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CLINICAL TRIAL REPORT

Strategy to Reduce Hypercapnia in Robot-Assisted Radical Prostatectomy Using Transcutaneous Carbon Dioxide Monitoring: A Prospective Observational Study

Hyun Jung Lee[1], Ji Seon Chae[2], Sang-Mee An[2], Hye-Won Oh[1], Youn Jin Kim[1], Jae Hee Woo[1]

[1]Department of Anesthesiology and Pain Medicine, College of Medicine, Ewha Womans University, Seoul, South Korea; [2]Department of Anesthesiology and Pain Medicine, Ewha Womans University Seoul Hospital, Seoul, South Korea

Correspondence: Jae Hee Woo, Department of Anesthesiology and Pain Medicine, College of Medicine, Ewha Womans University, 260 Gonghangdaero, Gangseo-gu, Seoul, 07804, South Korea, Tel +82-2-6986-4300, Fax +82-2-6986-4960, Email jheewoo@ewha.ac.kr

Purpose: Monitoring end-tidal carbon dioxide partial pressure ($P_{ET}CO_2$) is a noninvasive, continuous method, but its accuracy is reduced by prolonged capnoperitoneum and the steep Trendelenburg position in robot-assisted radical prostatectomy (RARP). Transcutaneous carbon dioxide partial pressure ($P_{TC}CO_2$) monitoring, which is not affected by ventilator–perfusion mismatch, has been suggested as a suitable alternative. We compared the agreement of noninvasive measurements with the arterial carbon dioxide partial pressure ($PaCO_2$) over a long period of capnoperitoneum, and investigated its sensitivity and predictive power for detecting hypercapnia.

Patients and Methods: The patients who underwent RARP were enrolled in this study prospectively. Intraoperative measurements of $P_{ET}CO_2$, $P_{TC}CO_2$, and $PaCO_2$ were analyzed. The primary outcome was the agreement of noninvasive monitoring with $PaCO_2$ during prolonged capnoperitoneum. Bias and precision between noninvasive measurements and $PaCO_2$ were assessed using Bland–Altman analysis. The bias and mean absolute difference were compared using a two-tailed Wilcoxon signed-rank test for pairs. The secondary outcome was the sensitivity and predictive power for detecting hypercapnia. To assess this, the Yates corrected chi-square test and the area under the receiver operating characteristic curve were used.

Results: The study analyzed 219 datasets from 46 patients. Compared with $P_{ET}CO_2$, $P_{TC}CO_2$ had lower bias, greater precision, and better agreement with $PaCO_2$ throughout the RARP. The mean absolute difference in $P_{ET}CO_2$ and $PaCO_2$ was larger than that of $P_{TC}CO_2$ and $PaCO_2$, and continued to exceed the clinically acceptable range of 5 mmHg after 1 hour of capnoperitoneum. The sensitivity during capnoperitoneum and overall predictive power of $P_{TC}CO_2$ for detecting hypercapnia were significantly higher than those of $P_{ET}CO_2$, suggesting a greater contribution to ventilator adjustment, to treat hypercapnia.

Conclusion: $P_{TC}CO_2$ monitoring measured $PaCO_2$ more accurately than $P_{ET}CO_2$ monitoring during RARP requiring prolonged capnoperitoneum and a steep Trendelenburg position. $P_{TC}CO_2$ monitoring also provides more sensitive measurements for ventilator adjustment and detects hypercapnia more effectively than $P_{ET}CO_2$ monitoring.

Keywords: intraoperative carbon dioxide monitoring, capnoperitoneum, robotic surgery, end-tidal carbon dioxide monitoring, general anesthesia

Introduction

Estimation of the arterial carbon dioxide partial pressure ($PaCO_2$) by direct analysis of arterial blood gases is the gold standard for monitoring carbon dioxide during general anesthesia. However, because the direct measurement of $PaCO_2$ is invasive and intermittent, end-tidal carbon dioxide partial pressure ($P_{ET}CO_2$) monitoring is preferred for the continuous monitoring of carbon dioxide.[1] An important limitation of $P_{ET}CO_2$ monitoring is its reduced accuracy due to factors such as ventilation-perfusion mismatch, shunt, and the surgical position of the patient, including the Trendelenburg or lateral decubitus position.[2]

