Development of unrestrained monitoring of human respiration during sleep based on body origin low frequency derivation

Original Article

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ABSTRACT

Sleep-disordered breathing (SDB) is a widespread disease with a variety of manifestations. In addition, insomnia is deeply related to autonomic neuropathy in people with chronic disease. There have been many recent papers related to insomnia and SBD. However, diagnosing SDB using polysomnography (PSG) is very difficult. Breathing in SDB is not only characterised by interruptions in breathing during occlusion, but also by a greater variation in the pattern of normal breaths. Despite the importance of sleep problems, many cases of SDB are not identified by screening. Therefore, we developed an unrestrained monitoring system for human respiration during the sleep state with low frequency oscillation signals originating in the organism. Respiration at the low frequency band of oscillation signals originating in the organism was from 20 Hz to 1000 Hz. To detect oscillation signals originating in the organism, a soundboard was used for direct contact with the organism, and an acceleration sensor was fixed to the end of the soundboard. Using frequency analysis and autocorrelation function analysis by fast Fourier transforms, we discriminated sleep breathing and snoring patterns during sleep based on the low frequency oscillation signals. In addition, we performed a detailed component analysis and trend extraction by multi-resolution analysis using wavelet transform as the method for long-term monitoring. The sleep respiration monitoring system is a novel method that uses the low frequency oscillation signal originating in an organism to discriminate sleep breathing and snoring patterns, which will be useful in diagnosing sleep problems.

KEY WORDS

low frequency oscillation, soundboard, sleep respiration monitoring, sleep breathing, snoring

Introduction

Sleep-disordered breathing (SDB) occurs in sleep respiratory disorders that originate in various underlying diseases such as sleep problems, sleep loss[1], bronchial asthma, respiratory depression, polypnea caused by medical and apnea syndromes thought to originate in problems of the autonomic nerve center of respiration such as heart disorder[2,3], diabetes mellitus, hypertension[4], and respiratory diseases[5]. In addition, SDB occurs in diseases such as Wallenberg syndrome, Horner's syndrome and Rett syndrome with lesions in the brainstem subordinate position and the medulla oblongata[6,7]. It is important to detect sleep respiratory disorders in such groups of diseases not only to identify apneic attacks, but also general breathing disturbance. In particular, the development of a sleep respiration monitoring method for long-term measurement that is non-invasive and does not restrain patients is necessary.

In a report on sleep respiratory disorder, Judith et al. reported results of an investigation concerning sleep respiratory disorder in infants. They suggested

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EEG
filing system

AMP

Data recorder

DAT Recorder

Acceleration type
cardiac microphone

PC

Soundboard (Spruce)
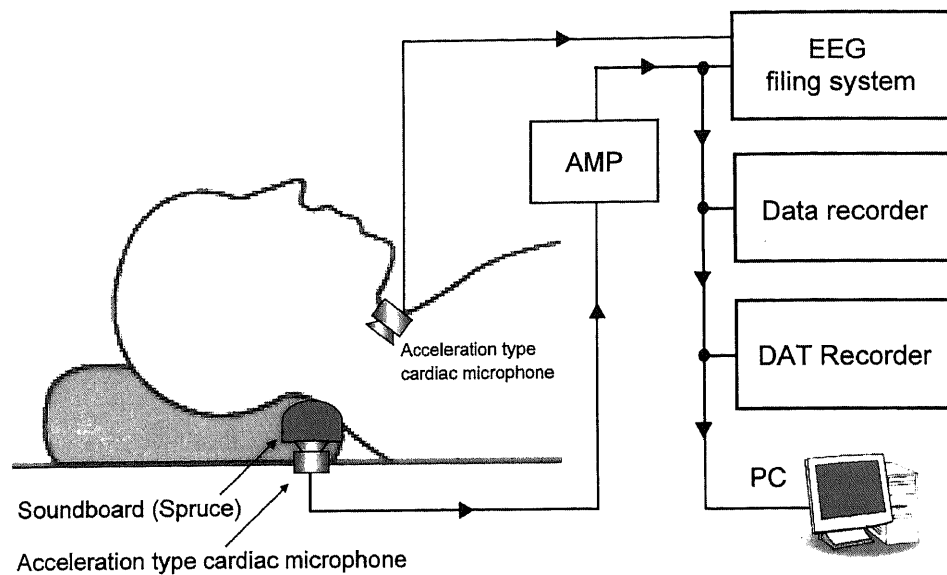
Acceleration type cardiac microphone

Figure 1. Diagram of polysomnography (PSG) using a sleep respiration monitoring system
The sleep respiration monitoring system consisted of a soundboard, an acceleration type cardiac microphone, amplifier and digital data recorder.

that PSG (polysomnography) is not performed in the majority of patients that are diagnosed as having obstructive sleep apnea syndrome with snoring and regarded treatment as being necessary[8]. At present, PSG is considered the most useful method of evaluating respiratory disorders during sleep. Although a transducer of the 70 Hz frequency band using PSG can detect snoring, the measurement of sleep breathing oscillation is difficult. In addition, PSG is difficult to perform because it requires specific equipment and facilities such as a recording device and shield room, etc. PSG requires the use of various sensors such as a breath flow sensor, electroencephalogram (EEG), electromyogram, strain gauges, and pulse oximeters. PSG recording detects a decrease in the partial pressure of oxygen in the blood and respiratory arrest etc., and evaluates the severity of a sleep respiratory disorder rather than making a diagnosis of the disorder.

