A Novel Mainstream Capnometer System for Non-invasive Positive Pressure Ventilation

Yuya Baba, Fumihiko Takatori, Masayuki Inoue and Isao Matsubara

Abstract— **Capnometry is a method to measure carbon dioxide (CO_2) in exhaled gas and it has been used to monitor patient respiratory status. CO_2 monitoring is also used for patients receiving non-invasive positive pressure ventilation (NPPV) therapy during mechanical ventilation. Ventilators actively dilute exhaled gas during non-invasive ventilation. In order to accurately measure end-tidal CO_2, an adequate amount of expired gas needs to be filled in a CO_2 measurement cell before expiratory positive airway pressure (EPAP) gas from the ventilator arrives to the cell. This is the reason why it is difficult to measure CO_2 stably during non-invasive ventilation using the conventional CO_2 measurement method. Therefore, we developed NPPV cap-ONE mask, which accurately measures CO_2 in exhaled gas during non-invasive ventilation. In this study, we evaluated the basic performance of the NPPV cap-ONE mask system. The NPPV cap-ONE mask system could accurately measure CO_2 in exhaled gas comparing to the conventional device in this study.**

I. Introduction

Capnometry, a method to measure carbon dioxide (CO_2) in exhaled gas, has been used in both intubated and non-intubated patients to monitor their respiratory status. The American Association for Respiratory Care 2011 Update summarizes indications for the use of CO_2 monitoring during mechanical ventilation [1]. These include indications that are particularly relevant to a patient receiving non-invasive positive pressure ventilation (NPPV) therapy [2] [3][4].

However, during non-invasive ventilation, measuring CO_2 in exhaled gas is difficult because ventilators actively dilute exhaled gas. Obtaining an accurate end-tidal CO_2 measurement requires an adequate amount of expired gas to be filled in a CO_2 measurement cell before the gas from the ventilator arrives to the cell[4].

There are two measurement methods for capnometer: mainstream method and sidestream method. Since the mainstream method uses a direct measurement of the patient exhaled CO_2, this method usually responds well to changes in exhaled CO_2 and rarely causes tube obstruction with water. However, sensors used for the mainstream method are relatively large and heavy so it may not be applicable for non-intubated patients[5][6]. During non-invasive ventilation, if the exhalation port is located close to the CO_2 mesaureing site, it would be difficult to monitor CO_2 acculately as an exhalation port generally flushes out the exhaled CO_2 gas before reaching the CO_2 measuring site[4]. The major problem of CO_2 measurement during non-invasive ventilation is that the choice of CO_2 measurement site location is limited because of the size and weight of the sensor. On the other hand, the sidestream method employs a sampling tube connected to a patient so that a small sampling of the patient's exhaled gas can be drawn into the capnometer for measurement. As the sidestream method generally uses a nasal cannula, which is attached under the patient's nose, the impact of the exhalation port position on the accuracy of CO_2 monitorinng is smaller, unless air flow from the ventilator is quite large. However, the choice of the location of the sampling site raises additional technical and physiologic issues that must be considered, including condensation of sample, obstruction with water, and waveform distortion[4]. According to a pilot clinical research using a side-stream nasal cannula in clinical settings, dislocation of the the nasal cannula during CO_2 measurements turned out to be a major problem[7]. This was probably caused by frequent displacement, due to delirious or restless patients.

A mainstream capnometer cap-ONE® (Nihon Kohden Corporation, Tokyo, Japan) was developed to overcome the disadvantages of both the sidestream method and the conventional mainstream method. cap-ONE is lightweight (4 g) so the choice of CO_2 measurement location is less limited[6][8][9][10][11].

The NPPV cap-ONE mask system, based on the mainstream method, was designed to monitor CO_2 during non-invasive ventilation. In this paper, we report the basic performance of the NPPV cap-ONE mask system as compared to a conventional device evaluated in this study using a breathing model.

II. Material and Methods

A. *NPPV cap-ONE mask system*

NPPV cap-ONE mask (VM-331Z, Nihon Kohden, Tokyo, Japan) and a mainstream capnometer, cap-ONE (TG-980P, Nihon Kohden, Tokyo, Japan), constitute the NPPV cap-ONE mask system. NPPV cap-ONE mask consists of a mask, inner cup, and a CO_2 measurement cell (Fig. 1). The mask, inner cup and CO_2 measuring cell are integrated to prevent dislocation. The NPPV cap-ONE mask system is attached to the patient's face, covering the nose and mouth, as shown in Fig. 2.