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Transcutaneous carbon dioxide partial pressure ($P_{TC}CO_2$) monitoring offers an alternative, noninvasive method for the continuous measurement of $PaCO_2$ from arterialized capillary blood in tissues. Unlike $P_{ET}CO_2$ monitoring, it is not influenced by ventilation–perfusion mismatch. The accuracy of $P_{TC}CO_2$ has been proven in pediatric patients, thoracic anesthesia, and laparoscopic surgery.[3–5]

Robot-assisted radical prostatectomy (RARP) for the treatment of prostate cancer requires that the patient should be placed in the steep Trendelenburg position, followed by the inflation of carbon dioxide gas into the peritoneal cavity to improve the surgical view and reduce bleeding. As a result, the organs in the abdominal cavity are pushed towards the diaphragm, thereby reducing both the functional residual volume and lung compliance. In addition, in robot-assisted surgery, the angle of the surgical table is steeper than the angle used in other laparoscopic surgeries, which may worsen ventilation-perfusion mismatch and cause pronounced intraoperative hypercapnia.[6,7] RARP is mainly performed in the elderly, in whom a higher risk for intraoperative hypercapnia has been attributed to the age-related decline in lung function.[8] In addition, subcutaneous emphysema is more common in this population due to weakened tissue, which in turn also contributes to the development of hypercapnia, acidosis and therefore sympathetic excitation, tachycardia, hypertension, hyperkalemia, and other complications.[9,10] As these complications may be lethal in older patients with preexisting cardiac and pulmonary disease, it is important to maintain normocapnia during RARP by accurately monitoring $PaCO_2$.

We hypothesized that, compared to $P_{ET}CO_2$ monitoring, $P_{TC}CO_2$ monitoring provides a more accurate approximation of $PaCO_2$ and contributes more to ventilator adjustment during RARP performed in patients in a steep Trendelenburg position and under prolonged capnoperitoneum. Therefore, this prospective study evaluated the accuracy of two noninvasive monitoring systems, $P_{TC}CO_2$ and $P_{ET}CO_2$, and the predictive power of each in detecting hypercapnia.

Materials and Methods

Participants

This study prospectively included 46 patients classified as American Society of Anesthesiologists physical status I–III scheduled for RARP from January 2020 to April 2021. Patients with a history of severe cardiovascular or respiratory disease, neuromuscular disease, a body mass index > 35 kg/m^2, or who required a vasoconstrictor during surgery were excluded.

Anesthesia

General anesthesia was induced with propofol (1–2 mg/kg), fentanyl (1–2 µg/kg), and rocuronium (0.6 mg/kg). Then the trachea was intubated, and the lungs were mechanically ventilated under pressure-controlled ventilation volume-guaranteed with a tidal volume of 8 mL per predicted body weight, and an I:E ratio of 1:2 with a positive end-expiratory pressure of 5 cmH_2O and a respiratory rate of 10 respirations per minute. The tidal volume was reduced by 25 mL to maintain a peak inspiratory pressure < 35 cmH_2O. At $P_{ET}CO_2$ > 40 mmHg or a $P_{TC}CO_2$ > 45 mmHg, the respiratory rate was increased appropriately and arterial blood gases (ABG) were simultaneously analyzed. Anesthesia was maintained using 1–1.5 minimum alveolar concentration of desflurane using 50% oxygen in air. A bolus of fentanyl or remifentanil infusion was administered as needed to ensure a bispectral index value between 40 and 60 and a systolic blood pressure within 20% of baseline. Patients who required a vasoconstrictor to increase blood pressure during surgery were removed from the study.

Intraoperative Monitoring

Intraoperative monitoring included an electrocardiogram, pulse oxygen saturation, noninvasive blood pressure, arterial blood pressure, peak airway pressure, and oropharyngeal body temperature. The patient's body temperature was kept at 36–37°C. $P_{ET}CO_2$ was monitored using a side-stream infrared CO_2 analyzer (Avance CS^2, GE Healthcare, Madison, WI, USA). $P_{TC}CO_2$ was measured using a TCM4 device (Radiometer, Copenhagen, Denmark). Before its placement, the electrode was cleaned, a new membrane was applied, and the device was calibrated according to the manufacturer's recommendation. The electrode was placed on the upper left chest and set at a working temperature of 42°C. The skin where the electrode was placed was swabbed with alcohol to facilitate adhesion of the disc to the skin. Capnoperitoneum was established and the intra-abdominal pressure (IAP) was maintained at 15–20 mmHg at the surgeon's discretion.

