Respiration monitoring of sleep apnea syndrome
using a pressure sensor bed

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Monitoring of respiration under unrestrained and noninvasive conditions is indispensable to determine natural respiration during sleep. A pressure sensor bed capable of detecting a decrease in electric resistance with compression was prepared (Denso Corp.) and used to observe respiration during sleep.

Subjects included four healthy adult volunteers (two males and two females, 25 to 31 years old) and 13 subjects with chief complaints of sleep apnea or snoring at night (8 males and 5 females, 25 to 62 years old and an average BMI 26.3). Apnea, blood oxygen saturation and movement of thoracoabdominal wall with respiration were monitored with the Microsleep. Respiration waveform during nightlong sleep was monitored by using the pressure sensor bed. Respiration during sleep was investigated comparatively by using the bed and the Microsleep.

Healthy subjects with normal respiration showed a regular respiratory waveform with the Microsleep and normal oxygen saturation and regular respiration with constant amplitude in respiration waveform with the pressure sensor. Subjects who complained of snoring recorded constant amplitude and regular respiratory waveform with the Microsleep and the pressure sensor regardless of the sound of snoring as well as subjects with normal respiration. Subjects diagnosed as having an obstructive apnea recorded similar periodic respiration waveforms (Cheyne-Stokes-like breathing waveform) with that of apnea both with the Microsleep and the pressure sensor. These waveforms were observed in all eight cases diagnosed with obstructive apnea.

A correlation was obtained between Cheyne-Stokes-like respiration waveforms, apnea index (AI) and oxygen desaturation 4% index (ODI4) in the measured results with the Microsleep in an hour. Sleep apnea could be detected by using a thoracoabdominal spirogram during sleep.

Key words: sleep apnea, pressure sensor bed, Cheyne-Stokes-like waveform

Introduction

Conventional determination of respiration has been performed with a sensor or a band attached to the body to monitor respiration. However, unrestrained and non-invasive determination of respiration is the most required condition to ascertain natural respiration during sleep. Takasaki et al. and Ushikubo et al. reported determination of respiration with image analysis. A bed equipped with pressure sensors that show the decrease in electric resistance with compression was prepared and named “pressure sensor bed,” and used to record respiration condition during sleep. The pressure sensor bed was further clinically applied to find and compare its usefulness with that of the Microsleep.

Subjects and Method

The present study subjects included four healthy adult volunteers (two males and two females, 25 to 31 years old) and 13 subjects whose chief complaint was sleep apnea or snoring (eight males and five females, 25 to 62 years old and average BMI 26.3).
The determination was carried out using the pressure sensor bed prepared by Nishida et al. (Denso Corp.) and monitored respiratory conditions during sleep at night. Simultaneously, frequencies of sleep apnea, blood oxygen saturation, movement of breast and abdomen with respiration, changes of posture and snoring were monitored with the Microsleep model 97 (Cynectics Co., Ltd.) all night long to investigate the usefulness of the pressure sensor bed in clinical application.

The principle and practice for determination of respiration with the pressure sensor bed used in this study will be explained.

1) Principles of the pressure sensor bed

The pressure sensor bed is composed of a pressure distribution determination sheet, a pressure sensor controller and a host computer (Gateway 2000P5-100J). The pressure sensor controller can be controlled with the host computer, and changes of pressure detected by one sensor in 210 sensor sheets can be output through an amplifier. The pressure distribution determination sheet uses a polymer film device as a sensor, which shows the decrease in electric resistance with compression. A total of 210 sheets of the pressure sensors are arranged about eight centimeters apart on the bed (Fig.1). Changes of pressure with breathing on the bed can be determined with the sheets.

2) Practice for determination of respiration.

Movement of the diaphragm with respiratory motion during sleep shows caudal direction in inspiration and cranial direction in expiration, with amplitude of about five centimeters. Abdominal viscera moves with the movement of the diaphragm, and the changes in pressure distribution at the contact points of the body with the pressure sensors vary. Thus, respiration can be detected as changes of pressure distribution (Fig.2).

