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Effects of the electrode temperature of a new monitor, TCM4, on the measurement of transcutaneous oxygen and carbon dioxide tension

Tomoki Nishiyama[1], Shinji Nakamura[1], and Koichi Yamashita[2]

[1] Department of Anesthesiology, The University of Tokyo, Faculty of Medicine, Tokyo, Japan
[2] Department of Anesthesiology and Critical Care Medicine, Kochi University Medical School, Kochi, Japan

Abstract
The transcutaneous measurement of oxygen (tcP_{O_2}) and carbon dioxide (tcP_{CO_2}) tensions may serve as a surrogate of arterial oxygen (Pa_{O_2}) and carbon dioxide (Pa_{CO_2}) tensions, respectively. We investigated the effects of the electrode temperature of a new device, TCM4, on the measurement of tcP_{O_2} and tcP_{CO_2}. Twenty-five patients scheduled for major lower abdominal surgery were enrolled. The electrode of the TCM4 was attached to the chest, with its temperature set to 37°C, 40°C, 42°C, 43°C, or 44°C. tcP_{O_2}, tcP_{CO_2}, end-tidal carbon dioxide tension (Et_{CO_2}), Pa_{O_2}, and Pa_{CO_2} were simultaneously measured at various Et_{CO_2} levels and inhaled oxygen concentrations. The times required for stabilization of the tcP_{O_2} and tcP_{CO_2} values were measured. A Bland-Altman plot was used to compare the two measurements. The time required for stabilization was shorter with a higher electrode temperature, but the shortest time was still more than 150s. TcP_{O_2} correlated well with Pa_{O_2} at 43°C and 44°C. TcP_{CO_2} correlated well with Pa_{CO_2} and Et_{CO_2} at 43°C. The bias and limits of agreement were larger with lower electrode temperature for TcP_{O_2}—Pa_{O_2}, tcP_{CO_2}—Pa_{CO_2}, and tcP_{CO_2}—Et_{CO_2}. We concluded that the electrode of the TCM4 should be heated to at least 43°C to measure tcP_{O_2} and tcP_{CO_2}. However, the absolute values of tcP_{O_2} and tcP_{CO_2} could not be used as surrogate measurements of Pa_{O_2} and Pa_{CO_2}, respectively.

Key words Transcutaneous oxygen tension · Transcutaneous carbon dioxide tension · Electrode temperature

Percutaneous oxygen saturation (Sa_{O_2}) determined by pulse oximetry, is now routinely used to determine oxygenation. However, Sa_{O_2} measures oxygen binding to hemoglobin, not dissolved oxygen measured as arterial oxygen tension (Pa_{O_2}). End-tidal carbon dioxide tension (Et_{CO_2}), measured with a capnograph, is commonly used as a surrogate measurement of arterial carbon dioxide tension (Pa_{CO_2}). However, Et_{CO_2} is sometimes inaccurate when used for patients without intubation. Transcutaneous measurements of oxygen (tcP_{O_2}) and carbon dioxide (tcP_{CO_2}) tensions have been investigated for their correlation with Pa_{O_2} and Pa_{CO_2}, respectively [1–4]. In these studies, the electrodes were heated to 42°C to 44°C to measure tcP_{O_2} and tcP_{CO_2}. However, the higher electrode temperature increases burn injury. Therefore, a lower temperature is preferable. Recently, a new device, TCM4 (Radiometer, Copenhagen, Denmark) to measure tcP_{O_2} and tcP_{CO_2} has been developed to stabilize the electrode faster than the previous devices. There are no studies investigating the effects of the electrode temperature of the TCM4 on the measurement of tcP_{O_2} and tcP_{CO_2}. We therefore investigated the effects of the electrode temperature of the TCM4 on the measurement of tcP_{O_2} and tcP_{CO_2} during general anesthesia.

