Estimation of Oxygen Desaturation by Analyzing Breath Curve

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Abstract

The unrestrained monitor reduces monitoring load, but the variety of physiological value is limited. We propose a new method for measuring oxygen desaturation frequency by analyzing Cheyne-Stokes-like breathing curves based on the fact that the characteristic pattern of the curve occurs at a high probability at oxygen desaturation. We confirm the effectiveness of our proposal in experiments on patients with sleep apnea and other disorders. This proposal is applicable to any sensors that monitor breathing curves and in calculating physiological values using unrestrained monitors at home and in screenings examination at hospitals having no special equipment.

Keywords: Non-invasive Unrestrained Monitoring, Respiration, Cheyne-Stokes Breath, Oxygen Desaturation Estimation

1 Introduction

Despite increased interest in health, means of monitoring physiological conditions are limited except at special facilities such as hospitals due to the lack of easy-to-operate, inexpensive instruments for such monitoring.

Studies to ease the monitoring load include unrestrained monitoring using sensors embedded in environement to monitor physiological conditions from the body surface or externally. Monitoring using portable instruments that do not interfere with daily life is also called unrestrained monitor, but our definition covers techniques that do not require attaching devices to the body. Some related studies are already commercialized. Salmi and Alihanka et al. monitored respiration, heart rate, and body movement using piezoelectric sensors on bed under sheets[1, 2]. Tamura et al. monitored body movement using thermal sensors on beds[3]. Ishijima monitored electrocardiogram using electroconductive fiber on beds[4]. Nishida et al. developed a pressure imaging system and proposed an imaging algorithm to monitor posture, respiration, and body movement with the system[5]. Harada et al. proposed an imaging algorithm to calculate positions of body parts in addition to position by comparing with templates automatically made from physical models of the body[6]. Watanabe et al. proposed monitoring at high accuracy pressure changes using a microphone in air mattresses and used a single system to monitor physiological values such as pulse, heart rate, respiration, snoring, body movement, and cough[7]. Using visual sensors, Ishihara et al. monitored respiration[8], Nakajima et al. monitored respiration, body movement, and pulse[9, 10], and Nishida et al. proposed diagnosing sleep apnea, respiration, and body movement using visual sensors above beds[11]. These unrestrained monitoring overcome problems of energy supply and instrument size by choosing optimal sensors sites and ensure freedom by using unattached monitoring instruments and reducing physiological and psychological loads on patients.

Thus, the study of unrestrained monitors includes varied system and process development of how to monitor basic vital signs easily. Such study is essential but, given physiological values, development is poor and techniques are limited to electrocardiograms, pulse, heart rate, respiration, respiratory sound, body movement, and posture. Study of monitoring for other physiological values is required. We propose calculating oxygen desaturation frequency by analyzing breathing curves. At present, oxygen saturation is monitored by an invasive method or non-invasive one. In the invasive method, a sensor is inserted into blood vessels or blood is sampled by drawing. Even in the non-invasive method, only oxyhemogblobin method is practicable and we must attach light emitting and receiving devices to fingers or toes. The latter is well developed and monitoring instruments based on this principle are widely used in clinics and at home thanks to its easy operation, low cost, high accuracy[12, 13]. Few studies, however, have calculated oxygen saturation or desaturation by unrestrained monitoring.

2 Oxygen Desaturation Monitoring Principle

2.1 Oxygen Saturation

Respiration keeps oxygen and carbon dioxide in body fluids within a constant range. Tidal air is controlled by respiratory muscles such as the diaphragm and intercostals based on the oxygen and carbon dioxide concentration detected by some internal sensors. The sensors exist in carotid body of the common carotid artery and central chemosensitive area of the medulla oblongata.

Oxygen saturation (S_aO_2) expresses the percentage of oxyhemoglobin molecules to all hemoglobin molecules and is almost 100 % in healthy subjects. Doctors find oxygen saturation monitoring important physiologically to judge whether respiration is normal. This hardly changes in slight variation in tidal air such as deep breathing or apnea of about 10 seconds, but in patients with breathing disorders, a change of 30-40% may be seen.