Outcome Assessment

The primary outcome was the agreement of noninvasive monitoring ($P_{TC}CO_2$ and $P_{ET}CO_2$) with $PaCO_2$. To assess of this, ABG were sampled and noninvasive monitoring measurements were recorded in the pre-capnoperitoneum state in a supine position, 30 minutes after CO_2 insufflation in the Trendelenburg position and every hour thereafter or whenever the $P_{TC}CO_2$ was > 45 mmHg or the $P_{ET}CO_2$ was > 40 mmHg, and 20 minutes after CO_2 deflation on resumption of the supine position. The first ABG sampling was conducted when the patient's blood pressure and heart rate had stabilized and the respiratory rate was constant for at least 5 minutes after tracheal intubation. The TCM4 device was calibrated in vivo based on the results of the first ABG analysis. We calculated the differences and absolute differences between the noninvasive monitoring values ($P_{TC}CO_2$ and $P_{ET}CO_2$) and $PaCO_2$. The absolute differences were determined because negative numbers would artificially lower the mathematical mean of the difference. An absolute difference of 5 mmHg was defined as within the clinically acceptable range indicative of the interchangeability of the two methods.[10,11] The secondary outcomes were the sensitivity and predictive power for detecting hypercapnia, defined as $PaCO_2$ > 45 mmHg, which would be the basis for deciding to adjust the ventilator settings. To assess these, $P_{TC}CO_2$ and $P_{ET}CO_2$ were dichotomized at $P_{TC}CO_2$ > 45 mmHg and $P_{ET}CO_2$ > 40 mmHg. No data were recorded within 30 minutes after the occurrence of an already-recorded hypercapnia event to avoid bias due to over-representation of any single hypercapnia event. $P_{TC}CO_{2,}$ $PaCO_{2,}$ $P_{ET}CO_2$, arterial blood pressure, heart rate, oropharyngeal temperature, and IAP were recorded simultaneously.

Statistical Analysis

The sample size was calculated using G*Power (ver. 3.1.4). This indicated that 48 subjects were required to achieve a 90% power to detect a 7.5 mmHg difference (with $\alpha = 0.05$) between the two methods with an estimated standard deviation of 15 mmHg using a paired *t*-test and a 10% dropout rate. This difference was based on a previous study.[12]

The statistical analyses were performed using SPSS ver. 26.0 (SPSS, USA). Quantitative data are presented as the mean ± standard deviation (SD) or median (interquartile range [IQR]) depending on the normality of the distribution. Correlation analysis with Pearson's correlation coefficient (*r*) was used to establish the relationship between the two noninvasive measurements ($P_{TC}CO_2$ and $P_{ET}CO_2$) and $PaCO_2$. To evaluate their agreement with $PaCO_2$, the bias (mean difference between the noninvasive monitoring values and $PaCO_2$) and precision (SD of the bias) were evaluated, using Bland–Altman analysis. The reliability of noninvasive monitoring was compared using the mean absolute difference, using a two-tailed Wilcoxon signed-rank test for pairs after assessing normality. Chi-square analysis or Fisher's exact test was used to compare the number of data with an absolute difference exceeding 5 mmHg. The sensitivity of the two noninvasive CO_2 monitoring systems for detecting hypercapnia was compared using Yates corrected chi-square method. The predictive power for detecting hypercapnia was compared by constructing a receiver operating characteristic curve and calculating the area under the curve (AUC). A P-value < 0.05 was considered statistically significant.

Results

Subject Characteristics

Of the 67 patients assessed for eligibility, 19 were excluded and 48 patients were enrolled in the study. Two patients were removed because they required vasoconstrictors during surgery to treat low blood pressure. Ultimately, the final analysis included 219 datasets from 46 patients (Figure 1).

All patients were male, with a mean age of 67.93 ± 9.30 years. Table 1 summarizes the patients' demographic factors and surgical characteristics. All patients underwent RARP performed by either of two surgeons. The angle of the operation table was 28°–30°, which was the maximum angle of the two tables used in our hospital. Thirty-two patients were placed in 28° of Trendelenburg and 14 patients at 30°. The IAP was maintained between 15 and 20 mmHg according to the surgeon's preference. The mean duration of capnoperitoneum was 175.93 ± 41.26 minutes and the mean body temperature of the patients during surgery was 36.10 ± 0.32°C. No complications related to prolonged $P_{TC}CO_2$ monitoring occurred.

