A Novel Mainstream Capnometer System for Polysomnography Integrated with Measurement of Nasal Pressure and Thermal Airflow

Kota Saeki, Yuya Baba, Fumihiko Takatori, Masayuki Inoue, Naoki Kobayashi, and Shinji Yamamori

Abstract—**Capnometry is a method to measure carbon dioxide (CO_2) in exhaled gas and its use during polysomnography (PSG) for diagnostic of sleep apnea-hypopnea syndrome is expanding. However, some problems exist for using capnometer in combination with other respiratory monitoring devices because capnometry requires additional sampling cannula or airway adapter attached to patients. To resolve these problems, we developed a novel mainstream capnometer system for PSG, which is designed to integrate multiple devices for measuring respiratory parameters. This system may provide comfortable and stable PSG including capnometry. We evaluated the basic performance of this system using a spontaneous breathing model. The result indicates that this newly developed system works adequately in PSG and moreover has superior characteristics of capnography signal and measurement stability against displacement of sensors, compared to conventional devices.**

I. Introduction

Capnometry is a method to measure carbon dioxide (CO_2) in exhaled gas and it has been used in both intubated and non-intubated patients to monitor their respiratory status. Monitoring exhaled CO_2 during polysomnography (PSG) for diagnostic of sleep apnea-hypopnea syndrome is also performed. Capnometry is commonly used for detection of hypoventilation or as an alternative sensor for scoring apneas, especially in pediatric PSG [1][2][3].

There are two measurement methods for capnometry: sidestream method and mainstream method. The sidestream method, which is most commonly used in PSG, uses a nasal cannula for sampling exhaled CO_2 to an external sensor which performs the measurement. In this method, a smaller patient-side attachment part usually can be used, but the ability of monitoring exhaled CO_2 can be impaired in oral breathing and by the occlusion of the sampling cannula. Additionally, it should be noted that the capnography signal can be delayed behind other respiratory airflow signals: nasal pressure and thermal airflow [2]. The mainstream method, which uses a sensor located on special airway adapter and directly measures exhaled CO_2 without gas sampling, usually responds well to changes of exhaled CO_2 and rarely causes airway adapter obstruction by secretions or humidified air, but generally needs relatively heavy and bulky sensors. A mainstream capnometer called cap-ONE® (Nihon Kohden Corporation, Tokyo, Japan) has been developed to overcome the problems of both sidestream and conventional mainstream methods [4][5][6]. cap-ONE is lightweight (4 g) and small enough (8.3×13.7×37 mm) to be fitted below the nose and it can be used for non-intubated patients.

As mentioned above it is necessary to attach the sampling cannula and the airway adapter to perform sidestream and mainstream capnometry. Generally, both methods have some problems for being used in combination with other respiratory monitoring devices during PSG. Since monitoring nasal pressure and thermal airflow is recommended in the AASM manual for detecting apnea and hypopnea [1], a pressure measuring cannula and a thermal airflow sensor are usually attached on patient's face. Additional sampling cannula or airway adapter for capnometry may cause patient discomfort, increase of the trouble in preparing for tests, and unstable monitoring due to displacement of sensors.

To address these problems, we developed a novel mainstream capnometer system specialized for PSG (cap-ONE system). This cap-ONE system was designed to integrate multiple devices for the measurement of three parameters: capnogram, nasal pressure, and thermal airflow. The integration can reduce the total size of the devices, save the trouble of attaching multiple sensors, and makes the device less likely to be affected by displacement of sensors, leading to more comfortable and stable PSG.

In this paper, we report the basic performance of the cap-ONE system comparing to conventional separate devices used in PSG, using a spontaneous breathing model.

II. Material and Method

A. cap-ONE System for Polysomnography

The cap-ONE system consists of the mainstream capnometer cap-ONE (TG-970P, Nihon Kohden Corporation, Tokyo, Japan), an oronasal airway adapter, and a thermal airflow sensor (Fig.1). These components are combined and attached on patient's face as shown in Fig.2.

cap-ONE consists of a light unit and a detector unit, which are located each other across the CO_2 measurement cell of the oronasal airway adapter. Light emitted from the light unit passes through the CO_2 measurement cell, where CO_2 molecules in exhaled gas absorb the infrared light of 4.3 μm, and is detected in the detector unit. Then cap-ONE calculates CO_2 concentration based on the measured infrared absorption intensity [6].

