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Transcutaneous P_{CO_2} monitors are more accurate than end-tidal P_{CO_2} monitors

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Abstract
Purpose. The accuracy of monitors for measuring transcutaneous P_{CO_2} (TcP_{CO_2}), end-tidal P_{CO_2} (EtP_{CO_2}), and nasal EtP_{CO_2} was evaluated.
Methods. The measuring devices included a TcP_{CO_2} monitor (TCM3; Radiometer Trading), an EtP_{CO_2} monitor (Ultima; Datex-Ohmeda), and a nasal EtP_{CO_2} monitor (TG-920P; Nihon Kohden). The sensor electrode of the TCM3 TcP_{CO_2} monitor was applied to the skin of the subject's upper arm. A sampling tube attached to the proximal end of the tracheal tube was connected to the Ultima EtP_{CO_2} monitor. The miniature sensor of the TG-920P nasal EtP_{CO_2} monitor was attached to the nostril. The values obtained were compared with direct measurements of arterial P_{CO_2}(Pa_{CO_2}) obtained by means of an ABL700 blood gas analyzer (Radiometer Trading) in surgically treated patients. The means ± 2 SD of the differences between variables were calculated.
Results. The TcP_{CO_2} monitor (0.19 ± 4.8 mmHg, mean ± 2-SD) was more accurate than the EtP_{CO_2} monitor (–4.4 ± 6.5 mmHg, mean ± 2-SD) in patients receiving artificial ventilation via an endotracheal tube and the TcP_{CO_2} monitor was also more accurate than the nasal EtP_{CO_2} monitor (–6.3 ± 9.8 mmHg, bias ± 2-SD) in patients breathing spontaneously.
Conclusion. We found that the TcP_{CO_2} monitor was more accurate than the EtP_{CO_2} or nasal EtP_{CO_2} monitor in surgically treated patients.

Key words Transcutaneous P_{CO_2} · End-tidal P_{CO_2} · Noninvasive monitor

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Introduction

The Severinghaus-type electrode is often used to determine Pa_{CO_2}, but it requires invasive measures, such as arterial blood sampling by arterial puncture and the intravascular placement of an electrode. Therefore, efforts have been made to develop noninvasive methods for Pa_{CO_2} measurement. Such noninvasive methods include the measurement of transcutaneous P_{CO_2} (TcP_{CO_2}) and end-tidal P_{CO_2} (EtP_{CO_2}).

The measurement of EtP_{CO_2} is useful when sudden changes in ventilation must be monitored. Because of its accuracy, noninvasiveness, continuity, and response time, a TcP_{CO_2} monitor is also useful when patients have a large arterial-alveolar P_{CO_2} difference or are undergoing laparoscopic surgery.

The present study compared these methods and assessed their accuracy with measurements from a TcP_{CO_2} monitor (TCM3; Radiometer Trading, Copenhagen, Denmark), and two types of EtP_{CO_2} monitors (a sidestream-type monitor [Ultima; Datex-Ohmeda, Wisonsin, USA] and a nasal mainstream-type monitor [TG-920P; Nihon Kohden, Tokyo, Japan]).

Subjects, materials, and methods

This study was performed at The Jikei University School of Medicine, Tokyo. The protocol was approved by the ethics committee of the institution. Informed consent was obtained from each subject. The measurement procedures with the three instruments are described below. Data obtained were analyzed by plotting the differences with directly measured Pa_{CO_2}.

The monitors were calibrated for each patient in accordance with the manufacturers' instructions. A blood gas analyzer (ABL700; Radiometer Trading) was used to measure Pa_{CO_2}. Two-point calibration was performed for the instrument.

Study 1. Measurements with the TCM3 TcP_{CO_2} monitor and the Ultima EtP_{CO_2} monitor in patients ventilated mechanically

The TCM3 monitor was used to measure TcP_{CO_2} and the Ultima monitor was used to measure EtP_{CO_2} in 15 adult Japanese patients who had undergone surgical procedures in the abdomen under general anesthesia via tracheal intubation. All patients had an American Society of Anesthesiologists (ASA) risk classification grade of I to III. The patients were 10 men and 5 women, 60 ± 12 years in age (mean ± SD), 55 ± 10 kg in weight, and 160 ± 8 cm in height. Anesthesia was maintained with mechanical ventilation, 3 l·min^{-1} of oxygen, 3 l·min^{-1} of nitrous oxide, and 0.5% to 2.5% of sevoflurane, 0.5% to 2.0% of isoflurane, or propofol-midazolam-fentanyl. Tidal volume was set at 10 ml·kg^{-1} of body weight and the minute volume was adjusted between 2.2 and 12.6 l during the experiment. Concurrent epidural anesthesia with 0.375% to 0.75% ropivacaine was also used as required depending on the surgical procedure performed. The sensor electrode of the TCM3 TcP_{CO_2} monitor was applied to the skin of the medial aspect of the upper arm and was set to a temperature of 44°C.