An oscillating frequency is generated along with organism activities such as heartbeat, pulse waves, and breath, etc. The original oscillating frequency is attenuated and modified by the volume conduction of tissues and osseous conduction. The modified oscillating frequency reaches the body surface, and is observed as a low frequency oscillation of 1000 Hz or

less. Nakashima et al. reported on an automatic, respiratory sound identification method that analyzes the breathing recording from the walls of the chest[9]. However, there are few reports on the analysis of respiratory oscillation during sleep. In this research, we developed a sleep respiration monitoring system that does not require a microphone to be directly attached to the subject. The monitoring system consists of a soundboard, an acceleration type cardiac microphone, amplifier and a digital data recorder. Then, we examined its application in the clinical setting.

Methods

1. Subjects

The low frequency oscillation record and PSG were examined in 4 adults with various underlying diseases and 4 healthy adults.

2. Derivation of low frequency oscillation

Since the transducer is not directly fixed to the patient for detection in the unrestrained state, a soundboard was used (Fig. 1). The soundboard was positioned inside the pillow so that the subject's posterior region of the neck remained in constant contact. The low frequency oscillation signal originating in the organism was obtained by mediating the soundboard. The transducer used an acceleration type cardiac
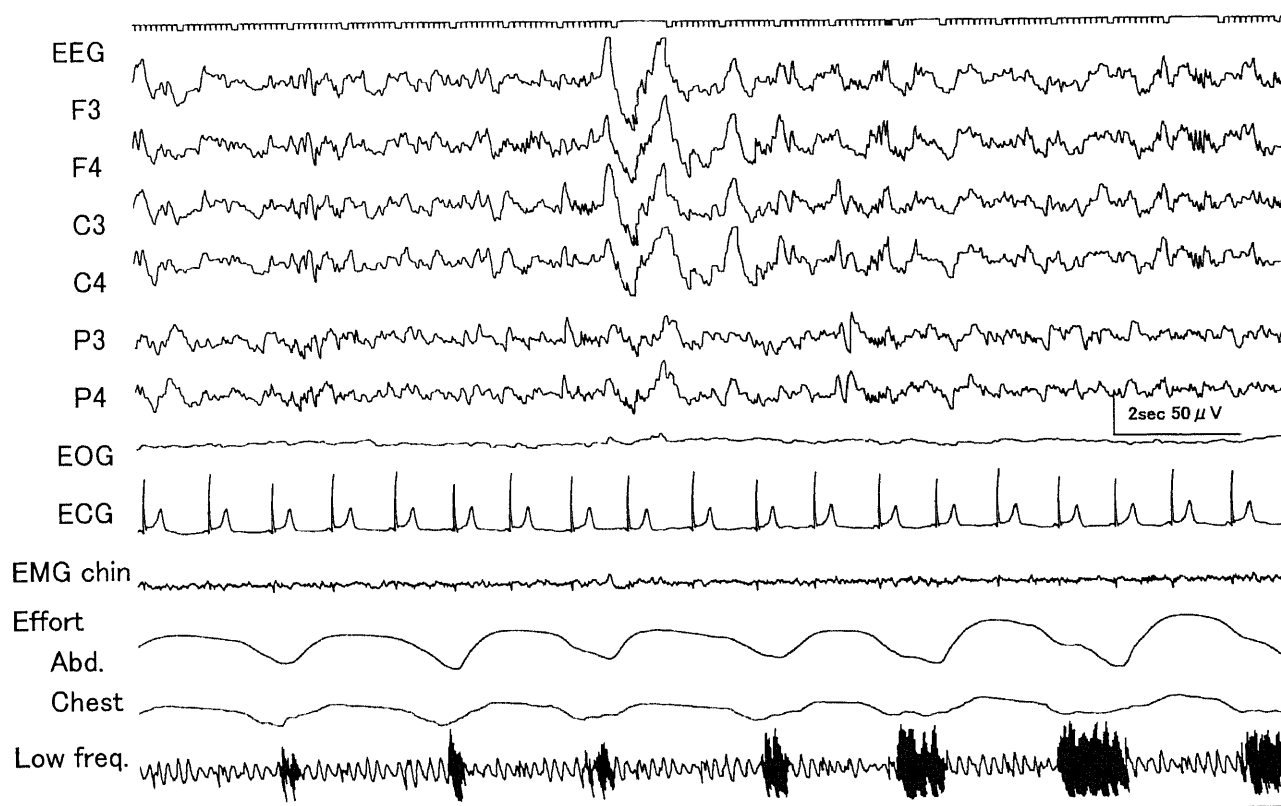
Figure 2. An example of a polysomnography (PSG) recording

microphone MA-240 (Fukuda Denshi K.K. Tokyo). After the obtained signal had been amplified with Op. Amp AD741 (Analog Devices, Inc. USA), the amplified signal was recorded by a Digital Audio tape-recorder TCD-D8 (Sony K.K. Tokyo) and personal computer. Analog to digital conversion was performed at a sampling rate of 44.1 kHz and 16 bit.

