ESTIMATION OF SLEEP STAGE IN HIGHER ORDER SPECTRUM ANALYSIS OF SLEEPING BREATH SOUNDS

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Although detecting the sleep stage in real time, is often necessary, doing so requires attaching measuring devices to the body, such as the Polysomnography (PSG) assessment tool and it can be difficult to detect. It has also been reported that the sleep stage changes before and after turning over. We measured sleeping respiratory sounds with a microphone in this study and examined the possibility of detecting sleep stage solely from breathing sound information and used bi-spectral analysis for respiratory sound analysis. In this paper, we proposed the sleep stage estimation using breath sounds based on the bi-spectral analysis of acoustical signals. Since bi-spectral analysis is not sensitive to noise, it can be used in the biological signal analysis. The analysis of respiratory sound was only performed for inspiratory sound, because it is known that the genioglossus (GG) muscle, which dilates the airway, is almost inactive during expiration while one is sleeping. The experiments were performed by measuring breathing sounds with a microphone. Sleep evaluation and detection of turning over were performed by the commonly used sensor mat as a reference. In addition, the characteristics of REM and NREM were obtained by the analysis of breath sounds before and after turning over. Therefore, we could estimate the sleep stage by non-invasive acoustical method.

Keywords: breath sounds, sleep stage, bi-spectral analysis, microphone array

1. Introduction

It is said that elderly people, aged 65 years and over, account for 35% of the population, so the population of carers, which increases in proportion to the number of elderly people, are also increasing in Japan. “Food, excretion, sleep” are the elements a care recipient requires to live in health and comfort. Sleep cannot be constantly monitored because sleep is difficult for others to support compared to the others. Thus, problems are increasing in medical institutions during late night sleep. For example, a patient with dementia may wander late at night or fall out of bed when going to the toilet. As a measure against this, it is important to monitor sleep and grasp the care recipient’s sleep state as grasping the sleep stage while sleeping is an important factor in determining the possibility that they wake up. If it is possible to anticipate waking up in advance, we can prepare in advance for the possibility that they might wander at midnight.
Information about the sleep stage is currently obtained using Polysomnography (PSG) equipment in a procedure in which data related to various body activities are acquired, including EEG waveforms, cardiac muscle activity, and breathing. This evaluation method can easily create discomfort due to the necessity that measuring instruments are attached directly to the body. On the other hand, it has become possible to evaluate sleep stage with a pressure sensor mat or smartphone application in recent years. However, the sensor mat changes how the bed molds around the sleeper and smartphone applications may discomfort both the elderly and their carers. Therefore, a new sleep monitoring system that is comfortable is needed. Sleep is known as repeating pattern of shallow sleep and deep sleep, and there are various features in breathing sounds according to the sleep stage. It is known that the breath rhythm and the sound volume are disordered in shallow sleep and stable in deep sleep\(^1\). Many studies have been conducted in medical fields to examine conditions such as sleep apnea syndrome due to these changing the characteristics of the sleeping breath sound. Paying attention to changes in breathing interval and volume enables the estimation of sleep stage and detection of sleep disorders by analyzing respiratory sounds. However, obtaining the moment when the sleep stage changes is difficult because changes in the sound volume and cycles necessitate measuring and analyzing the number of samples in which statistically significant differences appear in the breathing sound. Furthermore, since the microphone is worn near the nasal cavity or a stethoscope is used, there is the problem of avoiding discomfort in the measurement method. Respiratory sound has a lower signal strength than sounds such as utterances, so an analysis method that is unaffected by noise is suitable for obtaining the feature amount.

Ramin reports that it is possible to distinguish between REM and NREM through bi-spectral analysis of PSG inspiratory sound data\(^2\). This was expected, because it is known that the genioglossus (GG) muscle, which is the airway dilator muscle, is almost inactive during expiration while one is asleep\(^2, 5\). However, their research did not reveal the relationship between turning over and breath sound. This study investigates respiratory sound during sleeping and the characteristics of breathing sound during turning by bi-spectral analysis to estimate the sleep stage via non-invasive respiratory sound measurement.

2. Sleep Stage Estimation from Breath Sounds

2.1 Bi-spectral Analysis

Time-frequency spectral analysis is the most common signal analysis used when analyzing biological data. However, spectral analysis is a second-order analysis, and it assumes that the signal of interest is generated by a linear and Gaussian process. In addition, the signal phase information is lost by spectral analysis; if there is any phase coupling between frequencies, it will not be revealed by spectral analysis. However, higher order statistics such as bi-spectral analysis do not assume Gaussian or linearity, and can reveal phase information about a signal.