To measure EtP_{CO_2}, a sampling tube attached to the proximal end of the tracheal tube was connected to an Ultima EtP_{CO_2} monitor. After TcP_{CO_2} and EtP_{CO_2} had been stabilized for 15 min, a sample of arterial blood was collected, and the Pa_{CO_2} was determined with the ABL700 blood gas analyzer and compared with TcP_{CO_2}. or EtP_{CO_2}. The measurements were performed a total of 60 times at different Pa_{CO_2} levels.

Study 2. Measurement with the TCM3 TcP_{CO_2} monitor and the TG-920P nasal EtP_{CO_2} monitor in patients breathing spontaneously

The TCM3 TcP_{CO_2} monitor was used to measure TcP_{CO_2} and the TG-920P nasal EtP_{CO_2} monitor was used to measure EtP_{CO_2} in 24 Japanese adults with an ASA risk classification grade of I or II who had undergone a surgical procedure of the abdomen under general anesthesia via tracheal intubation, had regained consciousness, had their tracheal tubes removed, and were being observed in the recovery room. The patients were 12 men and 12 women, 60 ± 14 years in age (mean ± 2-SD), 59 ± 15 kg in weight, and 159 ± 6 cm in height. The electrode was attached to the skin of the medial aspect of the upper arm and set to a temperature of 44°C. The TG-920P nasal EtP_{CO_2} monitor is designed to directly measure the P_{CO_2} in expired gas from the nasal cavity or mouth by means of a miniature sensor attached to the nostril. Oxygen was delivered at a rate of 5 l·min^{-1} via a face tent. After ventilation had stabilized for 5 min, the measurement was performed, and, at the same time, arterial blood samples were obtained. The Pa_{CO_2} was determined with the ABL700 blood gas analyzer and compared with the measured TcP_{CO_2} or nasal EtP_{CO_2}.

Results

Study 1. Measurements with the TCM3 TcP_{CO_2} monitor and the Ultima EtP_{CO_2} monitor in patients ventilated mechanically

Measurements with the TCM3 TcP_{CO_2} monitor

The measured Pa_{CO_2} values ranged from 30 to 45 mmHg, with a mean of 0.19 mmHg and a 2-SD value of 4.8 mmHg (Fig. 1, Table 1). These means and 2-SD values indicate that the monitor performed adequately.

There was no significant difference between 0 and the mean of 0.19 ($P = 0.555$, one-point t-test).

Measurements with the Ultima EtP_{CO_2} monitor

The Pa_{CO_2} values ranged from 30 to 45 mmHg, with a mean of –4.4 mmHg and a 2-SD value of 6.5 mmHg (Fig. 2, Table 1). The mean values obtained with the Ultima monitor showed a greater bias than did the mean values obtained with the TCM3 TcP_{CO_2} monitor, but the 2-SD value was appropriate.

There was a significant difference between 0 and the mean of –4.4 ($P < 0.0001$, one point t-test). There was also a significant difference between the mean of 0.19 in the TCM3 TcP_{CO_2} monitor and the mean of –4.4 in the Ultima EtP_{CO_2} monitor ($P < 0.001$; paired t-test).

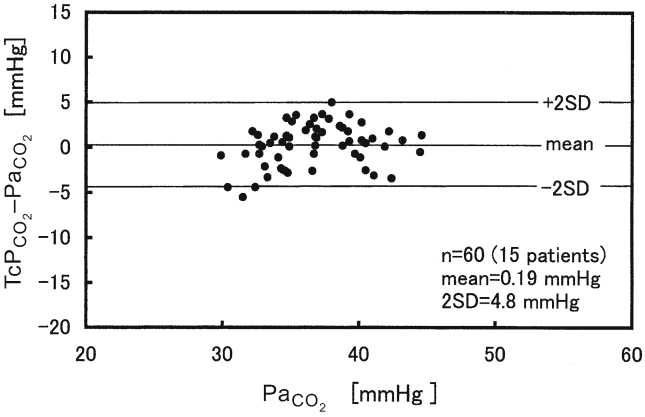

Fig. 1. Measurements with the TCM3 (Radiometer) transcutaneous P_{CO_2} (TcP_{CO_2}) monitor in patients ventilated mechanically. Data obtained were analyzed by plotting the difference between TcP_{CO_2} and Pa_{CO_2} against Pa_{CO_2}. The values for Pa_{CO_2} ranged from 30 to 45 mmHg, with a mean of 0.19 mmHg and a 2-SD value of 4.8 mmHg