The oronasal airway adapter consists of a CO_2 measurement cell, a nasal tube connected with a pressure transmitting tube, and a mouth guide (Fig.1). The nasal tube is inserted into the nares and the mouth guide is placed over the mouth to guide nasal and/or oral exhaled gas into the CO_2

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measurement cell. The nasal tube has internal ribs to make constricted section in the flow path (Fig.3). When airflow of inhalation or exhalation passes through the constricted section, the pressure difference is generated and measured as nasal pressure. Exhaled airflow passes through the ribs and blows into the CO_2 measurement cell. This structure enables to measure both CO_2 and nasal pressure without additional cannula. The mouth guide is wide shape with the rolled edge to catch oral exhalation airflow efficiently. The mouth guide has two holes to insert sensing portions of the thermal airflow sensor.

The thermal airflow sensor utilizes the difference between the temperature of exhaled airflow and inhaled ambient air to detect breathings. This sensor is composed of thermocouples and has four hot junctions served as sensing portion. This sensor is mounted on cap-ONE and the sensing portions are positioned in front of the nasal tube, that is below the nares, and inserted through the holes to be positioned inside of the mouth guide so that it can measure both nasal and oral breathing (Fig.4). This position of the sensing portions may reduce unstable measurement caused by contact with the skin, displacement of the sensing portions, and difference in the size of open mouth during oral breathing.