After obtaining the approval of the University of Tokyo Hospital and informed consent from the patients, 25 patients, aged 40 to 70 years, scheduled for major lower abdominal surgery in the supine position, were enrolled in the present study. Those who were obese (body mass index >25), and those who had respiratory, cardiac, or vascular disease were excluded. Anesthesia was performed with an epidural block, using mepivacaine, fentanyl, vecuronium, propofol infusion, and nitrous oxide in oxygen. Bladder temperature was monitored and a warming blanket was used to maintain body temperature. Blood pressure was kept in the range of ±20% of the patient's usual blood pressure. An arterial catheter was inserted in the left radial artery to measure Pa_{O_2} and Pa_{CO_2}. Et_{CO_2} was measured using the Ultima (Datex-Ohmeda, Helsinki, Finland). TcP_{O_2} and tcP_{CO_2} were measured with the TCM4, with the electrode attached to the chest (left side between the clavicle and nipple). Pa_{O_2} and Pa_{CO_2} were measured with the ABL 625 (Radiometer). Respiration was controlled by a ventilator and Et_{CO_2} was randomly changed be-

Address correspondence to: T. Nishiyama
3-2-6-603 Kawaguchi, Kawaguchi 332-0015, Japan
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tween 20 and 50 mmHg. Inspiratory oxygen concentration was also changed at random between 21% and 100%. The measurements was done at least 10 min after changing the ventilator setting or oxygen concentration. The electrode of the TCM4 was set to 37°C, 40°C, 42°C, 43°C, or 44°C. TcP_{O_2}, tcP_{CO_2}, Et_{CO_2}, Pa_{O_2}, and Pa_{CO_2} were simultaneously measured at various Et_{CO_2} levels and inhaled oxygen concentrations. In total, 40 measurements were done for each temperature. At the start of each measurement, the times required for stabilization of the tcP_{O_2} and tcP_{CO_2} values were measured. Correlations between the parameters were analyzed by linear regression analysis. A Bland-Altman plot was used to compare the two measurements, using the bias (the mean of the differences) and limits of agreement (bias ± 2SD of bias) [5].

There were 16 male and 9 female patients, aged 61 ± 8 years, with body weight 63 ± 11 kg and height, 164 ± 6 cm. Colectomy was done in 8 patients, sigmoidectomy in 8, resection of the uterus in 4, and resection of the bladder in 5. Duration of surgery was 279 ± 85 min. Bladder temperature was between 35.0°C and 37.3°C. The time required for stabilization was shorter with a higher electrode temperature, with no differences among 40°C, 42°C, and 43°C for tcP_{CO_2}, while the shortest time was 150 s (Fig. 1). TcP_{O_2} correlated well with Pa_{O_2} at 43°C and 44°C (Fig. 2). TcP_{CO_2} correlated well with Pa_{CO_2} and Et_{CO_2} at 43°C. The bias and limits of agreement were larger with lower electrode temperature for TcP_{O_2}—Pa_{O_2}, tcP_{CO_2}—Pa_{CO_2}, and tcP_{CO_2}—Et_{CO_2} (Fig. 2).

Considering the correlation coefficient, bias, and limits of agreement in the present study, an electrode temperature of at least 43°C was necessary for tcP_{O_2} and tcP_{CO_2} measurements with the TCM4. However, the absolute values of tcP_{O_2} and tcP_{CO_2} could not be used as