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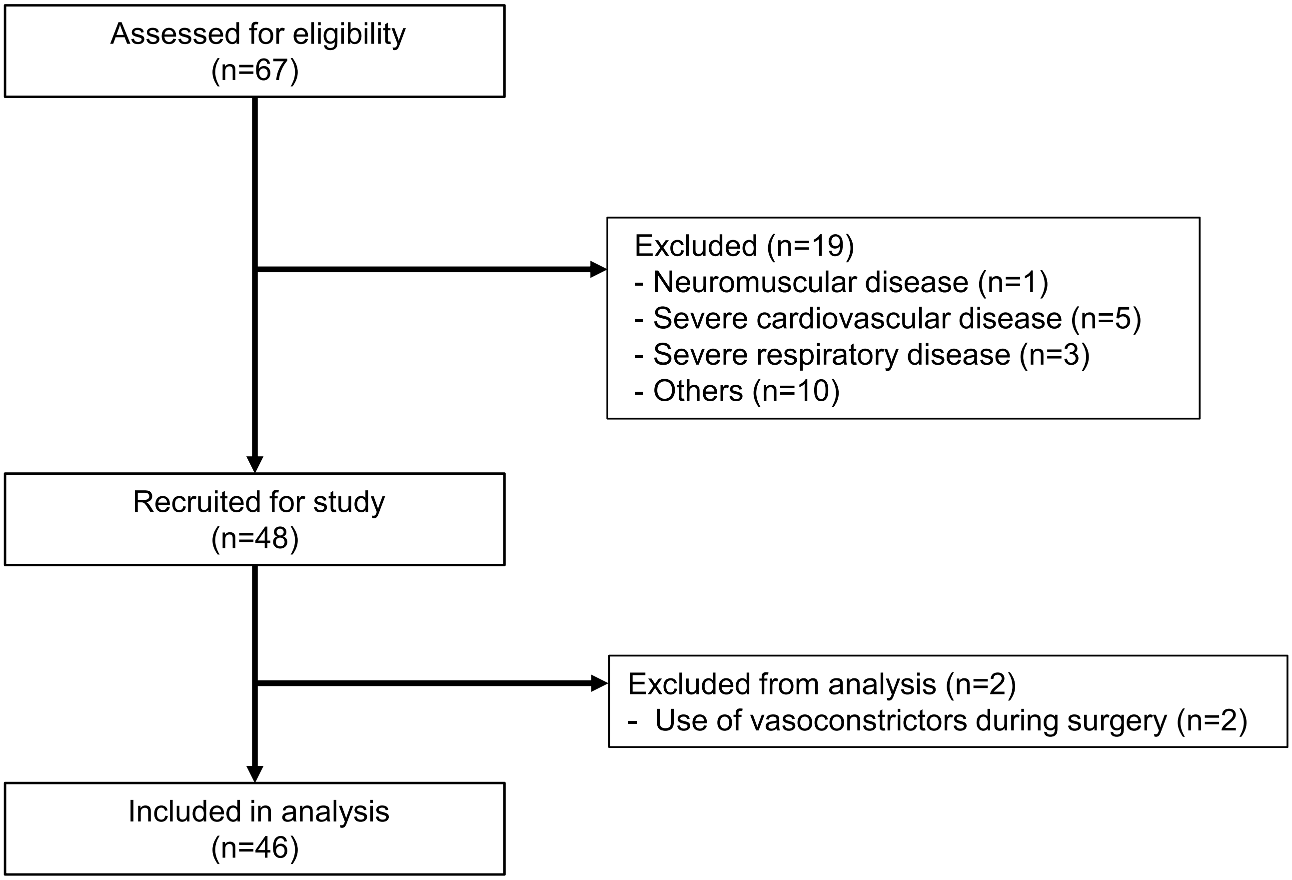

Figure 1 Flow chart of participant recruitment.