The inner cup in the mask is placed under the patient's nose and over the mouth to guide the patient's exhale flow into the CO_2 measurement cell (Fig. 3). The CO_2 measurement cell is connected to the inner cup of NPPV cap-ONE mask. The mainstream capnometer cap-ONE is designed to be placed on the CO_2 measurement cell outside of the mask (Fig. 3, 4).

cap-ONE consists of a light unit and a detector unit, which are located across the CO_2 measurement cell of NPPV cap-ONE mask. Light emitted from the light unit passes

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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].

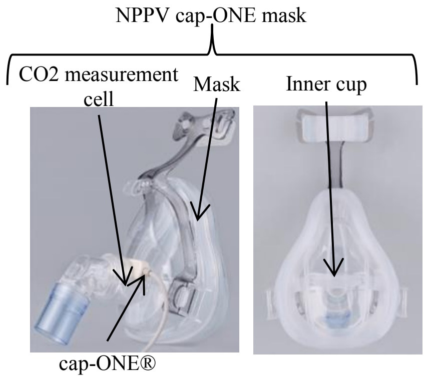

Figure 1. Schematics of NPPV cap-ONE mask system.

Figure 2. NPPV cap-ONE mask system attached on patient.

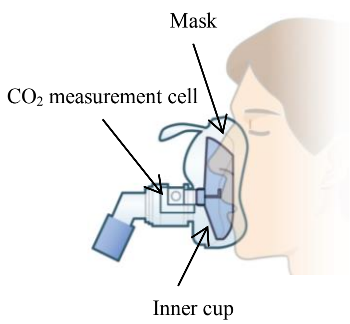

Figure 3. NPPV cap-ONE mask showing cross sectional view.

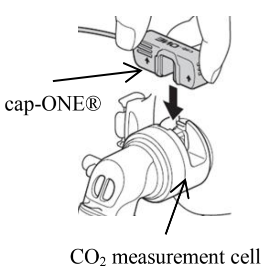

Figure 4. Enlarged view of cap-ONE® and CO2 measurement cell.

B. Conventional Device

The basic performance of the NPPV cap-ONE mask system was evaluated in comparison with the conventional mainstream airway adapter system. An airway adapter (YG-211T, Nihon Kohden, Tokyo, Japan) was connected to NPPV full face mask (VM-331Z, Nihon Kohden, Tokyo, Japan), and cap-ONE was placed on the airway adapter as shown in Fig. 5.

Figure 5. Schematics of airway adapter system.

C. Breathing model

Adult respiratory conditions were simulated using a breathing model, consisting of a lung simulator (ASL-5000, IngMar Medical, Pittsburgh, Pennsylvania), a ventilator (NKV-330, Nihon Kohden, Tokyo, Japan), an adult head manikin, and a mass flow controller (s-B40/B50, HORIBA STEC, Kyoto, Japan) (Fig.6).

The manikin has 2 cavities imitating the nose and mouth of a patient. The inhalation and exhalation airflow passed through the nasal or oral cavity in the manikin. While simulating nasal or oral breathing, the other cavity was sealed with a plastic plug.

CO_2 gas which was regulated by the mass flow controller was continuously supplied to ASL-5000 so that the exhaled airflow contains CO_2. The CO_2 concentration in exhalation at the airway near the manikin was measured as reference (Reference CO_2) by a mainstream capnometer (TG-980P, Nihon Kohden, Tokyo, Japan).

ASL-5000 simulating a patient with a ventilator, has three different ventilation patterns, COPD, ARDS, and Normal (Table 1) [12]. As shown in Table 1, the expiratory positive airway pressure (EPAP) was set at 4 or 8 cmH_2O and inspiratory positive airway pressure (IPAP) was adjusted to be the tidal volume between 250-300 mL.