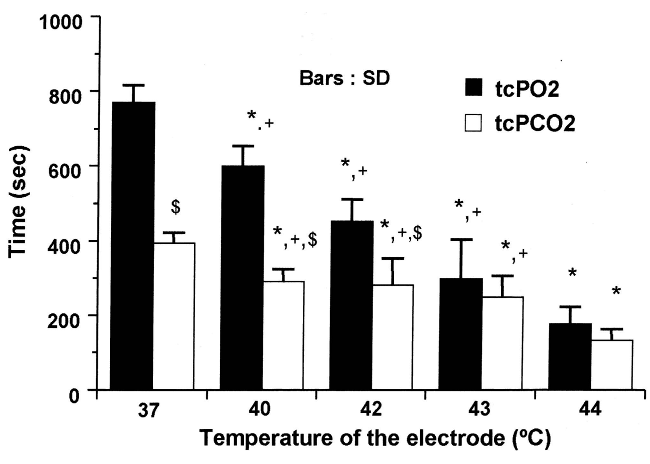
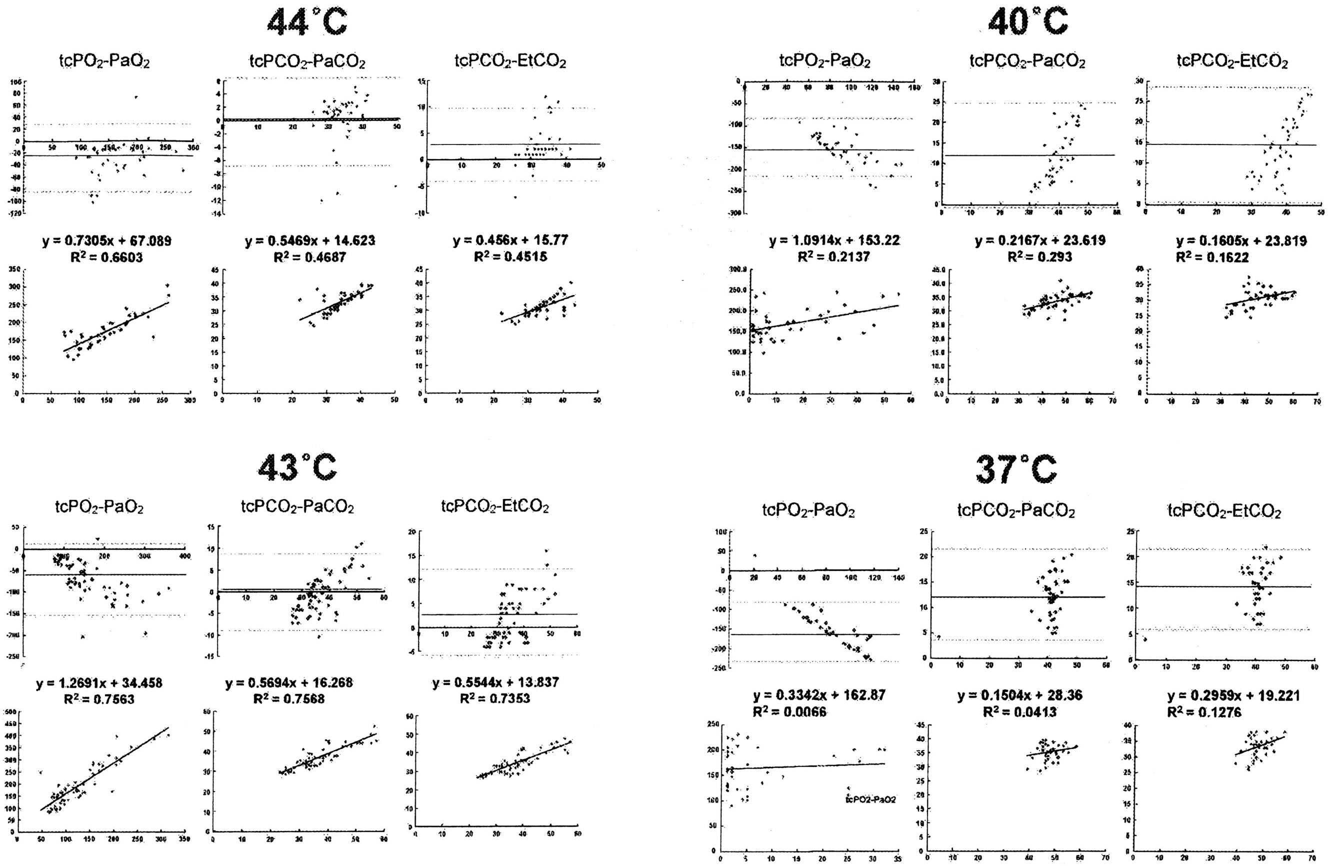


Fig. 1. Time required for stabilization of measurements. * $P < 0.05$ vs 37°C; $^{+}P < 0.05$ vs 44°C; $^{\$}P < 0.05$ vs tcP_{O_2}

surrogate measurements of Pa_{O_2} and Pa_{CO_2}, respectively, due to the large limits of agreement. The 95% response time of tcP_{O_2} to the change in inhaled oxygen concentration was reported to be about 2 min [6]. Et_{CO_2} changes almost immediately, but there is a short lag period for tcP_{CO_2}, due to the time of transmission from the pulmonary capillaries to the measurement site. These findings suggested that, in the present study, a 10-min interval between the measurements and changing the ventilator setting or oxygen concentration might be enough to stabilize the electrode. However, it took more than 150 s to stabilize the electrode. Therefore, this is not useful for emergency use, but is still suitable for elective use.