3. Comparison of frequency and amplifying characteristics of low frequency oscillation of the soundboard

The frequency and amplifying characteristics of the low frequency oscillation of the soundboard were analyzed by the frequency analysis method by inputting the sinusoidal wave using the diaphragm. A generation vowel was used for the formant analysis. The formant analysis of the generation vowel was conducted according to the method of Nemoto et al[10]. Generation vowels obtained from a moving-coil microphone directly attached to the anterior triangle of a subject's neck were recognised as an original sound of the generation vowel.

4. Recording method of PSG

Subjects attempted to sleep in a face-up position, at rest, and with eyes closed on a bed that had been set up in a shield room. PSG was composed of ophthalmography, a pneumogram, and electromyogram of the mentalis region, electrocardiogram and EEG (frontal pole, frontal, central, occipital region of head) in addition to the low frequency oscillation monitor at the sampling rate of 200 Hz by the EEG filing system EEG-4418 (Nihon Koden K.K. Tokyo) (Fig. 2). Deriving the low frequency oscillation confirmed that the soundboard was located at the middle point of the subject's occipital tuber and seventh cervical vertebra of the spinous process (Fig. 3). For a comparison of the characteristics of low frequency oscillation transducers, the acceleration type cardiac microphone was bonded directly to the anterior triangle, connected to the filing system, and the sound from the microphone and the signal from the transducer were recorded at the same time. The recording duration was about 100 minutes.

5. Analysis method of low frequency

After re-sampling at a 2000 Hz sampling rate, the derived low frequency oscillation underwent frequency

Recording technique of low frequency
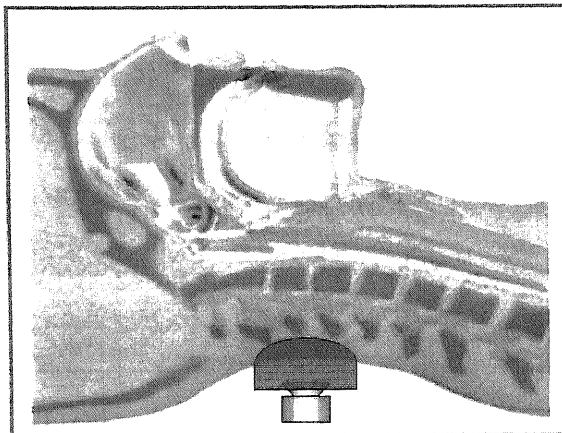
 Cardiac microphone

 Soundboard

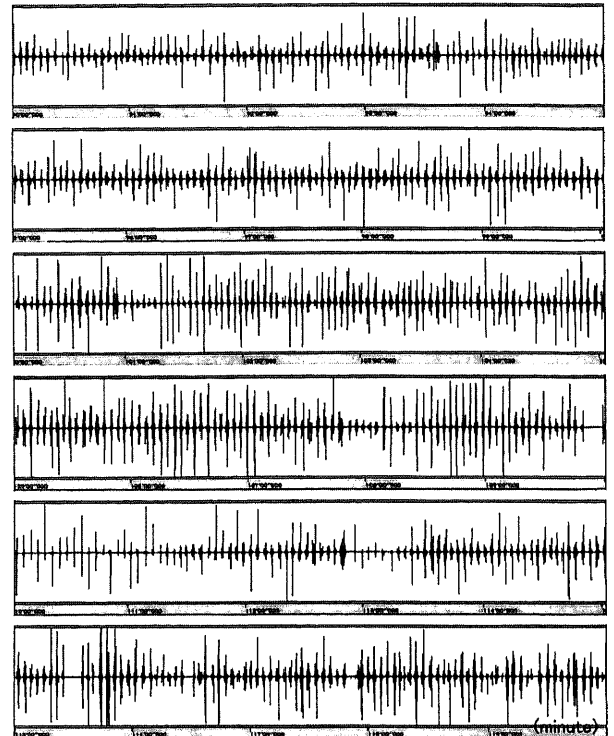## Recorded case of low frequency

Figure 3. The detection methods of sleep breathing oscillation during the sleep state

analysis by fast Fourier transforms with the software Amadeus II v3.2.3 (Martin Hairer, Switzerland) for Macintosh, and the background noise was removed. The component analysis was performed by multi-resolution analysis. Trend extraction using the wavelet transform, the autocorrelation function analysis, and the cross-correlation function analysis using the wavelet toolbox (The MathWorks, Inc., MA) of MATLAB were performed.

Results

1. Record of low frequency oscillation

The recorded low frequency oscillation contained the noise generated from the surrounding analyzer and the structure. Therefore, suitable filtering processing and noise rejection processing were necessary for the recorded low frequency oscillation to remove the noise (Fig. 4). The removal of the background noise of the original signals was possible by removing the sampling noise from the recorded signal in the analyzed part using the background noise sampled beforehand as the sampling noise.