This paper proposes a new method for estimating oxygen desaturation frequency, not the absolute oxygen saturation, by analyzing Cheyne-Stokes-like breathing defined later. Oxygen Desaturation 4% index, which means how many times oxygen saturation falls 4% par hour, is widely used to evaluate the seriousness of breathing disorders and share data among researchers.

2.2 Extimation of Oxygen Desaturation

2.2.1 Cheyne-Stokes-Like Breathing

In sleep apnea and other disorders, respiration such as Cheyne-Stokes breathing occurs often. Cheyne-Stokes breathing is periodic respiration in which period of excess respiration with large tidal air and apnea are repeated and tidal air gradually increases and decreases, then respiration stops altogether, i.e., central apnea occurs (Fig. 1)[14, 15].

Figure 2 shows Cheyne-Stokes breathing observed in 3 patients with sleep apnea. The ordinate shows abdominal movement in respiration . This is monitored by a breathing monitor described later, and by monitoring distortion of chest and abdomen. In normal respiration, tidal air and respiratory movement are closely related. Strictly speaking, this is not Cheyne-Stokes breathing because breathing does not stop completely, but such breathing curves often occur in patients with breathing disorders during sleep. Cheyne-Stokes breathing should be discussed distinguished from obstructive apnea caused by upper airway obstruction because their causes are different. We focused on the curve and expand the definition of Cheyne-Stokes breathing defined as respiration with ventilation or effort respiration without ventilation accompanying gradual increase and gradual decrease, or sudden increase and gradual decrease, i.e., Cheyne-Stokes-like breathing.