Primary Outcome

Table 2 gives the mean values of $PaCO_2$, $P_{ET}CO_2$, and $P_{TC}CO_2$ before, during, and after capnoperitoneum. Correlation analysis at each time-point showed correlations between $P_{TC}CO_2$ and $PaCO_2$ (r = 0.99, 0.84, 0.67, respectively; $P < 0.05$), and between $P_{ET}CO_2$ and $PaCO_2$ (r = 0.70, 0.70, 0.57, respectively; $P < 0.05$). Bland–Altman analysis indicated

Table 1 Clinical and Surgical Characteristics of the Patients (n = 46)

Variables	Data
Age (year)	67.93 ± 9.30
Sex	Male
Weight (kg)	70.12 ± 12.73
Height (cm)	166.15 ± 7.66
BMI (kg/m^2)	25.29 ± 3.31
ASA physical status classification: I/II/III (n)	3 /38/ 5
FEV_1(L)	2.78 ± 0.64
FVC (L)	3.80 ± 0.68
Non-smoker/ex-smoker/current-smoker (n)	20/15/11
Maximum table angle (°)	28 (28–30)
IAP (mmHg)	12.61 ± 3.13
Capnoperitoneum time (min)	175.93 ± 41.26

Notes: Data are expressed as the mean ± SD, median (interquartile range) or number of patients.
Abbreviations: BMI, body mass index; ASA, American Society of Anesthesiologists; $FEV_{1,}$ forced expiratory volume in one second; FVC, forced vital capacity; IAP, intra-abdominal pressure.

Table 2 Correlation Analysis of $P_{ET}CO_2$ and $PaCO_2$, $P_{TC}CO_2$, and $PaCO_2$ at Three Time Points

Variable	Pre-Capnoperitoneum, Supine Position		During Capnoperitoneum, Trendelenburg Position		Post-Capnoperitoneum, Supine Position	
	(mmHg)	r	(mmHg)	r	(mmHg)	r
$PaCO_2$	35.67 ± 4.03	-	41.70±5.88	-	41.06 ± 4.65	-
$P_{ET}CO_2$	33.28 ± 3.54	0.70[a]	36.38±5.17	0.70[a]	34.61 ± 4.25	0.57[a]
$P_{TC}CO_2$	35.46 ± 4.21	0.99[a]	42.13±7.22	0.84[a]	41.33 ± 6.59	0.67[a]

Notes: Values are expressed as the mean ± SD. *r* represents Pearson's correlation coefficient. [a]P <0.05.

better agreement with lower bias and higher precision of $P_{TC}CO_2$ for $PaCO_2$ compared with $P_{ET}CO_2$ (Figure 2). As shown in Table 3, the mean absolute difference between $PaCO_2$ and $P_{TC}CO_2$ was smaller than the difference between $P_{ET}CO_2$ and $PaCO_2$ at all time points, indicating better reliability. The $P_{ET}CO_2$ continued to differ from $PaCO_2$ by more than 5 mmHg after 1 h of CO_2 insufflation. Of the 219 datasets, an absolute difference ≥ 5 mmHg was observed in 100 $P_{ET}CO_2$ datasets (45.7%) and in 28 $P_{TC}CO_2$ datasets (12.79%).

Secondary Outcome

During surgery, the respiratory rate was adjusted 51 times in 31 patients, according to the CO_2 management protocol. The increment in the respiratory rate was made based on the $P_{TC}CO_2$ in 23 times (45.10%), on the $P_{ET}CO_2$ in 9 times (17.65%), and on both parameters in 19 times (37.25%). There were 37 hypercapnia events in 19 patients; 28 during capnoperitoneum and nine after CO_2 deflation. Of the 28 events during capnoperitoneum, a $P_{TC}CO_2$ > 45 mmHg occurred in 23 events and a $P_{ET}CO_2$ > 40 mmHg in 14 events. Using the predefined cut-off values of $P_{TC}CO_2$ > 45 mmHg and $P_{ET}CO_2$ > 40 mmHg, the sensitivity of two monitoring methods was 82.14% and 50.0%, respectively (P = 0.024). Of the nine events after CO_2 deflation, $P_{TC}CO_2$ > 45 mmHg occurred in seven events, and $P_{ET}CO_2$ > 40 mmHg in two. The sensitivity of $P_{TC}CO_2$ and $P_{ET}CO_2$ monitoring was 77.78% and 22.22%, respectively (P = 0.059).