Table 1. Summary of results from studies 1 and 2

Study no.	Ventilation	Number of patients	*n*	EtP_{CO_2} monitor	TcP_{CO_2} monitor	Pa_{CO_2} monitor	Measurement	Mean	2SD	Fig. no.
1	Mechanical	15	60	Ultima (Datex-Ohmeda)	TCM-3 (Radiometer)	ABL-700 (Radiometer)	TcP_{CO_2}-Pa_{CO_2}	0.19	4.8	1
							EtP_{CO_2}-Pa_{CO_2}	–4.4	6.5	2
2	Spontaneous	24	24	TG-920P (Nihon-Kohden)	TCM-3	ABL-700	TcP_{CO_2}-Pa_{CO_2}	0.48	8.2	3
							EtP_{CO_2}-Pa_{CO_2}	–6.3	9.8	4

The measurement data obtained were compared against Pa_{CO_2}. The means ± 2-SD of the difference between these two variables were calculated. The TcP_{CO_2} monitor was more accurate than the EtP_{CO_2} monitor and the nasal EtP_{CO_2} monitor

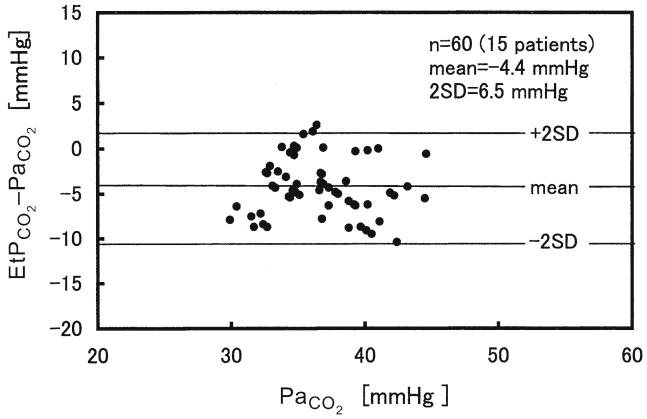

Fig. 2. Measurements with the Ultima (Datex-Ohmeda) end-tidal P_{CO_2} (EtP_{CO_2}) monitor in patients ventilated mechanically. Data obtained were analyzed by plotting the difference between EtP_{CO_2} and Pa_{CO_2} against Pa_{CO_2}. The values for Pa_{CO_2} ranged from 30 to 45 mmHg, with a mean of –4.4 mmHg and a 2-SD value of 6.5 mmHg

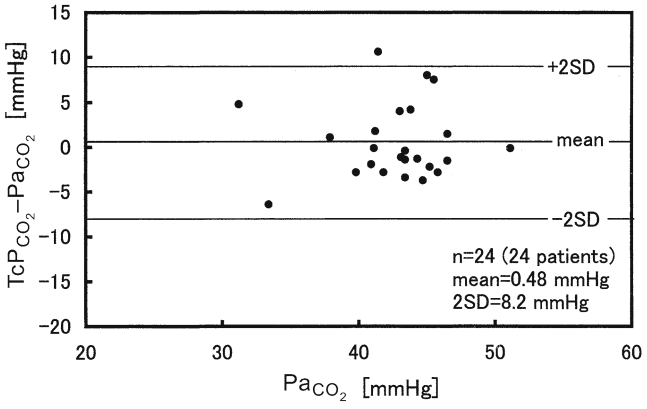

Fig. 3. Measurements with the TCM3 TcP_{CO_2} monitor in patients breathing spontaneously: data obtained were analyzed by plotting the difference between TcP_{CO_2} and Pa_{CO_2} against Pa_{CO_2}. The values for Pa_{CO_2} ranged from 31 to 51 mmHg, with a mean of 0.48 mmHg and a 2-SD value of 8.2 mmHg

Study 2. Measurement with the TCM3 TcP_{CO_2} monitor and the TG-920P nasal EtP_{CO_2} monitor in patients breathing spontaneously

Measurement with the TCM3 TcP_{CO_2} monitor

The Pa_{CO_2} values ranged from 31 to 51 mmHg, with a mean of 0.48 mmHg and a 2-SD value of 8.2 mmHg (Fig. 3, Table 1). Although the bias was small, the 2-SD value was considerably greater than that obtained with the same device in the tracheally intubated patients (4.8 mmHg).