In practical determination, that sensor that detects respiration most frequently is selected as the reference sensor. Subtraction of the sensor output in reverse phase from the sum of the output of the sensor in the same phase and that of the reference sensor gives the value representing the changes in respiration.

The reference sensor is a sensor whose output has the largest integrated power spectrum at 0.25–0.33 Hz. The reference respiration rate is 15–20 times/minute and is capable of sensitively detecting the smallest changes in pressure accompanied with respiration movement.

The detected signals of the pressure sensors shown
in the Fig. 3 are classified into two groups: circle (○) and dot (●), and the reference sensor signal is indicated by a square (□). The circle (○) and the dot (●) indicate, respectively, the phase difference of about 0 [rad] (−0.25π < τ < 0.25π [rad]) and 0.75π < τ < 1.25π [rad] from that of the reference sensor square (□).

These sensors show that 1) respiration can be detected over a wide area of the body, 2) the changes of pressure distribution accompanied with respiratory movement have phase differences between each other, and 3) load shift occurs between circle (○) and dot (●) areas with respiratory movement.

The combined sum of the two groups represent respiratory movement and the difference of the sums of the two groups provides a favorable sum considering the phase difference in the changes in pressure. Thus, the influences of noise and setoff due to phase difference can be eliminated.

The spiromgrams calculated from the pressure distribution based on the above-mentioned principle represent, respectively, from the top (a) the spirogram obtained by simply counting the data, (b) the spirogram obtained by data sum of one group of the aforementioned two groups, and (c) the spirogram obtained by the present method (Fig. 4). Fig. 4 shows that the present method can detect respiration more accurately than the simple counting method. Furthermore, spiromgrams according to posture are shown in the order of supine, lateral and prone positions from the top. This data indicates that respiration can be detected in any one posture (Fig. 5 a, b, c). In the present study, spiromgrams were determined according to the above-mentioned principles.

In practice, sensors are distinguished by the degree of pressure and indicated by the corresponding color marks showing higher pressure in red on the monitor.

Supine and prone positions have different maxi-

![Image](https://example.com/image.png)

**Fig. 4** Principles of spirogram
a: Based on unit addition.
b: Based on addition within one group.
c: Based on the present method.
Fig. 6-1 Difference in center of gravity in dorsal and prone positions.

Fig. 5 Comparison of spirometry with posture
a Upper column: dorsal position
b Middle column: lateral position
c Lower column: prone position

Results

Respiratory waveforms of four healthy adult volunteers and 13 subjects with chief complaints of sleep apnea or snoring at night were recorded with the Microsleep and pressure sensors in the same time phase. In this study, 17 subjects, who simultaneously gave both data, were included in the investigation (Table 1).
Subjects with normal respiration showed regular respiratory waveforms on the Microsleep with normal blood oxygen saturation, as well as constant amplitude in respiratory wave and regular respiration in the pressure sensors (Fig. 7a, b). Subjects who complained of snoring recorded constant amplitudes and regular respiratory waveforms in the Microsleep and pressure sensors regardless of the sound of snoring.

Subjects diagnosed as having obstructive apnea showed periodic respiratory waveforms consistent with those of apnea on both the Microsleep and
Air flow at nose and mouth

Movement at chest and abdomen

Blood oxygen saturation

Breath curve by pressure sensor bed

**Fig. 8** Comparison of respiration waveforms with a Microsleep (a) and that of the pressure sensor bed (b) in subject with obstructive apnea (35-year-old male, BMI 27.3, AI 56.1).

**Fig. 9** Definition of Cheyne-Stokes-like waveform: Six times or more respiration or forced respiration with a variation range in amplitude of 30% or over compared to average amplitude.

- a: Six times or more respiration or forced respiration
- b: Variation range of amplitude
- c: Average amplitude

The periodic respiration in the present study was named Cheyne-Stokes-like waveform with definitions of respiration or forced respiration for six times or over with changes in width of amplitude of 30% or over in comparison to that of average amplitude (Fig. 9 a, b, c). The Cheyne-Stokes-like waveform was established as the reference waveform and used for the investigation into whether thoracoabdominal respiration waveform in the pressure sensors can be used for determination of sleep apnea frequency. The Cheyne-Stokes-like waveform frequency on the pressure sensor bed and apnea with the Microsleep, and number of OD4 (oxygen desaturation 4%: amount of respiration that decreases blood oxygen saturation at a rate of 4%) were recorded at 10 minutes intervals for the 58-year-old female with BMI (Body Mass Index) 25.9 and AI (Apnea Index) 32.2. The obtained data showed similar patterns (Fig. 10). Other cases diagnosed as obstructive apnea showed similar results.