2. Selection of soundboard

For the sleep respiration monitoring record, the selection of the soundboard for the best low frequency oscillation transducer was decided based on the result of the formant analysis and the amplifying characteristic comparison that used generation vowels. Then the soundboard was applied to the anterior triangle of the neck, and the derived generation vowels were compared (Table 1). The absolute power of the signal output by RMS (root mean square) was compared as the index. In the comparison of soundboard materials that use the absolute power of RMS, attenuation and amplification in rubber and aluminum were barely recognised although the attenuation tendency was recognised with cuff, ramin and expanded polystyrene. When spruce (Hokkaido spruce) was used for the soundboard, RMS power showed 1.4 times amplification on average compared with the original sound, and it was superior to any of the other soundboards in resonant characteristics, too. The low frequency oscillation transducer that used the spruce for the soundboard could detect the snoring element
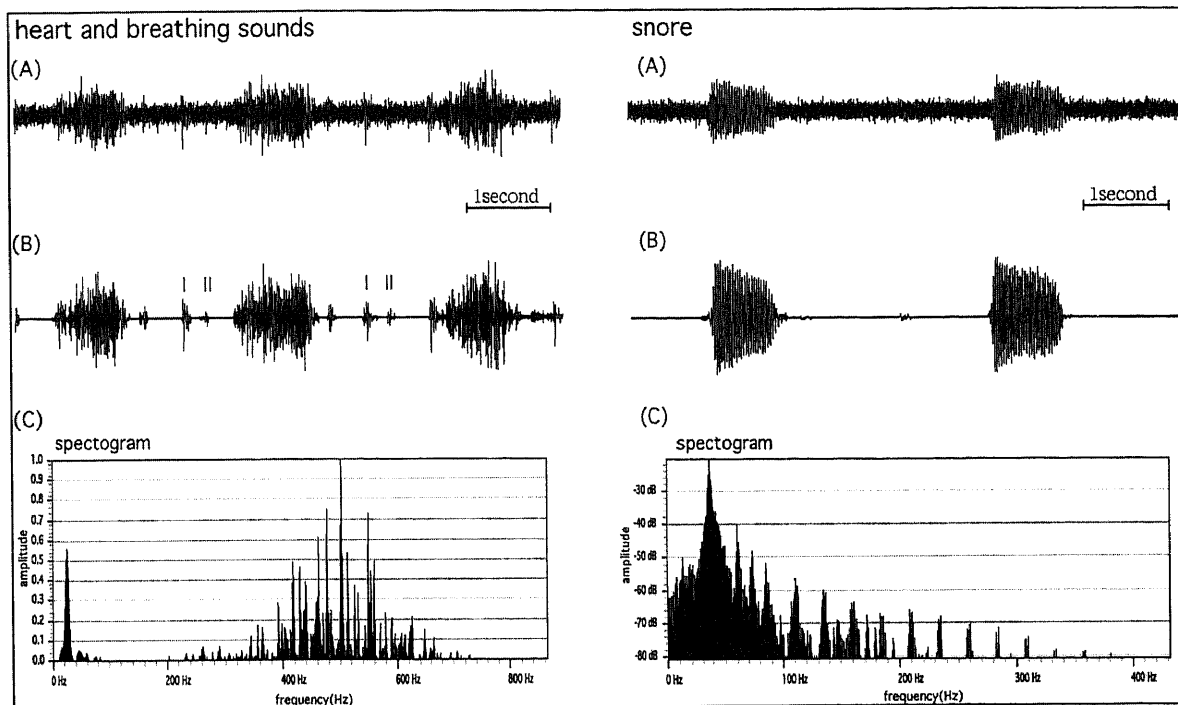
Figure 4. Example of data processing
(A) Raw sampling data (B) Processing data with filtering and noise rejection
(C) Spectrogram
A logarithmic scale was used in the spectrum analysis of snoring because of its high dynamic range. I : first heart sound II: second heart sound

possessing the resonance with the highest sensitivity.

3. Low frequency oscillation in PSG record

In the PSG record using the low frequency oscillation transducer composed of an acceleration type cardiac microphone and the soundboard, heartbeat, sleep breathing, and the snoring element were successfully detected. On the other hand, the pulmonary sound, the tracheal sound, pulse waves of the cervical part, and the position change by breath were barely recognised. The heartbeat was captured using the low frequency oscillation transducer as a low frequency oscillation accompanying the resonant characteristic and had the fundamental frequency from 20 Hz to 30 Hz (Fig. 4). The sleep breathing oscillation had the frequency component from 200 to 700 Hz, and was observed as a low frequency oscillation of the continuity, the peak of which was about 500 Hz. The snoring oscillation had the fundamental frequency element from about 30 Hz to 40 Hz, and was observed as a low frequency oscillation accompanying the resonance up to about 300 Hz. Bruxism, head position change, and saliva swallowing were taken as other low frequency oscillation elements.

4. Comparison of sleep stages of electroencephalogram and low frequency oscillation

Generation of sleep breathing was recognised by its synchronization with the sleep spindle and the vertex sharp transient corresponding to Sleep Stage 2 on the EEG, although it was barely detected in the light sleep period of Sleep Stage 1. Snoring occurred most often in the light sleep period of Sleep Stage 2 and in the deep sleep period of Sleep Stage 3. The development of sleep breathing and snoring by the transition of sleep stages could be clarified by frequency analysis of the low frequency oscillation at each sleep depth (Fig. 5). The generation of snoring was clearly identified by its synchronization with the sleep breathing that increased gradually along with the sleep depth, and by occurrence at the stage where sleep was deepest.