There was no significant difference between 0 and the bias of 0.48 ($P = 0.534$ one-point *t*-test).

Measurements with the TG-920P nasal EtP_{CO_2} monitor

The Pa_{CO_2} values ranged from 31 to 51 mmHg, with a mean of –6.3 mmHg and a 2-SD value of 9.8 mmHg (Fig. 4, Table 1). The bias was slightly lower than that of the Ultima EtP_{CO_2} monitor in tracheally intubated patients, but there were noticeable variations, whereas the 2-SD value was nearly twice as great as those with the TcP_{CO_2} monitors. During the expiratory phase we did not observe an obvious plateau, a finding suggesting that the measured end-expiratory P_{CO_2} may be erroneous. Ventilatory frequency was 15 ± 5.1 times·min^{-1} (mean ± SD) in this group.

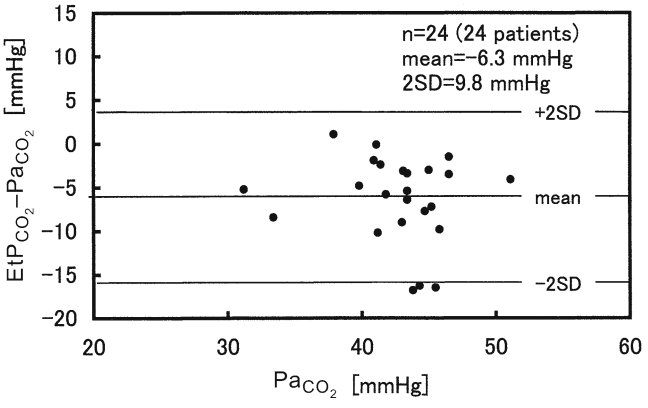

Fig. 4. Measurement with the TG-920P (Nihon-Kohden) nasal EtP_{CO_2} monitor in patients breathing spontaneously: data obtained were analyzed by plotting the difference between nasal EtP_{CO_2} and Pa_{CO_2} against Pa_{CO_2}. The values for Pa_{CO_2} ranged from 31 to 51 mmHg, with a mean of –6.3 mmHg and a 2-SD value of 9.8 mmHg

There was a significant difference between 0 and the mean of –6.3 ($P < 0.0001$, one-point *t*-test). There was also a significant difference between the mean of 0.48

in the TCM3 TcP_{CO_2} monitor and the mean of –6.3 in the TG-920P nasal EtP_{CO_2} monitor ($P < 0.001$, paired *t*-test).

Discussion

In the present study, the accuracy of monitors for measuring TcP_{CO_2}, EtP_{CO_2}, and nasal EtP_{CO_2} was evaluated. The measuring devices used were a TcP_{CO_2} monitor (TCM3; Radiometer), an EtP_{CO_2} monitor (Ultima; Datex-Ohmeda), and a nasal EtP_{CO_2} monitor (TG-920P; Nihon Kohden). In previous studies, the mean ± 2-SD of the difference between two variables was not fixed, being, for example, 0 ± 7 when the sensor was mounted on the trunk or extremities [1] and 1.22 ± 7.38 [2] or 1.2 ± 12 [3] when the sensor was attached to an ear lobe. Also, the nasal EtP_{CO_2} sensor was said to be useful only for indicating the presence of ventilatory movement, and its accuracy had not been evaluated. We performed the present study because we were not aware of any study comparing these instruments.

Bland-Altman analysis is performed to compare measured values obtained with an experimental method and values obtained with a standard method by exploring the range of dispersion of plots of mean measured values on the abscissa against their differences on the ordinate [4]. However, Kagawa and Severinghaus [5] have shown that measured Pa_{CO_2} values rather than mean values for Pa_{CO_2} and TcP_{CO_2} should be displayed on the abscissa, when the Pa_{CO_2} determined with a Severinghaus electrode is considered the gold standard. Unlike in other studies [1,3,6–8] using Bland-Altman analysis, in the present study the Pa_{CO_2} was displayed on the abscissa.