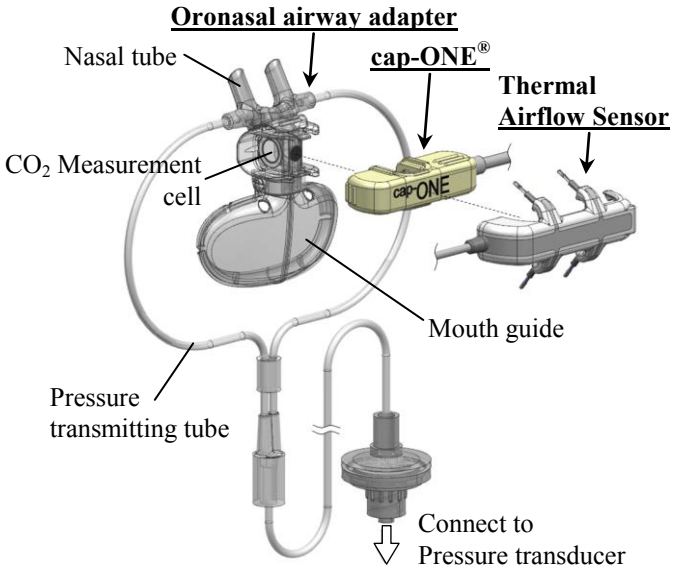

Figure 1. Components of the cap-ONE system specialized for PSG

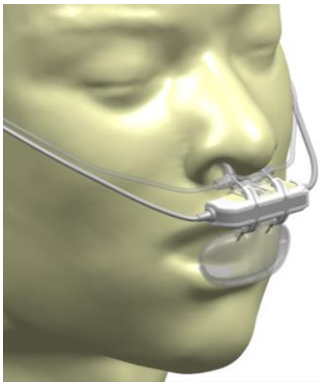

Figure 2. cap-ONE system attached on patient's face

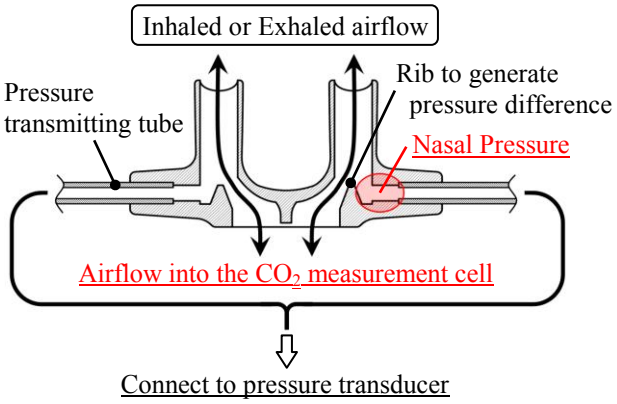

Figure 3. Internal structure of the nasal tube

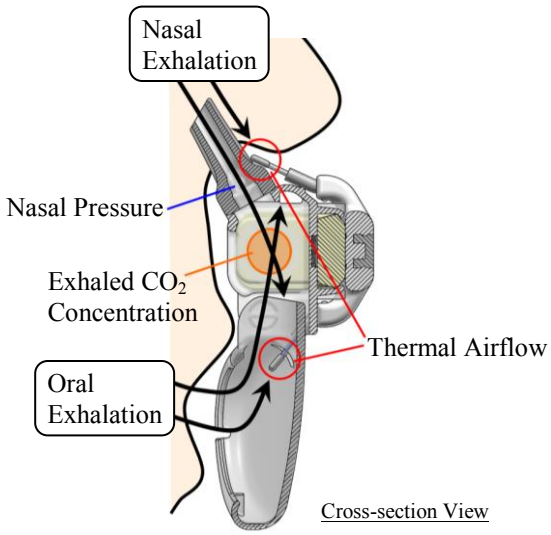

Figure 4. Direction of exhaled airflow and sensing portions of each sensor

Exhaled airflow from nose and mouth, guided by the oronasal airway adapter, is measured in each sensing portion of the sensors (Fig.4); therefore, the cap-ONE system provides simultaneous measurement of capnogram, nasal pressure, and thermal airflow.

B. Conventional Devices

Conventional respiration detecting devices and a sidestream capnometer described below (conventional devices) are compared to evaluate the basic performance of the cap-ONE system:

(a) Nasal pressure cannula: Pro-Flow nasal cannula (P1259, Philips Respironics, Pennsylvania, US)
(b) Thermal airflow sensor: Thermocouple nasal/oral airflow (P1222, Philips Respironics, Pennsylvania, US)
(c) Sampling cannula for sidestream capnometer: Smart CapnoLine® Plus (Oridion, Jerusalem, Isael)

These conventional devices were attached on a face as shown in Fig.5.

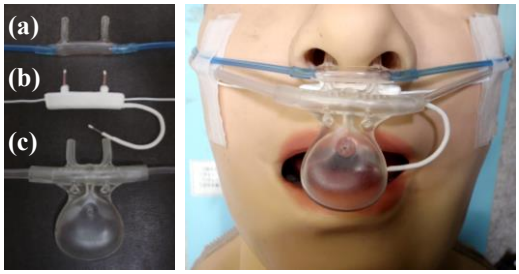

Figure 5. Conventional devices for comparison

C. Spontaneous Breathing Model

A spontaneous breathing model used for evaluation consists of a test lung (model 1600, Michigan Instruments, MI, US), a ventilator (Evita2, Dräger, Lübeck, German), a mass flow controller (PE-D20, HORIBA STEC, Kyoto, Japan), a heating belt, and a facial model (Fig.6).

The inhalation and exhalation airflow was generated by the spontaneous breathing lung when the driving lung was moved up and down by connected ventilator, and passed through the nose or mouth of the facial model. When simulating nasal breathing, the facial model's mouth was covered with tape, and when simulating oral breathing, the nasal cavities were sealed with cotton balls. Tidal volume, respiration rate, and inhalation/exhalation ratio (IE ratio) of simulated spontaneous breathing were controlled by changing the settings of the ventilator.

CO_2 gas which was regulated by the mass flow controller was continuously supplied to the spontaneous breathing lung so that the exhaled airflow contains CO_2. The CO_2 concentration in exhalation at the airway near the facial model was measured as reference by a mainstream capnometer (TG-950P, Nihon Kohden Corporation, Tokyo, Japan) and adjusted to approximately 40 mmHg.

The airflow through the facial model was heated by the heating belt to simulate warm exhalation. The temperature of exhalation was measured by sensitive fine wire thermocouple (ST-55, dia. 0.076 mm, RKC INSTRUMENT INC., Tokyo, Japan) and adjusted to approximately 35 degree C by a variable transformer connected to the heating belt.

D. Data Collection

Mainstream capnograms of the cap-ONE system and sidestream capnograms of the conventional devices were measured by OLG-2800 (Nihon Kohden Corporation, Tokyo, Japan) and Microcap® (Oridion, Jerusalem, Israel), respectively. In both the cap-ONE system and the conventional devices, nasal pressure and thermal airflow was measured by a manometer (MT210, Yokogawa Electric Corporation, Tokyo, Japan) and a built-in amplifier recorder (TR-V550, KEYENCE, Osaka, Japan), respectively.

On each evaluation, The maximum amplitude of capnogram waveforms were measured as end-tidal partial pressure of carbon dioxide ($PetCO_2$) values. The nasal pressure and the thermal airflow values were measured from the peak-to-peak values obtained from their signal waveforms. These values were averaged for 10 breathings.