Observation with the Microsleep was performed on 35 cases (including 17 cases of the present study), and comparison of AI and number of Cheyne-Stokes-like waveforms per hour [hereinafter referred to as CSI (Cheyne-Stokes index)] showed a correlation coefficient of 0.74 (Fig. 11). Furthermore,
Respiration monitoring of sleep apnea syndrome

Fig. 10 Progress in apnea and OD4 with the Microsleep and Cheyne-Stokes-like respiration rate with a pressure sensor in a subject with obstructive apnea (BMI 25.9, AI 32.2).

Fig. 11 Correlation coefficient of 0.74 apnea index (AI) with the Microsleep and Cheyne-Stokes index.

CSI and OD4 showed a correlation coefficient of 0.92, thus indicating a correlation (Fig. 12).

The number of Cheyne-Stokes-like waveforms on the pressure sensor bed in one hour [PCSI (Pressure CSI)] for 17 out of 35 cases and AI observed with the Microsleep showed a correlation coefficient of 0.67 (Fig. 13). In addition, PCSI and OD4 observed with the Microsleep showed a correlation coefficient of 0.71 (Fig. 14).

These results indicate that sleep apnea can be detected from thoracoabdominal respiratory waveforms on the pressure sensor bed.

Fig. 12 Correlation coefficient of 0.92 in OD4 with the Microsleep and Cheyne-Stokes index.

Discussions

Sleep apnea syndrome (SAS) which causes apnea during sleep is defined as repeated suspension of ventilation for 10 seconds or longer at 30 times or over during seven hours of sleep, or five or more apnea index (AI) per unit period. The diagnosis of sleep apnea has been conventionally carried out by observation of frequency of apnea, in which thoracoabdominal movement with respiration and blood oxygen saturation during sleep is observed by attaching various sensors or monitors on the
body. However, observation of respiration under unrestrained and non-invasive conditions is indispensable for the observation of natural conditions. Lewin (1969) prepared an apnea-alarm mattress capable of indirect detection of apnea of premature infants and reported a method for non-invasive determination of respiration through observation of respiratory movement in bed. In addition, Brake et al. (1970) and Caro et al. (1971) reported observation of respiration of suckling infants in beds. Furthermore, Alihanka et al. (1981) reported observation of pulse rate, respiration and body movement using a static charge-sensitive bed (SCSB) based on the determination principle of electric recording of body movement in bed. Salmi et al., Polo et al., and Kirjavainen et al. determined sleep apnea using the principle. After which, Lojander et al. (1998) reported the relationship between body movement using SCSB, and ODI4 and SaO2. Thereafter, a system for determination of movement of the body surface, respiration and pulse rate using a vinyl covered lead wire sewed on a sheet was developed. In addition, a system for determination of respiration rate, pulse rate, body movement during sleep using pressure sensors placed on the bed or under the bed sheet have been developed. Takasaki et al. attempted to record video footage to determine movements of chest and abdomen using a vision sensor followed by image analysis with a computer to elucidate respiratory movement during sleep and reported its clinical applicability.

As explained above, various methods have been reported regarding the determination of respiration by attaching monitors. In the present study, a pressure sensor bed using pressure sensors that show the decrease in electric resistance with compression was used to carry out unrestrained and non-invasive observation of respiration. As reported by Nishida et al., the sensitivity of the pressure sensors used in the present study can detect the changes in pressure distribution with the movement of diaphragm and viscera due to respiration. While no determination of respiration can be performed when the subject turned over in one big motion.