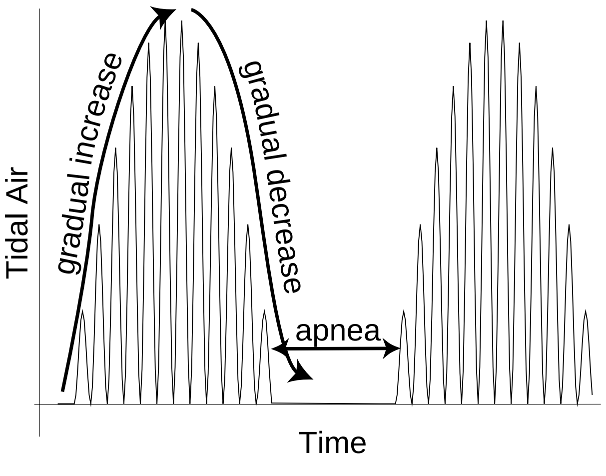

Fig.1: Cheyne-Stokes breath

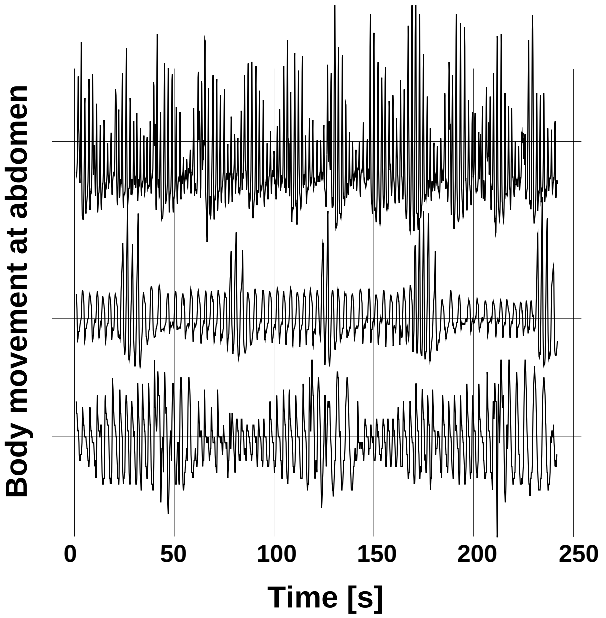

Fig.2: Example of Cheyne-Stokes-like breath

2.2.2 Estimation of Oxygen Desaturation Frequency

We studied the relation between respiration change and Cheyne-Stokes-like breathing (Fig. 3). Four representative physiological values describe respiration: snoring, nose and mouth airflow, chest and abdomen movement and oxygen saturation. We used sensors (Fig. 4) of a typical system diagnosing for breathing disorders to monitor breathing, i.e., pressure sensors to monitor chest movement, temperature sensors to monitor nose and mouth airflow, microphones to monitor snoring, oximeters to monitor oxygen saturation, and mercury sensors to monitor posture. Figure 3 shows 1 case of apnea and 4 of Cheyne-Stokes-like breathing, which correlates well with oxygen desaturation.

We found the fact that Cheyne-Stokes-like breathing occur at high probability in oxygen desaturation as proved in the next section. Based on the fact, this paper proposes a method for estimating oxygen desaturation frequency by measuring Cheyne-Stokes-like breathing frequency.

2.2.3 Verification Experiment of Monitoring Principle

To verify the effectiveness of our proposal, we monitored apnea index (AI), oxygen desaturation 4% index (ODI4), and Cheyne-Stokes index in 34 subjects —23 men and 11 women— having a body mass index (BMI) of $25.57[Kg/m^2]$, a mean age of 46.8 years, and breathing disorders of differing seriousness (Fig. 5-7). AI, ODI4, and Cheyne-Stokes index show mean frequency per hour. The correlation of ODI4 to Cheyne-Stokes index is 0.92, that of AI to Cheyne-Stokes index is 0.76, and that of ODI4 to AI is 0.85. These results demonstrate high correlation among ODI4, AI, and Cheyne-Stokes index. The Cheyne-Stokes index shows a

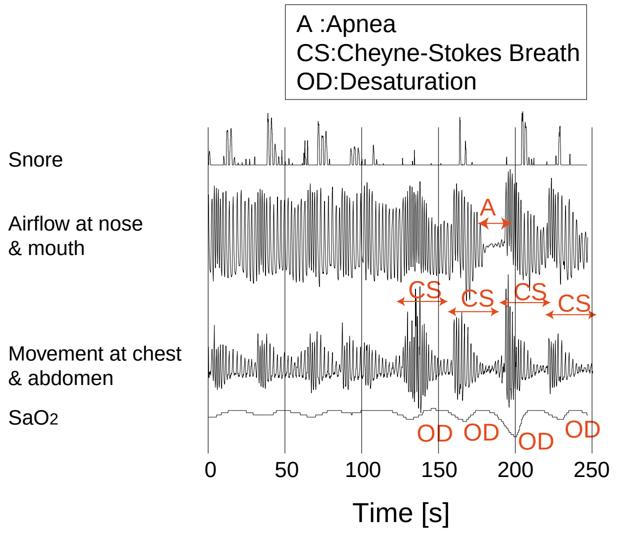

Fig.3: Comparison among parameters for monitoring breath

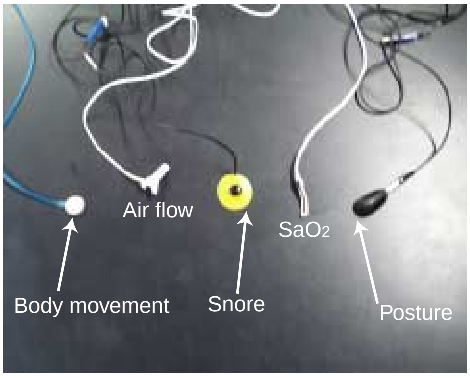

Fig.4: Typical sensors for monitoring breath status

higher correlation to the ODI4 than to AI (Fig. 5 and 6). The apnea index tends to be unstable in patients with slight hypoxemia (Fig. 7). Thus, no apnea does not mean no oxygen desaturation. On the other hand, the Cheyne-Stokes index shows uniform results for patients from slightness to seriousness. That means the index can be used for estimation of oxygen desaturation frequency and for evaluating seriousness of hypoxemia.