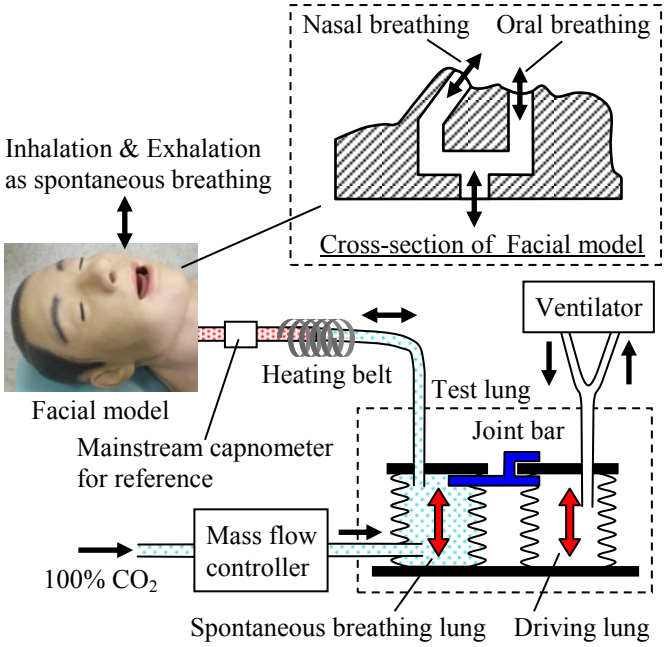

Figure 6. Spontaneous breathing model

E. Method for Evaluation

1. Measurement of simulated apnea

We compared the signals obtained by the cap-ONE system and the conventional devices in simulated apnea of an awake subject. The subject was a healthy male adult. Following the normal breathing, the subject held their breath for approximately 15 seconds from just after the start of inspiratory phase. The obstructive apneas often occur in this manner.

2. Signal variation related to the tidal volume change

We evaluated the variation of signals of each parameter when the tidal volume of the spontaneous breathing model was changed as follows: 200 ml, 300 ml, 400 ml, and 500 ml. Respiration rate and IE ratio of the ventilator were remained at 12/minute and 1:2, respectively.

3. Measurement stability during oral breathing

It is generally considered that the measurement during oral breathing is unstable because the sensing portions are prone to displace and the size of open mouth varies with individuals.

Thus we evaluated the stability of measurement during oral breathing using the spontaneous breathing model. Instead of the facial model, three different diameter pipes (10 mm; 20 mm; 30 mm) were used to simulate the size variations of open mouth. Signal variation was measured when the cap-ONE system and the conventional devices were displaced from the center of each pipe to the lateral direction for the following range; 0 mm (no-displacement), 10 mm, and 20 mm. Each mouth guide of the cap-ONE system and the conventional devices was positioned at 10 mm above the pipes. Throughout this evaluation, ventilator settings was remained at tidal volume of 500 ml, respiration rate of 12/minute and IE ratio of 1:2.

III. Result

1. Measurement of simulated apnea

Fig.7 shows examples of signals when simulated apnea was measured. Although this result was obtained from just one subject, it would seem to show qualitative features. The waveforms obtained by the cap-ONE system were almost equivalent to the conventional devices. Additionally, the capnogram of the cap-ONE system can detect apnea without delay.

2. Signal variation related to the tidal volume change

Fig.8 shows the variation of each parameter in nasal and oral breathing with different tidal volumes of the spontaneous breathing model. Compared to the conventional devices, the cap-ONE system presented almost equivalent variation in values of both $PetCO_2$ and nasal pressure. In contrast, thermal airflow of the cap-ONE system seems to be more sensitive than the conventional sensor. In addition, Fig.8 indicates that the signals of thermal airflow during oral breathing were smaller than during nasal breathing both in the cap-ONE system and the conventional devices.