5. Autocorrelation function analysis of sleep breathing and snoring (Fig. 6)

From the autocorrelation function analysis, the snoring showed a typical damping oscillation. Snoring

Table 1. Comparison of soundboard materials

vowel	RMS power ratio of original voice	materials of soundboard					
		cuff	spruce	ramin	e.p.	rubber	aluminum
/a/	1.0	0.7	1.7	0.3	0.9	0.5	0.6
/i/	1.0	0.9	1.4	0.7	0.7	1.0	1.0
/u/	1.0	0.9	1.4	0.5	0.7	1.0	1.0
/e/	1.0	0.9	1.2	0.7	0.8	1.0	0.9
/o/	1.0	0.8	1.4	0.4	0.7	0.8	1.0
average	1.0	0.9†	1.4*	0.5 *	0.7 *	0.9	0.9

† : $P<0.01$　* : $P<0.005$, compared to the average value of RMS power by the Mann-Whitney U-test.
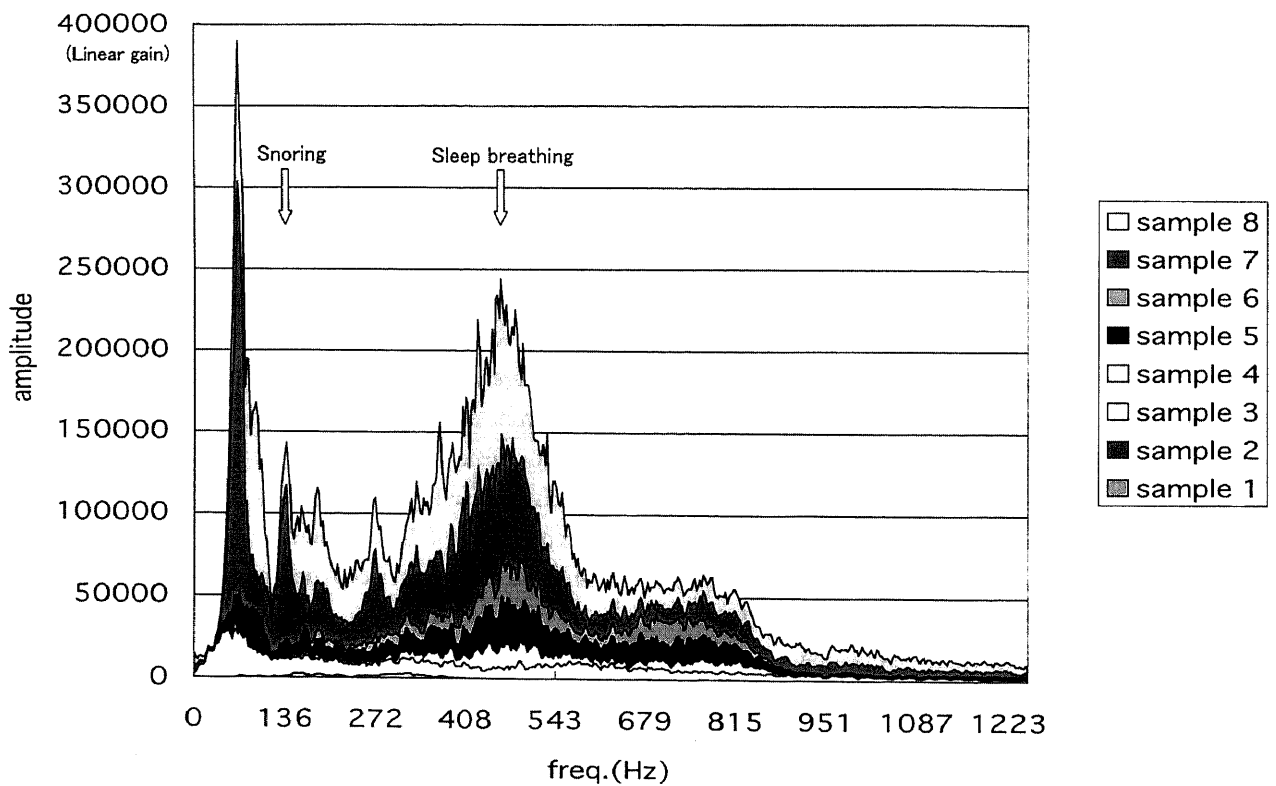

Figure 5. Frequency analysis of PSG
Sample 1: body artifact　Sample 2: wakefulness　Sample 3: body artifact
Sample 4: breathing during sleep　Sample 5: exhaling noise
Sample 6: breathing during sleep　Sample 7: snore　Sample 8: snore