2.2.4 Model of Cheyne-Stokes-Like Breathing

Oxygen desaturation is not caused only by obstructive apnea, but most clinical apnea is this type, so we focused on it (Fig. 8). In a simplified obstruction of the pharynx

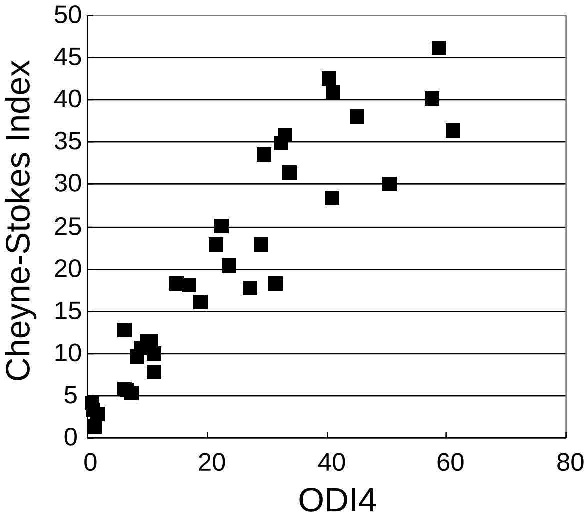

Fig.5: Comparison between ODI4 and Cheyne-Stokes index

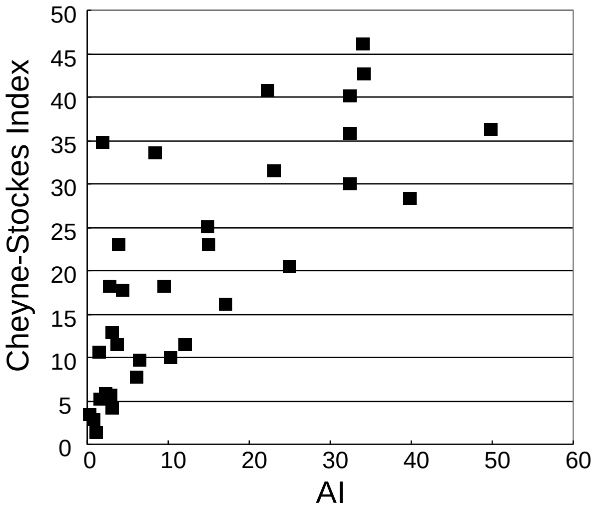

Fig.6: Comparison between AI and Cheyne-Stokes index

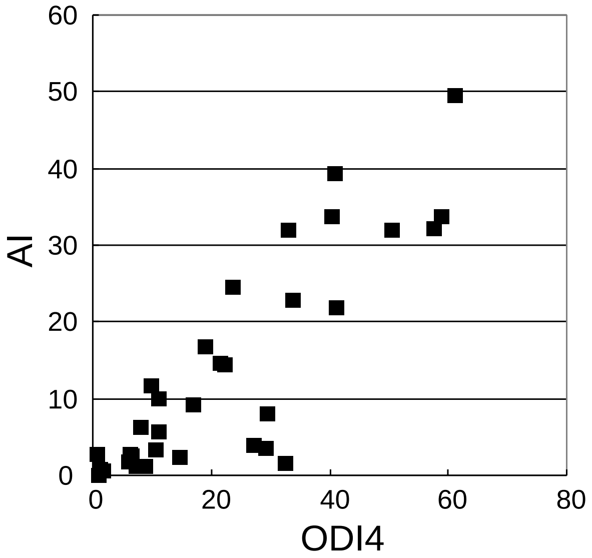

Fig.7: Comparison between ODI4 and AI

in obstructive apnea, Pout expresses oral internal pressure and Pin internal esophageal pressure. Pout and Pin are equal if there is no obstruction, and differ if obstruction occurs, i.e., P_{in} is less than P_{out} at inhalation and P_{in} is greater than P_{out} at exhalation, and the force F_p is applied to the part where the obstruction occurs.

$$F_p = S(P_{out} - P_{in}) \tag{1}$$

Where S represents the cross section area of the obstruction.