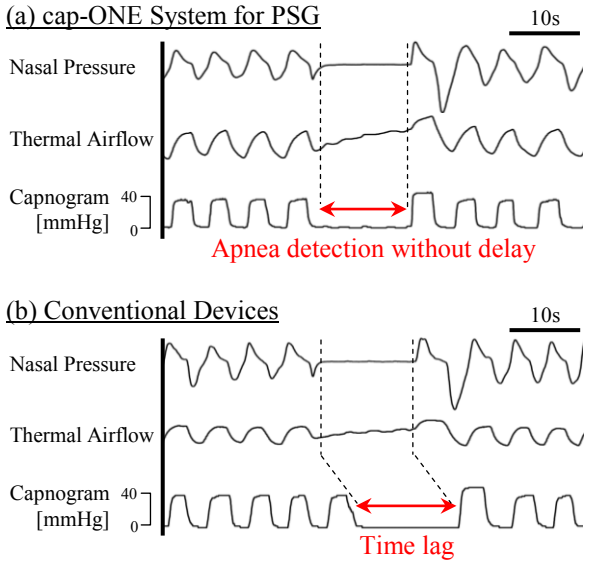

Figure 7. Examples of signals when simulated apnea was measured

Fig.9 shows the change of capnograms with different tidal volumes. In normal ventilation (tidal volume of 500 ml), capnograms obtained by cap-ONE and the sidestream capnometer were almost identical to the reference waveforms. In reduced ventilation (tidal volume of 200 ml), capnograms obtained by cap-ONE presented small decline at the end-tidal point, while capnograms obtained by the sidestream capnometer showed triangle waveforms and its plateau disappeared.

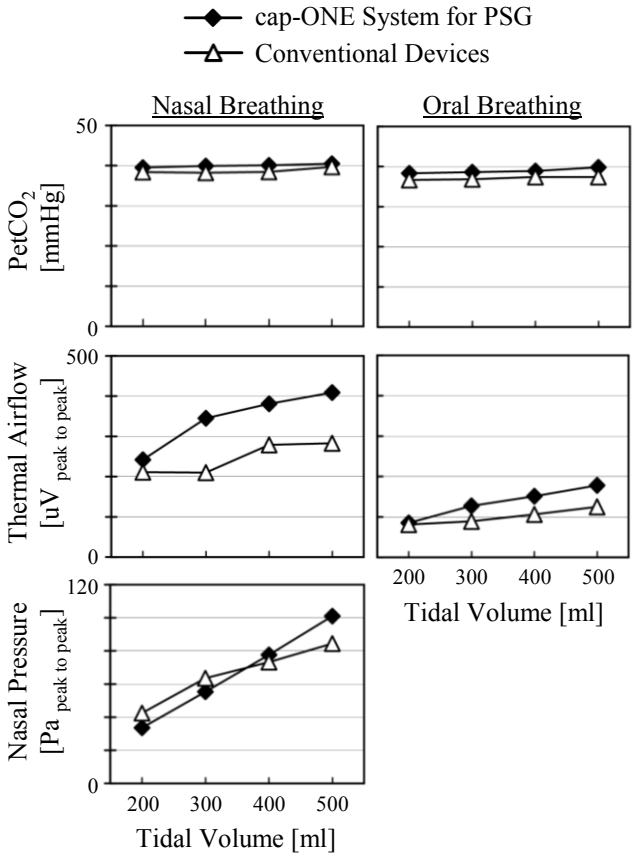

Figure 8. Signal variation related to the tidal volume changed

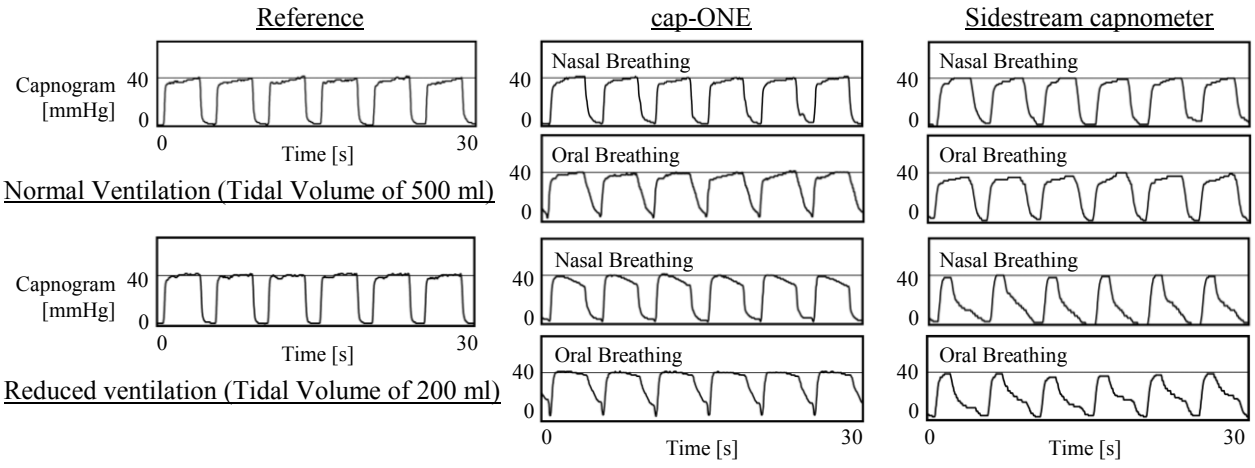

Figure 9. Capnograms of spontaneous breathing model

3. Measurement stability during oral breathing

Fig.10 shows the stability of measurement during oral breathing when sensors were displaced. The variation of measured value obtained by the cap-ONE system were less than the conventional devices. In particular, $PetCO_2$ of the cap-ONE system exhibited good stability against the displacement and the size variations of open mouth.