To classify the breath sounds, which leads to the sleep stage estimation, these sounds would be labeled based on the characteristics appears in the bi-spectrum analysis\(^3, 4\). The bi-spectrum is the third-order frequency-domain measurement, and can be estimated as,

\[
B_{xy}^x(\omega_1, \omega_2) = \sum_{\tau_1=-\infty}^{\infty} \sum_{\tau_2=-\infty}^{\infty} c_3^x(\tau_1, \tau_2) \exp\left(-i(\omega_1\tau_1 + \omega_2\tau_2)\right) \tag{1}
\]

where \(c_3^x\) is the third-order cumulant, and is calculated as,

\[
c_3^x = EX(kX(k + \tau_1)X(k + \tau_2)) \tag{2}
\]

where \(E\) is the statistical expectation of the signal \(X\) shifted by \(\tau_1, \tau_2\) in time. In this study, diagonal mapping (Fig. 1) was performed after extracting the real part of the bi-spectral matrix.
2.2 Sleep Stage Estimation

Assuming that the feature quantity of respiratory sound is similar to NREM, it is close to deep sleep; if it is dissimilar, it is assumed to be close to shallow sleep and the following method was performed. Based on the average for NREM obtained in advance, the transition in the sleep stage was determined by obtaining the time transition of the correlation coefficient with respect to the bi-spectral feature value of the inspiratory sound. At a time interval of five minutes, one noiseless breathing sound, including snoring was randomly selected.

This study investigated the characteristics of inspiratory sound with respect to the time zone during which the sleep stage was detected by the sensor mat and the accompanying sleeping stage occurred. The bi-spectral features of the inspiratory sound for several times were compared before and after turning. We performed a nonparametric test on each average since the bi-spectral feature quantity is not Gaussian.

3. Evaluation

3.1 Measurement Setup

Selected inspiratory sounds (10 samples) from the time zone of REM and NREM were judged by the sensor mat. At the time, selected inspiratory sounds did not include noise such as snoring. After that, the average of the bi-spectral features for each inspiratory sound was calculated and compared. A comparison was done with Cosine-similarity.

The overnight sleep of three subjects was recorded with a microphone (ECM-800, Behringer) and pressure sensor mat (sleep scan, TANITA) in the measurement environment. Three healthy young adult men without any sleeping disorder or subjective symptoms (Age: $23 \pm 1$ year, Height: $1.73 \pm 0.04$ m, Body weight $72 \pm 5$ kg) were conducted. Two microphones were used so that measurement was possible, even if the face was landscape-oriented. This research was approved by the university ethics committee, and informed consent was obtained from the subjects and carried out in all experiments below.

3.2 Results

Figure 2 shows the results of sleep stage estimation according to the subject’s sensor mat and the results of sleep stage estimation calculated. In addition to the fact that not all breath sounds could be detected, one respiratory sound was selected randomly at five minute intervals, so this study could not accurately measure sleep stage estimation. Figure 3 shows the comparison between the bi-spectrum template of the NREM and REM for each subject. The difference between bi-spectrum of NREM and REM is clearly confirmed for each subject. Figure 4 shows the relationship between turning over and breathing sound. By comparing the feature amount, the difference is confirmed between before and after the turning over. Figure 5 shows the box beard chart compares correlation coefficients. Since
significant differences were observed before and after turning over, it was suggested that there is a strong relationship between turning and breathing sound change that accompanies sleep stage change.

**Figure 2: Comparison of inspiration in NREM and REM**

**Figure 3: Feature of bi-spectrum in NREM and REM (S1, S2, S3: subjects)**
3.3 Discussion

Through the experimental result, it was possible to estimate sleep stage by examining the characteristics of the measured respiratory sound even when a microphone is worn directly on the body or without using a stethoscope. In addition, differences in the characteristics of breathing sound were observed before and after the turnover accompanying the sleep stage change. However, since this measurement method cannot detect all breath sounds, it cannot provide commentary on accurate sleep stage estimation. Regarding the time periods during which respiratory sounds cannot be detected, it is considered that the sleep stage is deep there since the breathing sounds are too small. If this assumption is correct, since it is possible to measure breathing sound during shallow sleeping, it is considered effective for detecting the possibility of a subject getting up.

4. Conclusion

This purpose of this paper was to estimate the sleep stage via non-invasive respiratory sound measurement. In this paper, we proposed the sleep stage estimation using breath sounds based on the bi-spectral analysis of acoustical signals. Since bi-spectral analysis is not sensitive to noise, it can be used in the biological signal analysis. The analysis of respiratory sound was only performed for...
inspiratory sound, because it is known that the genioglossus (GG) muscle, which dilates the airway, is almost inactive during expiration while one is sleeping. The experiments were performed by measuring breathing sounds with a microphone. Sleep evaluation and detection of turning over were performed by the commonly used sensor mat as a reference. In addition, the characteristics of REM and NREM were obtained by the analysis of breath sounds before and after turning over. Therefore, we could estimate the sleep stage by non-invasive acoustical method.

REFERENCES