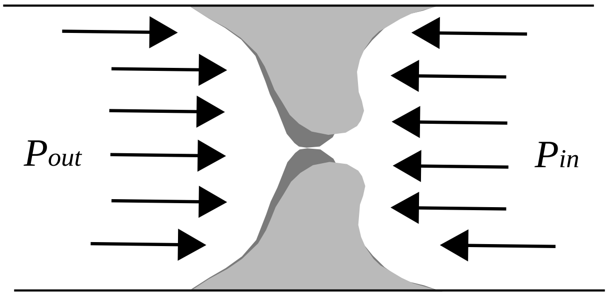

Fig.8: Model of peripheral apnea

The approximation equation (2) is satisfied between 1 breath tidal air $\dot{V}$ (tidal air), and the partial pressure of arterial carbon dioxide () and partial pressure of arterial oxygen (P_{O_2}). This indicates that increased P_{CO_2} and decreased P_{O_2} increase tidal air. Decrease P_{O_2} greatly intensifies the effect of tidal air increase by increased P_{CO_2}.

$$\dot{V} = D(P_{CO_2} - B)\left(1 + \frac{A}{P_{O_2} - C}\right) \tag{2}$$

A,B,C, and D are constants.

Obstructive apnea is caused when the force which respiratory muscles such as diaphragm and intercostals generate for respiration (respiratory muscle force) does not contribute to ventilation. Using work $\dot{W}_r$ done by respiratory muscles for 1 respiration, eq. (2) is transformed into eqs. (3) and (4).

$$\dot{V} = \begin{cases} E \cdot \dot{W}_r & F_p > F_b \text{(opening conditions of obstruction)} \\ 0 & F_p \leq F_b \end{cases} \tag{3}$$

$$\dot{W}_r = F(P_{CO_2} - B)\left(1 + \frac{A}{P_{O_2} - C}\right) \tag{4}$$

E and F are constants.

The Cheyne-Stokes-like curve in obstructive apnea is explained by the above equations from work by respiratory muscles. Until F_p in eq. (1) satisfies F_b to open the obstruction, P_{O_2} decreases and P_{CO_2} increases because ventilation does not occur (lower in eq. (3)), and work by respiratory muscles increases dramatically (eq. (4)). When $F_p > F_b$ is satisfied and the obstruction opens (upper in eq. (3)), P_{O_2} gradually increases (see eq. (4)).

The Cheyne-Stokes-like curve monitored is a gradual decrease after a sudden, not gradual increase(Figs. 2 and 3). The reason why a sudden increase appears instead of a gradual increase expected from the above equations is that the curves shown in Figs. 2 and 3 are monitored with chest and abdomen movement, not with respiratory muscle work which is used as a variable in the above equation, The relation between respiratory muscle work and chest and abdomen movement are explained as follows:

1) While obstruction is occurring, negative pressure in the chest becomes higher when a person try to inhale air. In this situation, the force of respiratory muscles is spent decompressing pressure in the chest and moving internal organs, not inhaling air. The respiratory muscle work is not reflected in chest and abdomen movement. As a result, chest and abdomen movement seems to increase little, although a high respiratory muscle force is generated. Respiratory muscle work is not correlated to actually observed movement of chest and abdomen; 2) when the obstruction becomes unblocked, explosive inhalation occurs, observed as sudden movement; 3) after the obstruction disappears, respiratory muscle work and observed movement of chest and abdomen correlate well because the force of respiratory muscles is mainly spent ventilation, and chest and abdomen movement gradually decreases depending on tidal air.