The limit of 4 h at 43°C must be considered as a rule for safety, but some have reported no skin burn after 6 to 8 h at electrode temperatures of 43°C to 44°C [7–11]. Although no burn injury was observed in the present study with the maximum duration of 2 h at 44°C, the electrode temperature should be as low as possible. The lowest reported electrode temperature used for tcP_{CO_2} has been 42°C [12]. However, in the present study, we did not find a good correlation between tcP_{CO_2} and Pa_{CO_2} at 42°C. In neonates [13] and infants [14], the correlation coefficient between tcP_{CO_2} and Pa_{CO_2} was high enough to be clinically applicable, while in adults in the present study, using a new device, the correlation coefficient was still not as high as that in children. The tcP_{CO_2} is increased by 4% for every 1°C rise in electrode temperature between 37°C and 45°C, caused by arterialization of capillaries [15] and by increased CO_2 production in the skin [16]. Therefore, tcP_{CO_2} is usually higher than Pa_{CO_2}. The tcP_{CO_2}/Pa_{CO_2} ratio was reported to be 1.4 with an electrode temperature of 44°C [17]. In the present study, tcP_{CO_2} at 43°C and 44°C, was closer to Pa_{CO_2} than in the previous studies and this may have been due to calculated corrections for the device.

Heating the skin beyond 40°C changes its structure, and this change is thought to allow oxygen to diffuse faster [18], and to increase the local oxygen tension by shifting the oxyhemoglobin dissociation curve [19]. These effects partially compensate for the P_{O_2} diffusion gradient between the capillary blood and the electrode face. Therefore, in subjects with a normal circulatory state, the tcP_{O_2}/Pa_{O_2} ratio typically ranges from 0.7 to 0.9 [2,3]. Individual transcutaneous values were reported to differ by as much as 50 mmHg from arterial values [20]. In the present study, the difference between tcP_{O_2} and Pa_{O_2} was over 50 mmHg at an electrode temperature of less than 43°C. For tcP_{O_2}, an electrode temperature of at least 43°C was reported to be necessary to produce a reasonable correlation between tcP_{O_2} and capillary P_{O_2} [21]. This is consistent with our present results, using the new TCM4 device. Sympathetic block with epidural mepivacaine may have some effects on the measure-



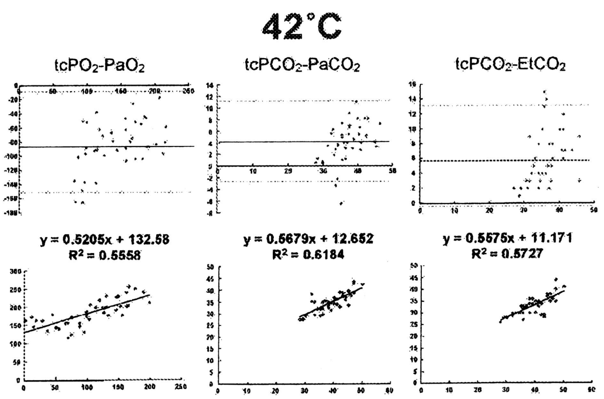


Fig. 2. Effects of the temperature. Bland-Altman plots (*upper graphs*) and scatter plots (*lower graphs*) are shown. In the upper graphs, the *y* axis shows tcP_{O_2}—Pa_{O_2} (*right*), tcP_{CO_2}—Pa_{CO_a} (*middle*) and tcP_{CO_2}—Et_{CO_2} (*left*). *Solid lines* indicate bias (mean of the difference) and *dotted lines* indicate limits of agreement (bias ± 2 SD of bias). In the *lower graphs*, the *y* axis shows Pa_{O_2} (mmHg) and the *x* axis shows tcP_{O_2} (mmHg) (*right*); the *y* axis shows Pa_{CO_2} (mmHg) and the *x* axis shows tcP_{CO_2} (mmHg) (*center*); and the *y* axis shows Et_{CO_2} (mmHg) and the *x* axis shows tcP_{CO_2} (mmHg) (*left*)

ment of tcP_{O_2}. Although we did not check the level of the epidural block in our subjects, it was performed for lower abdominal surgery; therefore, the level could have been lower than the place where the electrode was attached. In addition, even if the sympathetic activity electrode of the area had been blocked, vasodilatation produced by general anesthesia and the heating of the skin may have had a nontrivial effect on the results.

In conclusion, the electrode of the TCM4 should be heated to at least 43°C, to measure tcP_{O_2} and tcP_{CO_2}. However, the absolute values of these parameters could not be used as surrogate measurements of Pa_{O_2} and Pa_{CO_2}, respectively.

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