Comparison of determined data of sleep apnea with the pressure sensors and the Microsleep showed similar results for snoring for those of normal subjects and showed that the pressure sensors could detect respiration regardless of sound. Observation
of respiration waveforms during apnea for subjects with sleep apnea showed periodic respiration waveforms, and Cheyne-Stokes-like respiration waveforms were observed in both determination methods.

Cheyne-Stokes respiration appears as a pathological pattern of respiration disturbance during sleep accompanied with a gradual increase and decrease of tidal volume and respiratory rate followed by complete respiratory arrest, that is, periodic repetition of central apnea. However, periodic respiration sometimes occurs in cases of unstable sleep in the hypnagogic phase of healthy adults, or exhibits an increase in the amplitude of spirogram and tidal volume with awakening and a decrease with sleep in elderly subjects.

In obstructive apnea, obstruction in the upper airway increases the pressure at the site of obstruction and starts ventilation when the pressure exceeds a threshold value. Blood oxygen saturation decreases until breathing resumes and forced respiration increases. The decrease of blood oxygen saturation is recorded as ODI4 together with the periodic respiration waveform. Practically, the waveform determined using the Microsleep and the pressure sensors is called Cheyne-Stokes-like waveform. In regards to obstructive apnea, breathing movement continues in the thoracoabdominal region even under ventilation arrest, thus determination of respiratory movement with pressure sensors can be performed.

The present respiration determination using the pressure sensor bed revealed a correlation between Cheyne-Stokes-like waveform, AI and ODI4. As discussed above, respiration determination using the Cheyne-Stokes-like waveform as an indicator provided unrestrained and non-invasive determination of sleep apnea without attaching any sensors to the body.

Dowdell et al. reported a relationship between Cheyne-Stokes respiration and SAS, and Iwai et al. reported the appearance of periodic respiration at an average rate of 64.2% during the entire sleep period in SAS and in correlation with BMI, OD4 and AI.

In the present study, determination of Cheyne-Stokes-like waveforms with the pressure sensor bed confirmed that the diagnosis of SAS could be performed. The characteristic feature of the present method for determination of respiration using the pressure sensor is that observation of respiration based on the principle that the decrease in electric resistance with the increase in given force can be observed under natural sleep conditions without attaching sensors. The clinical application of the pressure sensor bed is focused on the observation during sleep of elderly subjects or children in consideration of screening of apnea at home, and respiration management in the postoperative intensive care unit. The present method can avoid the uncertainty of unexpected sensor detachment during sleep of the conventional system that employs attached determining tools.

Observations of respiration during sleep, movement of chest and abdomen due to respiration, and blood oxygen saturation of patients with sleep apnea have been carried out by directly attaching sensors to the body. However, observation of respiration under unrestrained and non-invasive conditions is indispensable to determine natural conditions during sleep. A bed equipped with the pressure sensors that show a decrease in electric resistance with compression was prepared and used for observation of respiratory movement during sleep. Furthermore, conditions of respiration during sleep were observed with the pressure sensor bed and Microsleep, and both results are comparatively investigated. A correlation between frequencies of Cheyne-Stokes-like waveform in an hour, and AI and ODI4 obtained by the Microsleep was found. Thus, detection of sleep apnea from thoracoabdominal spirograms can be carried out.
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References


睡眠時無呼吸症例の圧力センサベッド
による呼吸観察

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睡眠中の呼吸を無拘束無侵襲で観察する目的で加圧に伴って電気抵抗値が減少する圧力センサを使用したベッドを作製し、睡眠中の呼吸運動を観察した。また、圧力センサベッドとともにマイクロスリープ・モデル97（サイネティクス社製）による睡眠時の呼吸状態につき観察結果を比較検討した。

睡眠時無呼吸と診断された症例においてマイクロスリープ、圧力センサの両者無呼吸に一致して周期性の呼吸波形が観察され、これをチェーンストークス類似波形と名付けた。圧力センサの一時間中のチェーンストークス類似波形数がマイクロスリープの計測結果である AI, ODI4 と相関が得られ、圧力センサベッドにより睡眠中の無呼吸の検出は可能であった。

キーワード：睡眠時無呼吸，圧力センサベッド，チェーンストークス類似波形