3 Clinical Experiment Using Pressure Sensor Bed

3.1 Pressure Sensor Bed

Using a pressure sensor bed (Fig. 9), we studied the applicability of calculating oxygen desaturation based on the Cheyne-Stokes-like breathing curve; 210 high molecular thick film devices (FSRs)(Interlink) are located at 7[cm] spacing and ,using the property that as force applied on FSR increases, its electric resistance decreases, we obtain pressure distribution imaging of 12[bits](Fig10).

Fig.9: Pressure Sensor Bed

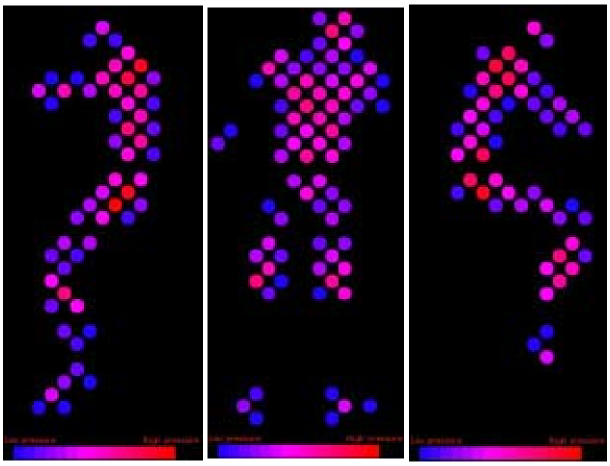

Fig.10: Pressure Image

3.1.1 Detection of Cheyne-Stokes-like breathing Using Pressure Sensor Bed

We detected respiration by the equal phase sum method. Respiratory movement is detected by the change of weight distribution at contacts of sleeping subjects and the bed. When the whole body is taken as the pressure image, breathing curves cannot be accurately monitored by a simple sum of pressure due to the influence of offset by the phase difference in the pressure change because the subject's weight does not change. The equal phase sum method enables accurate detection of respiration by appropriate summing controlling offset considering the phase difference in pressure charge[5].

Figure 11 shows an example of Cheyne-Stokes-like curve using the equal phase sum method. The figure shows, from the top, nose and mouth airflow, respiratory chest and abdomen movement, oxygen saturation, and breathing curve detected by applying the equal sum method to pressure images monitored using the pressure sensor bed. The Cheyne-Stoke-like curve is detected using the pressure sensor bed.

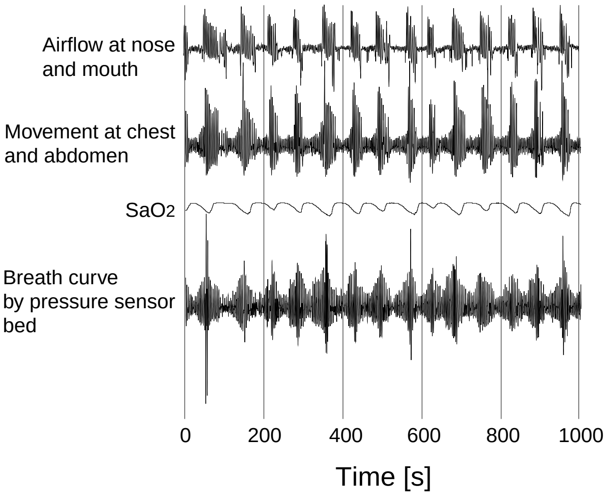

Fig.11: Cheyne-Stokes-like breath

3.1.2 Finding Cheyne-Stokes Index Using Pressure Sensor Bed

With a group of 16 subjects —8 men and 8 women— composed of people of sound healthy and patients with sleep apnea, we detected the Cheyne-Stokes index by unrestrained monitoring using the pressure sensor bed and compared the result to ODI4 detected by an apnomonitor. The mean age of the subjects is 46.7 years and BMI 24.86$[Kg/m^2]$(Fig. 12). A high correlation of 0.85 was confirmed between the Cheyne-Stokes index detected by the pressure sensor bed and ODI4.

Figure 13 compares the frequency of Cheyne-Stokes-like breathing and oxygen desaturation 4% at an interval of 10 minutes with 3 patients with disease of different seriousness. A high correlation was confirmed between the

Cheyne-Stokes index monitored by the pressure sensor bed and ODI4.