If the ± 2-SD of the difference between two variables against Pa_{CO_2} is within the clinically acceptable range, the results of the analysis are interpreted as indicating a satisfactory agreement of the data between the two methods; a smaller SD indicates a better degree of agreement.

In patients receiving artificial ventilation via tracheal intubation, the TCM3 monitor showed 2-SD values of 4.8 mmHg, which were within the clinically acceptable range of measurement. Values obtained with the Ultima EtP_{CO_2} monitor showed a mean of –4.4 mmHg and were sufficiently accurate if this bias value was added to the measured values.

In conscious, spontaneously breathing patients recovering from general anesthesia, the data from the nasal EtP_{CO_2} measured with the TG-920P monitor showed a mean of –6.3 mmHg and a 2-SD value as large as 9.8 mmHg. The TG-920P monitor was designed to measure P_{CO_2} in expired air during breathing either through the nose or the mouth [9]; however, values obtained during spontaneous breathing may be considerably less accurate than values obtained under artificial ventilation via tracheal intubation. The data from concurrent TcP_{CO_2} monitoring with the TCM3 obtained under spontaneous ventilation were not encouraging.

The present data have shown that the accuracy of the TcP_{CO_2} monitor was greater than that of the EtP_{CO_2} monitor, but the data did vary with the conditions of use.

The accuracy of TcP_{CO_2} monitors has been controversial. Herrejon et al. [10], Cuvelier et al. [11], and Janssens et al. [12] have demonstrated that values obtained with a TcP_{CO_2} monitor are accurate in adult patients with respiratory disorders, healthy adult volunteers, and elderly subjects breathing spontaneously, respectively. Casati et al. [13] have found that a TcP_{CO_2} monitor is more accurate than an EtP_{CO_2} monitor in subjects receiving artificial ventilation via tracheal intubation, a result consistent with our present findings. In addition, Dullenkopf et al. [14] and Tingay et al. [7] have also reported that a TcP_{CO_2} monitor is more accurate than an EtP_{CO_2} monitor in infants and newborns receiving artificial ventilation. Bendjelid et al. [3] have reported that evaluating Pa_{CO_2} data on the basis of TcP_{CO_2} values is clinically acceptable, although the relationship between TcP_{CO_2} and Pa_{CO_2} varies in patients breathing spontaneously in the intensive care unit. In contrast, Nishiyama et al. [1] have suggested that absolute TcP_{CO_2} values determined with a TCM4 monitor are unreliable and cannot replace Pa_{CO_2} measurements in patients receiving artificial ventilation via a tracheal tube under general anesthesia. Aliwalas et al. [15] have obtained similar results in critically ill preterm infants receiving artificial ventilation.

How can the discrepancy between these conclusions be explained? Two possible causes of the discrepancy can be considered. One possible cause is the time lag involved in the determination of TcP_{CO_2}. Nishiyama et al. [1] have reported time lags of 120 s or longer, and Eberhard et al. [2] have shown that 2.5 min is needed for an electrode to indicate a change in arterial blood. It is quite natural that a difference is noted between Pa_{CO_2} and TcP_{CO_2} if a respiratory change, however small, occurs to alter Pa_{CO_2}; this difference may have accounted for the discrepancy in performance reported in these articles. Another possible cause is the stability of the electrode itself. Domingo et al. [6] have reported that 20 min is needed for an electrode to stabilize. Kagawa and Severinghaus [5] and Kagawa et al. [16] have demonstrated that measured TcP_{CO_2} values are too high for 20 min after electrode attachment, thereby interfering with accurate measurement. These two factors may have contributed to the differences in the conclusions of these articles.

In the present study, therefore, we took into account respiratory stability during measurement and the time

after attachment of the electrode. The TcP_{CO_2} is considered to reflect Pa_{CO_2} well, as long as these possible sources of inaccuracy are considered, and may be useful for testing for apnea in possible cases of brain death, during bronchoscopic examinations, and in sleep studies where there is no method of continuously estimating Pa_{CO_2} [17–20].

If the respiratory condition is stabilized, the above results and considerations have led to the following conclusions: (1) in patients receiving artificial ventilation via a tracheal tube, a TcP_{CO_2} monitor and an EtP_{CO_2} monitor show clinically acceptable accuracy, with the TcP_{CO_2} monitor being more accurate; and (2) in patients breathing spontaneously after extubation, the TcP_{CO_2} monitor is more accurate than a nasal EtP_{CO_2} monitor.

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