The AUC [95% confidence interval (CI)] of $P_{TC}CO_2$ at detecting $PaCO_2$ > 45 mmHg during and after capnoperitoneum was 0.88 (0.82–0.95) and 0.90 (0.78–1.00), respectively. The corresponding AUCs (95% CI) of the $P_{ET}CO_2$ were 0.81 (0.71–0.90) and 0.80 (0.62–0.98), respectively. The overall AUC value of $P_{TC}CO_2$ was significantly higher than that of $P_{ET}CO_2$ (0.916 vs 0.826; P = 0.044).

A Case Report

One case merits further discussion (Table 4). In an 82-year-old patient with moderate aortic regurgitation and mild chronic obstructive pulmonary disease (COPD), $P_{TC}CO_2$ increased suddenly after 2 minutes of CO_2 gas insufflation, from 37 to 46 mmHg, whereas the $P_{ET}CO_2$ increased slowly to 40 mmHg. Subcutaneous emphysema was detected by palpating the upper chest. After the surgeon was notified, the respiratory rate was adjusted from 10 to 12 respirations per minute. During the subsequent 30 minutes of capnoperitoneum, CO_2 retention continued, resulting in $PaCO_2$, $P_{ET}CO_2$, and $P_{TC}CO_2$ values of 65.7, 55, and 78 mmHg, respectively, despite increasing the respiratory rate to 20 respirations per minute and lowering the IAP from 20 to 12 mmHg. The ABG analysis showed a pH of 7.186, indicative of acidosis. Approximately 1 h later, there was little change in his $PaCO_2$ (66.1 mmHg); his $P_{ET}CO_2$ decreased to 49 mmHg but his $P_{TC}CO_2$ decreased only slightly, to 72 mmHg. The highest $P_{ET}CO_2$ value after the detection of subcutaneous emphysema was 55 mmHg, whereas the $P_{TC}CO_2$ peaked at 89 mmHg. Twenty minutes after CO_2 deflation, the patient's $PaCO_2$ was 40.8 mmHg and his $P_{ET}CO_2$ 36 mmHg, but his $P_{TC}CO_2$ was still elevated at 64 mmHg. The patient completed RARP without conversion to open surgery.

Discussion

This study demonstrated the superior accuracy of transcutaneous carbon dioxide measurement over $P_{ET}CO_2$ monitoring to estimate $PaCO_2$ during RARP. $P_{TC}CO_2$ is more sensitive in detecting hypercapnia during prolonged capnoperitoneum,