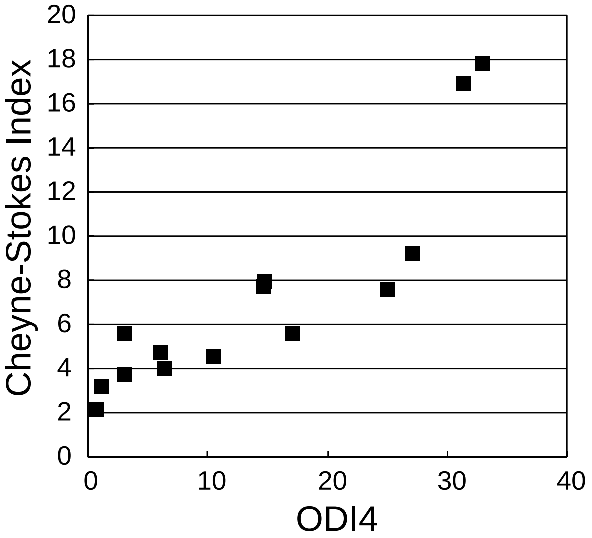

Fig.12: Comparison of ODI4 detected by conventional sensor and Cheyne-Stokes index detected by pressure sensor bed

4 Conclusions

We proposed estimating oxygen desaturation frequency by analyzing the breathing curve detected by unrestrained monitoring.

The principle of this method uses Cheyne-Stokes-like breathing curves, which occur at a high probability in oxygen desaturation, and conversely by detecting the curve, oxygen desaturation frequency is counted.

We experimented with healthy people and patients with disease of different seriousness, confirming our proposal's effectiveness. We studied unrestrained monitoring applying this to proposed a pressure sensor bed we have developed.

Because this proposed method is applicable to sensors to monitor breathing curve, it is expected to be applied to calculate physiological values by unrestrained monitoring at home and screening tests at hospitals having no special equipment.

Themes for future discussion are: 1) clinical examination to judge whether this method is applicable to healthy subjects, including infants and the elderly, and patients with other diseases, because we studied only healthy people and patients with sleep apnea, and 2) improvement of the breathing curve analysis algorithm to abstract the Cheyne-Stokes-like curve.

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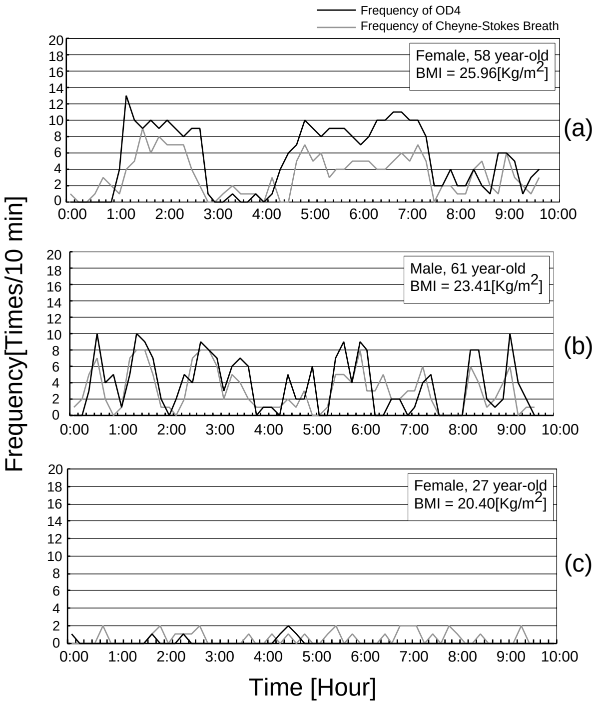

Fig.13: Comparison of histogram of Oxygen desaturation 4% (OD4) detected by conventional sensor and Cheyne-Stokes-like breathing detected by pressure sensor bed

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