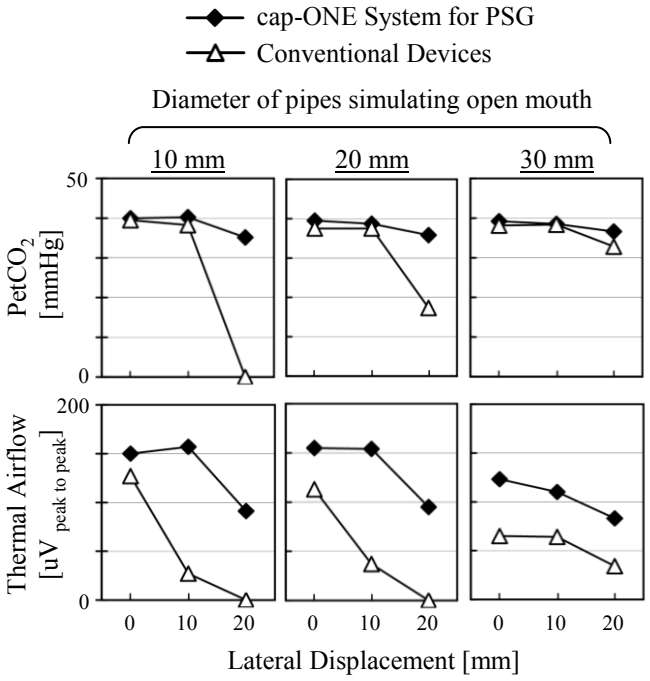

Figure 10. Stability of measurement during oral breathing when sensors were displaced

IV. Discussion

The conventional devices require individual attachments of three devices, thus the preparation is complex and time-consuming. In contrast, all that required in the cap-ONE system was to combine three components and simply insert the nasal tube; therefore, we speculate that the cap-ONE system contribute to save the trouble of the preparation.

The characteristics shown in Fig.7 and Fig.8 indicate that the cap-ONE system works adequately in PSG, thus it can be used as an alternative to the conventional devices.

Fig.9 suggests the advantage of cap-ONE over the sidestream capnometer. Since the sidestream method requires continuous aspiration, the dilution by ambient air affects capnogram when the aspirated exhalation gas is insufficient, and that causes the disappearance of plateaus leading to triangle waveforms in the sidestream capnogram during reduced ventilation. In contrast, using cap-ONE, the exhaled gas is directly blown into the CO_2 measurement cell, thus dilution is unlikely to occur compared to sidestream capnometers. There was no difference between the maximum amplitude of capnogram obtained by cap-ONE and the sidestream capnometer in this evaluation. However, in the case of the respiratory condition such as actual value of end-tidal portion being quite higher, $PetCO_2$ value by the sidestream capnometer is expected to become lower.

Fig.10 indicates the efficacy of the wide-shaped mouth guide in the cap-ONE system. In particular, stability of the thermal airflow was greatly improved by the combination with the mouth guide. These results suggests that slight displacement of sensor makes the conventional devices difficult to detect oral breathing, leading to present false apneas. This evaluation shows that the cap-ONE system can be effective to solve this problem.

V. Conclusion

In this study, we evaluated the basic performance of the novel mainstream capnometer system specialized for PSG: the cap-ONE system. This system was designed to integrate multiple devices for measurement of respiratory parameters so as to provide comfortable and stable PSG. First, we verified that the capnogram of the cap-ONE system can detect apnea without delay in simulated apnea of an awake subject. Second, we used the spontaneous breathing model and evaluated the variation of signals at different tidal volumes. The result indicates that the cap-ONE system has almost equivalent characteristics to the conventional devices. Additionally, the thermal airflow sensor of the cap-ONE system was more sensitive; capnograms were more appropriate even at the low tidal volume. Moreover, the cap-ONE system showed good stability of measurement against the displacement and the size variations of open mouth during oral breathing.

Although further evaluations including consideration of applicable patients, assessment of usability, and statistical analysis are required to establish the effectiveness, we believe that the cap-ONE system can contribute to improve the quality of PSG including capnometry.

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