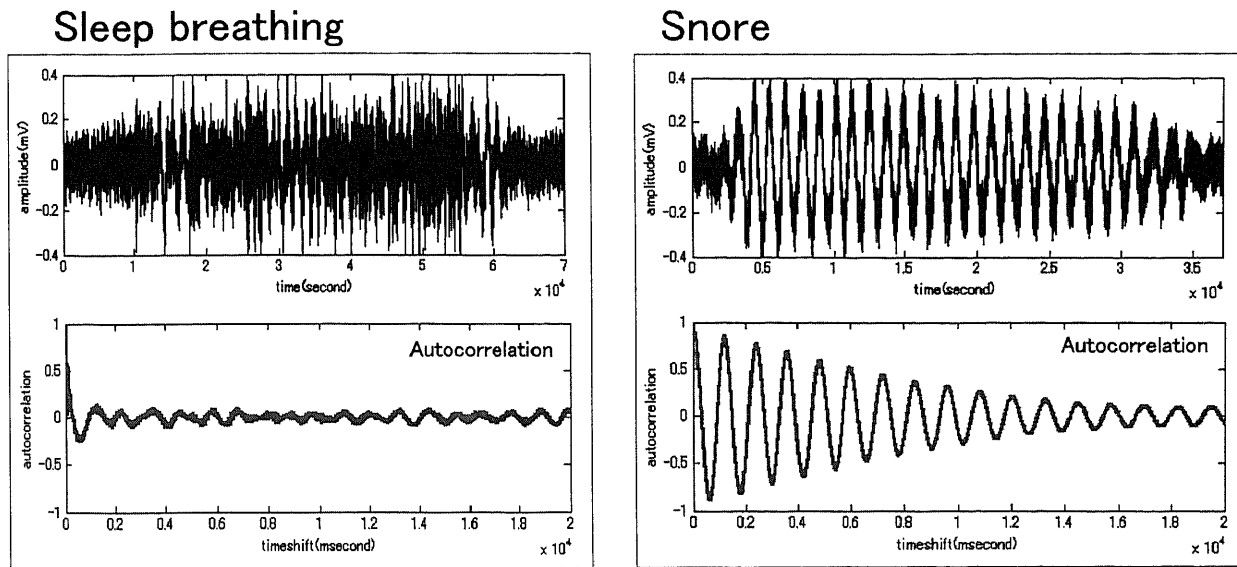## Sleep breathing

Snore

Figure 6. Autocorrelation function analysis of low frequency oscillation

was a low frequency oscillation element with a potential cycle process. On the other hand, in sleep breathing, the autocorrelation function was almost null apart from Delay Time 0, and it was a continuity signal without periodicity. The autocorrelation function was found to be a useful analysis method to reveal the situation of snoring occurrence.

6. Multi-resolution analysis by wavelet transform and cross-correlation function analysis

Wavelet transform that used a discrete Meyer's mother wavelet was performed using the low frequency oscillation signal recorded by the PSG, and multi-resolution analysis was performed (Fig. 7). The heartbeat element, the sleep breathing element, and the snoring element were extracted successfully according to the reconstruction from the wavelet decomposition at multiple levels. In the cross-correlation function analysis of the extracted element and the original signal, the cross-correlation coefficient was 0.49 and a weak correlation was shown in Detail 6 at the sleep breathing extraction of the component level (Fig. 8). On the other hand, the cross-correlation coefficient in Detail 9 and Detail 10 at the snoring extraction of the component level was 0.26 and 0.78, respectively. By reconstructing Detail 9 and the Detail 10 level in the wavelet decomposition structure, the snoring element alone could be extracted in almost complete shape.

Discussion

In recent years, transducers for the respiratory oscillation used for portable sleep respiration monitoring devices have been designed to detect snoring at a sampling frequency of about 200 Hz, but they cannot detect sleep breathing oscillation in the resting state. Tobita developed a sleep breathing oscillation, portable, monitoring device for home use in which a micro-microphone is attached to the trachea upper neck skin, and records the sleep breathing oscillation[11]. This device is used to detect an apneic attack in sleep apnea syndrome, and it is used for the diagnostic testing of patients who have comparatively severe symptoms. In this study, we used a transducer for the sleep respiration monitoring that could obtain high sensitivity in the low frequency zone region of 20 Hz-1000 Hz. Moreover, the generated low frequency oscillation could be detected from the body surface through the soundboard without attaching the transducer directly to the body surface. The transducer in this study enables detection of a mild-type sleep respiratory disorder that underlies ischemic heart diseases and cerebrovascular diseases. Moreover, it is useful for patients that find it difficult to tolerate the restraint over long periods.

