3    | 58.4    | 65.6    | 66.8    |
| Minimum                     | 25.3    | 21.6    | 18.5    | 27.5    | 20.3    |
| Average                     | 49.1    | 41.8    | 52.7    | 47.7    | 45.6    |
| Level 1                     | 4       | 15      | 3       | 12      | 14      |
| Level 2                     | 34      | 29      | 11      | 40      | 29      |
| Level 3                     | 23      | 17      | 47      | 9       | 18      |

2.3 Subjective quality of sleep using OSA-MA
In this sleep experiment, the subjective quality of subjects was evaluated using the OSA-MA [12–16]. The score was calculated by dividing it into five categories using the written questionnaire after wake-up. Figure 3 shows the scores for the five categories calculated per night. In [36], subjective quality of sleep was simply evaluated by 3 levels using a quality questionnaire of sleep after wake-up,
Fig. 2. Frequency analysis of 12 parameters with FFT.

Fig. 3. The scores for the five categories calculated per night.
however, OSA-MA which can professionally evaluate sleep quality by scores was used in this study. The scores obtained on the OSA-MA were equally divided into 3 levels using the minimum and maximum scores for each category to confirm whether they have the same tendency as the result of one subject. Table II shows the maximum, minimum, and average values for each category of scores calculated for 61 nights. Furthermore, it shows the result of counting the number of subjects included in each level score and classifying it into 3 levels, with level 1 indicating the lowest sleep quality and 3 indicating the highest sleep quality. In the case of OSA-MA 4, which is the score of refreshing, the number of level 3 was lower than that of other categories. In this sleep experiment, it was found that the subjects did not overall feel refreshing the next morning.

3. Results and discussion

We discuss and evaluate the association between the phase of an extracted 90-MPS and the subjective quality of sleep in sleep experiments of multi-subjects for the wake-up support system. A 90-MPS is extracted from the LF/HF data selected in Section 2.2. Figure 4 shows the analysis method of this study as follows; 1) Perform FFT using the LF/HF signal from bedtime measured by the State parameter of the vibration sensor to 90(N-1) minutes, where N is the number of 90-MPS from bedtime to wake-up time 2) Extract a 90-MPS using a filter 3) Predict the phase of wake-up time from the extracted signal 4) Evaluate association between the phase and subjective quality of sleep. The phase of the 90-MPS was separated into four stages which are falling (I), minimum (II), rising (III), and maximum (IV) in order to evaluate the association between that and subjective quality of sleep at the wake-up time.

In this sleep experiment, the sleep time is from the bedtime measured by the vibration sensor to the wake-up time. Dividing it into a 90-minute period and using frequency analysis and filtering at a time of 90(N-1), the 90-MPS from 90(N-1) to the wake-up time is estimated. This analysis method will be applied to the wake-up support systems to improve quality of sleep in the future. At that time, the wake-up time in this analysis becomes the desired wake-up time by the user, such as a set alarm time. The wake-up support system wakes the user at the phase of 90-MPS, where quality of sleep is judged to be the highest according to the analysis results of this study. However, the phase of 90-MPS selected as the analysis result may not exist because one period of 90-MPS from 90N to the desired wake-up time by the user is not included. When there is the phase as shown in Fig. 5(a), the

(a) Case 1 : With the phase  
(b) Case 2 : Without the phase

Fig. 5. Change of wake-up time with or without the phase between 90N and desired wake-up time.
user is awakened between 90N and the desired wake-up time. However, if the phase does not exist between 90N and the desired wake-up time as shown in Fig. 5(b), the user should be awakened before reaching 90N. Therefore, FFT and filtering to extract 90-MPS should be performed at 90(N-1) so that the user can wake up before the desired wake-up time.

MATLAB R2014b was used for the calculation. Figure 6 shows the results of anyone night in detail among the results of the 61 nights data analysis. Figure 6(a) and Fig. 6(e) show measured and calculated LF/HF during sleep time to 90(N-1) minutes and total sleep time, respectively. Figure 6(b) shows the FFT result of Fig. 6(a). Figure 6(c) is the result of extracting the PSD of 90-MPS using a bandpass filter. Figure 6(d) is the result of iFFT calculation in Fig. 6(c), and it means the result of extracting 90-MPS from Fig. 6(a). Figure 6(g) shows the total 90-MPS when the result of Fig. 6(d) is extended to the total sleep time. Figure 6(f) zoom in the predicted part in Fig. 6(g). The predicted 90-MPS phase was confirmed using the phase defined in Fig. 4. And that was compared with quality of sleep.

Figure 7 shows the association between the phase of a 90-MPS and subjective quality of sleep using OSA-MA. The vertical axis of the graphs is the frequency of the night with respect to the phase of 90-MPS, horizontal axis, for each subjective quality of sleep. When the quality of sleep was level 3, the distribution was centered on phase III of 90-MPS at four categories excluding refreshing (OSA-MA 4) among the five categories of OSA-MA. This result is consistent with the result of evaluating the association between the phase of 90-MPS and subjective quality of sleep when the subject is only one [36]. Through this experiment in which multi-subjects participated, it has been confirmed that the highest quality of sleep can be obtained when the waking up phase is III. In the case of OSA-MA 4, as mentioned in Chapter 2.3, because the number of subjects classified in the level 3 group of subjective quality of sleep was small, the distribution did not appear remarkably.

4. Conclusion

In this paper, LF/HF that has data with a clear 90-minute period from the sensor data during sleep was selected using FFT. Furthermore, a 90-MPS is extracted by using the filter, and the association between the phase of 90-MPS at wake-up time and quality of sleep using OSA-MA was analyzed. The association between subjective quality of four categories of OSA-MA and phase of a 90-MPS was evaluated. Furthermore, using the result of this study, the applicability of the wake-up support
In the near future, we will develop a wake-up support system and perform verification experiments using the improved analysis method used in this study. Using the analysis method of this study, the wake-up support system should wake the user approximately an hour before the user’s desired wake-up time in the worst case. It is necessary to evaluate the relationship between desired sleep time and quality of sleep. According to the result of this study, we will conduct research on whether to wake up exactly in phase III of 90-MPS or the next best thing. Furthermore, we will improve the analysis of data through statistical analyses that consider between and within-subjects variance.
We will proceed with a study to a rough estimation of the ultradian phase using a non-stationary or real-time data analysis for a high-performance wake-up support system.

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