TABLE I. VENTILATION PATTERN

	COPD	ARDS	NORMAL
RC(s)	1.22	0.47	0.58
respiration rate (breath/min)	13	16	17
EPAP/IPAP (cmH_2O)	13/4 17/8	14/4 18/8	14/4 18/8
Tidal volume(ml)	280 ± 10	260 ± 10	280 ± 10

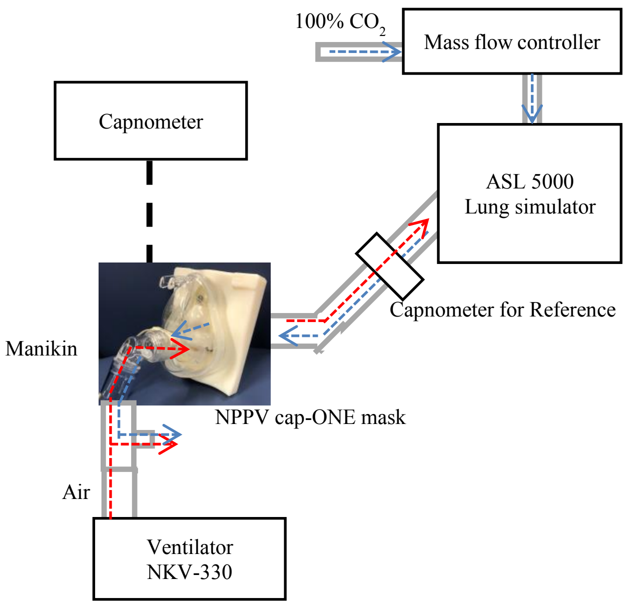

Figure 6. Breathing Model.

D. Data Collection

Both mainstream capnograms of the NPPV cap-ONE mask system and of the airway adapter system were measured by a CO_2 monitor (OLG-2800, Nihon Kohden, Tokyo, Japan).

The maximum amplitude of capnograms was calculated as partial pressure of end-tidal carbon dioxide ($PetCO_2$). CO_2 waveforms were recorded for over 2-minutes in each ventilation pattern and averaged for last 20 breaths.

III. RESULT

1. Capnogram of NPPV cap-ONE mask system

Fig. 7and 8 show a representative capnogram of nasal and oral respiration under the COPD ventilation pattern. The capnogram obtained by the NPPV cap-ONE mask system presented partial loss of plateau in the setting of EPAP at both 4 and 10 cmH_2O. On the other hand, in the capnogram of the airway adapter system, almost all plateau was lost in the setting of EPAP at 4 and 10 cmH_2O. When the EPAP was 8 cmH_2O, the total air leak reached 50 L/min.

2. PetCO2 measurement accuracy of NPPV cap-ONE mask system

The $PetCO_2$ measurement accuracy was evaluated by comparing $PetCO_2$ obtained by the NPPV cap-ONE mask system and the airway adapter system with a reference $PetCO_2$ by the airway adapter (Fig.9, 10). The $PetCO_2$ differences obtained by the NPPV cap-ONE mask system ware more stable than the airway adapter system for all ventilation patterns for both nasal and oral respiration.

IV. DISUCUSSION

The capnogram of the NPPV cap-ONE mask system was much more stable than the airway adapter system during non-invasive ventilation. Exhale flow in plateaus can be easily diluted by air flow from the ventilator, because exhalation flow is small. The NPPV cap-ONE mask is designed to guide the exhaled CO_2 gas to the CO_2 measuring cell using the inner cup before the air flow from the ventilator arrives to the CO_2 measuring cell (Fig. 11). Thereby, CO_2 can be measured during non-invasive ventilation. On the other hand, the waveform of the conventional airway adapter system was not sufficient for accurate measurement of CO_2, because the exhalation port flushes out the exhaled CO_2 gas before reaching the CO_2 measuring cell. Thus, CO_2 cannot be measured during non-invasive ventilation with the conventional system.

The results showed that the NPPV cap-ONE mask system might be useful in clinical use. Further clinical evaluation is necessary to determine the clinical benefits of using the NPPV cap-ONE mask system.

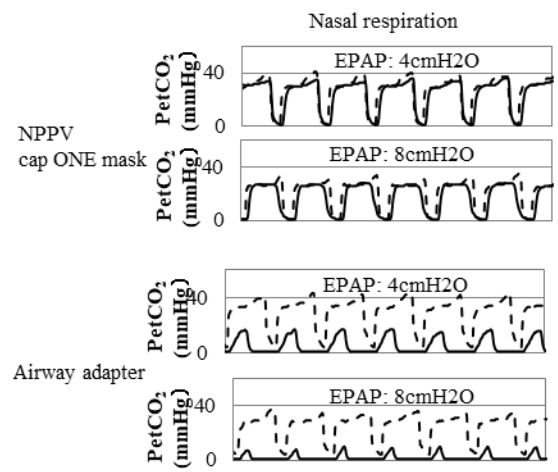

Figure 7. Representative capnogram of nasal respiration with NPPV cap-ONE mask system and airway adapter system.