Peter et al. investigated the respiratory state in obstructive sleep apnea syndrome. They showed that the difference in the interval between breaths (Breath-to-
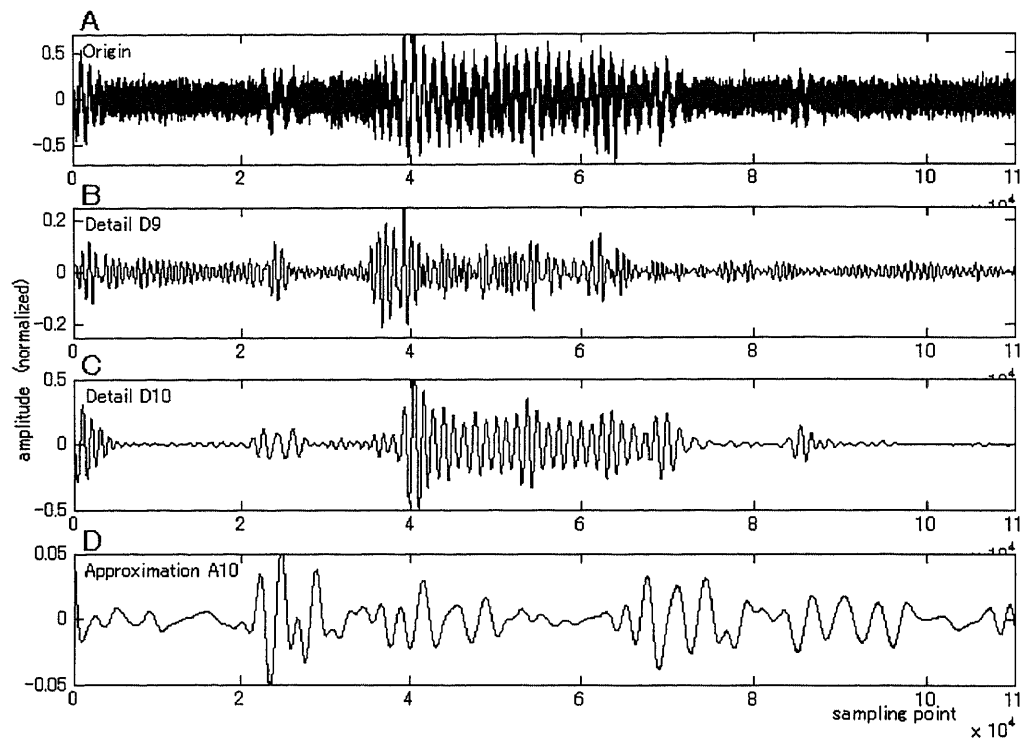
Figure 7. Multi-resolution analysis using wavelet transform
A. Reconstruction of original signal from wavelet decomposition structure
B. Reconstruction of detail in Level 9 (sleep breathing extraction of component)
C. Reconstruction of detail in Level 10 (snoring extraction of component)
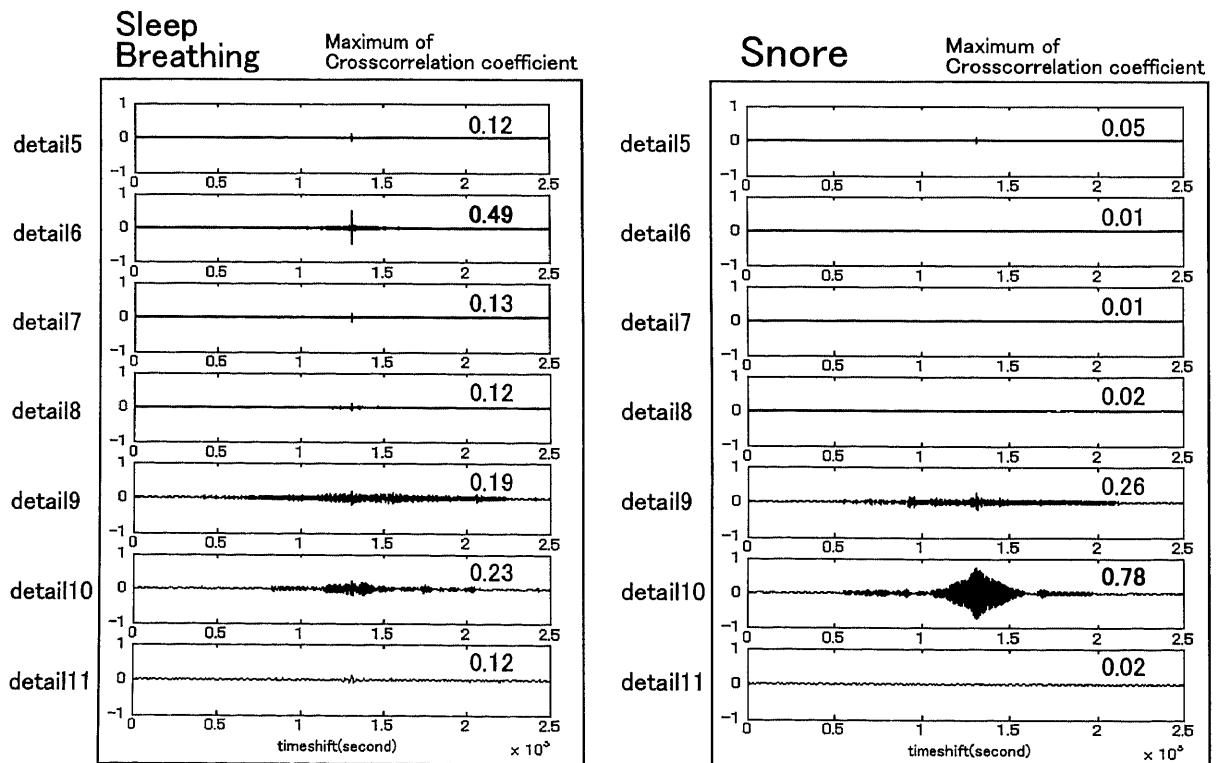D. Reconstruction of approximation in level 10 (heartbeat extraction of component)

Figure 8. Cross-correlation function analysis of multiple-level decomposition

breath variability) is larger than in a healthy person, and indicated the diagnostic usefulness of the interval breaths[12]. As a new index, RDI (Respiratory disturbance index) is advocated for sleep respiration monitoring of the portable type[13]. The present monitoring system can detect the breath disorder (breathing disturbance) in a non-apneic attack state by recording and analyzing sleep breathing generated at the comparatively early stage of sleeping. In addition, it is advantageous for patients, especially with mild symptoms and with an extremely low frequency of apneic attack.

Measuring respiration at rest and in the non-apneic attack state during sleep is much simpler than using PSG, which counts the frequency of the decrease in the partial pressure of blood oxygen and the detection of an apneic attack all night for evaluation. Detection of breathing disturbance by analyzing respiration in sleep can provide useful data even if the recording duration is about 2 h in the hypnagogic state.

In the low frequency oscillation transducer used in this study, sleep breathing oscillation generated according to the transition of sleep stages was successfully detected and analyzed although respiratory oscillation during sleep could not be detected. Sleep breathing could be clearly discriminated from snoring using frequency analysis. Useful information was obtained by pursuing each movement of each element by improving the analytical method.

In the examination concerning the character of various soundboards, spruce greatly amplified the low frequency oscillation, indicating that the resonance characteristics of the pine excel in the low frequency oscillation region. For this reason, pine was used as the soundboard in the sleep respiratory system.

Autocorrelation function analysis revealed that the signal properties of the sleep breathing oscillation and the snoring oscillation were quite different. In both, commonality in the period process is not recognised completely, suggesting that the origin of both elements was different. Although the sleep breathing and the snoring were superimposed in many cases, discrimination and the extraction of each element were comparatively easy using an advanced multi-resolution analysis of the wavelet transform.

The mechanism of the generation of sleep breathing

is unclear. However, the instability of respiratory control during sleep may be involved in the generation of sleep breathing[14]. Increased upper airway resistance and decreases in the residual volume of lungs occurs due to distortion of the upper respiratory tract in the supine position. Moreover, increased upper airway resistance occurs due to tension of the respiratory muscles of the neck, and extension of the blood circulation time occurs due to hypovolemia and suppression of the ventilatory response to carbon dioxide in the hypnagogic state[15]. These phenomena indicate that if many respiratory muscles do not work in the sleep state compared to the awake state, the body is unable to maintain the necessary amount of ventilation. Analysis of sleep breathing may provide a useful index for changing breathing while sleeping.

Maurice et al. reported that bruxism accompanied by tooth clenching or grinding while sleeping is a high risk factor for sleep respiratory disorder[16]. In this research, the low frequency oscillation that originates in the movement of the mouth and salivates was measured, and analysis of the various derived low frequency oscillations overall was possible by applying suitable filtering and noise removal.

For accurate diagnosis of sleep respiratory disorder, it is necessary to evaluate both the sleep state and body functions during sleep. However, the simple type diagnostic devices for sleep respiratory disorder that are available commercially only detect respiratory abnormality and do not detect sleep problems due to breathing problems during sleep. Therefore, an accurate evaluation of sleep respiratory disorder including various symptoms is difficult. As further research, by advancing the research that uses this sleep monitoring respiration system, judging the sleep depth by analyzing sleep breathing and detecting respiratory abnormality, we aim to develop a sleep respiratory monitoring system where the therapeutic effect can be determined and a possible follow up monitor for home use.

Conclusions

We developed a sleep respiration monitoring system that does not require a microphone to be directly attached to the subject. The monitoring system consists of a soundboard, an acceleration type cardiac

microphone, amplifier and a digital data recorder. Frequency analysis and multi-resolution analysis using the low frequency oscillation transducer revealed the pathognostic characteristics of heartbeat, sleep breathing oscillation, and snoring oscillation, and the discrimination of each element was easy. This sleep respiration monitoring system can be applied in the clinical setting without the need to restrain the subject.

Acknowledgment

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生体由来低周波振動導出による無拘束型睡眠呼吸モニターの開発

大江　宏康

要　　旨

　本研究は、生体由来低周波振動に注目した無拘束型睡眠呼吸モニターの開発を目的とした。音響板、加速度型心音マイクロフォン、増幅部およびディジタルテープレコーダの構成により作成した低周波振動トランスデューサーは、20Hz〜1000Hzの生体低周波振動を高感度に導出することができ、長時間の睡眠呼吸モニターが可能であった。得られた低周波振動は、高速フーリエ変換による周波数解析および自己相関分析により、心音や睡眠中に発生する寝息、いびきを鑑別することができた。さらに、ウェーブレット変換を利用した多重解像度解析によって、詳細な成分解析やトレンド抽出ができ、長時間モニターにおける解析方法として有用であることを認めた。生体由来低周波振動を用いた睡眠呼吸モニター法は、睡眠深度の変化にともなう寝息やいびきの発生過程を追跡することも可能であり、従来の睡眠呼吸モニター法にない特性を有していることが示唆された。