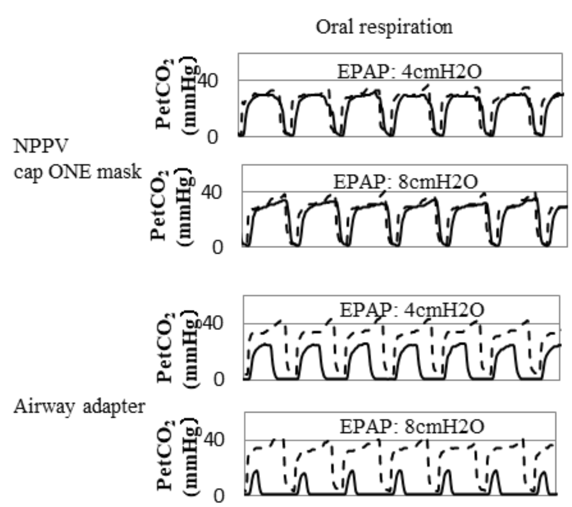

Figure 8. Representative capnogram of oral respiration with NPPV cap-ONE mask system and airway adapter system.

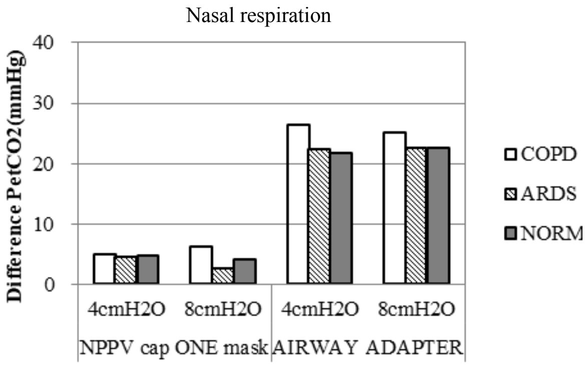

Figure 9. Comparison of NPPV cap-ONE mask system and airway adapter system for partial pressure of end-tidal carbon dioxide (PetCO2) accuracy of nasal respiration

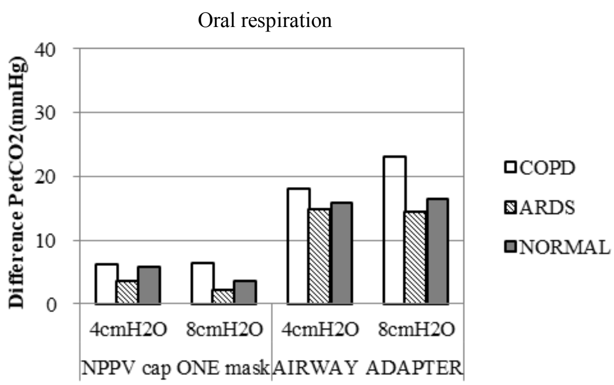

Figure 10. Bench comparison of NPPV cap-ONE mask system and airway adapter system for partial pressure of end-tidal carbon dioxide (PetCO2) accuracy of oral respiration .

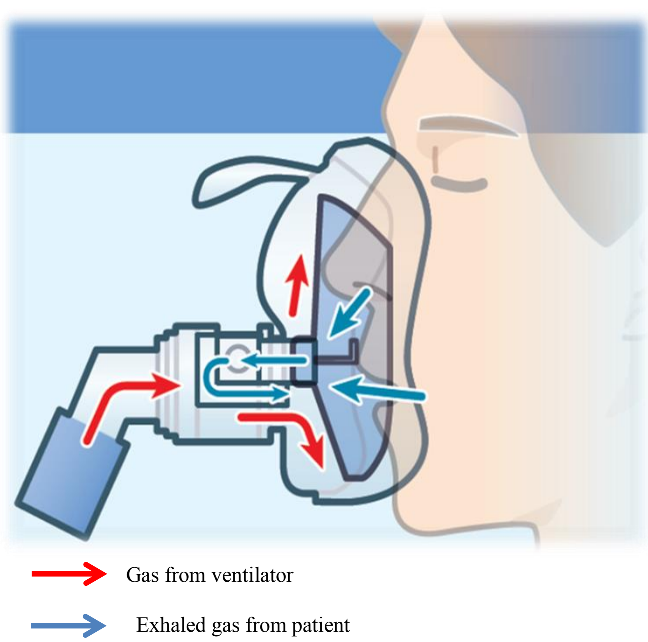

Figure 11. Exhaled gas from patient and gas from ventilator flow dynamics of NPPV cap-ONE mask showing cross sectional view

V. Conclusion

We developed the NPPV cap-ONE mask system to monitor CO_2 during non-invasive ventilation. This study has shown that the CO_2 measurement accuracy of the NPPV cap-ONE mask system may be better compared to the airway adapter system.

References

[1] B. K. Walsh, D. N. Crotwell, and R. D. Restrepo, “Capnography/Capnometry during mechanical ventilation: 2011,” *Respir. Care*, vol. 56, no. 4, pp. 503–509, 2011, doi: 10.4187/respcare.01175.

[2] N. S. Hill, J. Brennan, E. Garpestad, and S. Nava, “Noninvasive ventilation in acute respiratory failure,” *Crit. Care Med.*, vol. 35, no. 10, pp. 2402–2407, 2007, doi: 10.1097/01.CCM.0000284587.36541.7F.

[3] S. Mehta and N. S. Hill, “Noninvasive ventilation,” *Am. J. Respir. Crit. Care Med.*, vol. 163, no. 2, pp. 540–577, 2001, doi: 10.1164/ajrccm.163.2.9906116.

[4] J. S. Gravenstein, Michael B. Jaffe, Nikolaus Gravenstein, and David A, “Capnography in non-invasive positive pressure ventilation, ” Capnography, Second Edition, Section 1 Chapter 15, pp. 135–144, 2011.

[5] M. Weingarten, “Respiratory monitoring of carbon dioxide and oxygen: A ten-year perspective,” *J. Clin. Monit.*, vol. 6, no. 3, pp. 217–225, 1990, doi: 10.1007/BF02832150.

[6] K. Kabumoto, F. Takatori, and M. Inoue, “A novel mainstream capnometer system for endoscopy delivering oxygen,” *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBS*, pp. 3433–3436, 2017, doi: 10.1109/EMBC.2017.8037594.

[7] M. Nouwen, E. Helmich, D. Tjan, and M. Steen, “Side Stream End-Tidal CO2 Monitoring in Subjects Undergoing Non-Invasive Ventilation for Respiratory Failure: A Pilot Study,” *Glob. J. Respir. Care*, vol. 3, no. 0, pp. 1–9, 2016, doi: 10.12974/2312-5470.2016.03.1.

[8] N. Morioka, S. Yamamori, M. Narushima, C. Nozaki, and M. Ozaki, “Evaluation for New Main-Stream Capnography with Sedativenon-Intubated Volunteers in Comparison with Side-Stream Capnography,” *Anesthesiology*, vol. 99, p. A564, 2003.

[9] D. J. Sakata *et al.*, “Flow-through versus sidestream capnometry for detection of end tidal carbon dioxide in the sedated patient,” *J. Clin. Monit. Comput.*, vol. 23, no. 2, pp. 115–122, 2009, doi: 10.1007/s10877-009-9171-2.

[10] Y. Kasuya, O. Akça, D. I. Sessler, M. Ozaki, and R. Komatsu, “Accuracy of postoperative end-tidal Pco2 measurements with mainstream and sidestream capnography in non-obese patients and in obese patients with and without obstructive sleep apnea,” *Anesthesiology*, vol. 111, no. 3, pp. 609–615, 2009, doi: 10.1097/ALN.0b013e3181b060b6.

[11] S. Yamamori, Y. Takasaki, M. Ozaki, and H. Iseki, “A flow-through capnometer for obstructive sleep apnea,” *J. Clin. Monit. Comput.*, vol. 22, no. 3, pp. 209–220, 2008, doi: 10.1007/s10877-008-9126-z.

[12] Jean-Michel Arnal, Aude Garnero, Dominik Novonti, Didier Demory, Laurent Ducros, Audrey Berric, Stéphane Yannis Donati, Gaëlle Corno, Samir Jaber and Jacques Durand-Gasselin, “Feasibility study on full closed-loop control ventilation (IntelliVent-ASV™) in ICU patients with acute respiratory failure: a prospective observational comparative study,” Critical Care 2013, 17:R196.