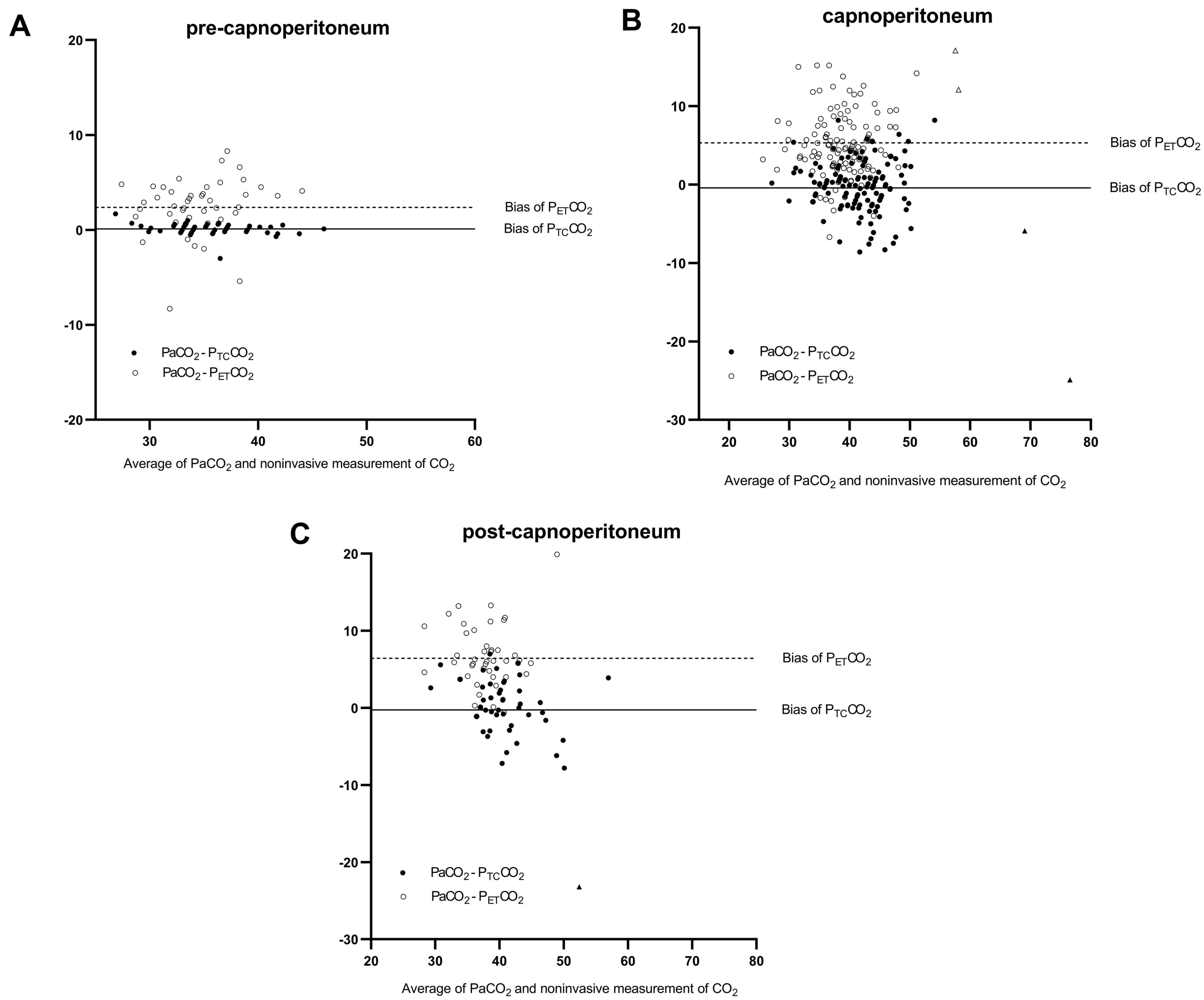

Figure 2 Agreement of two noninvasive monitoring systems ($P_{TC}CO_2$ and $P_{ET}CO_2$) and $PaCO_2$ by Bland–Altman analysis. Black circles indicate the difference in $PaCO_2$ and $P_{TC}CO_2$ and white circles indicate the difference in $PaCO_2$ and $P_{ET}CO_2$. (**A**) During the pre-capnoperitoneum period in the supine position, the difference between $PaCO_2$ and $P_{TC}CO_2$ converged on zero, while the difference between $PaCO_2$ and $P_{ET}CO_2$ was greater than zero and the range of agreement was wider. (**B**) During the period of capnoperitoneum in a steep Trendelenburg position, the difference between $PaCO_2$ and $P_{TC}CO_2$ was closer to zero than the difference between $PaCO_2$ and $P_{ET}CO_2$. The triangles indicate the data for the patient with subcutaneous emphysema: black triangles are the difference between $PaCO_2$ and $P_{TC}CO_2$ and white triangles the difference between $PaCO_2$ and $P_{ET}CO_2$. (**C**) During the post-capnoperitoneum period in the supine position, the bias in the $P_{ET}CO_2$ remained higher, even after CO_2 deflation. The black triangle indicates the difference in $PaCO_2$ and $P_{TC}CO_2$ for the patient with subcutaneous emphysema.

which can otherwise lead to respiratory acidosis. The combined use of $P_{TC}CO_2$ and $P_{ET}CO_2$ monitoring may enable anesthesiologists to provide more meticulous ventilator management.

A previous study reported the inconsistent correlation between $P_{ET}CO_2$ and $PaCO_2$ after CO_2 inflation in laparoscopic surgeries with prolonged capnoperitoneum.[10] In morbidly obese patients undergoing laparoscopic bariatric surgery, capnoperitoneum may exacerbate a reduction in the functional residual capacity and increase ventilation–perfusion mismatch, thereby diminishing the accuracy of $P_{ET}CO_2$.[11] In our study, the correlation of $P_{TC}CO_2$ and $P_{ET}CO_2$ with $PaCO_2$ decreased as capnoperitoneum was prolonged. The mean absolute difference between $PaCO_2$ and $P_{ET}CO_2$ exceeded 5 mmHg after 1 h of capnoperitoneum.[10,13,14] By contrast, the mean absolute difference between $PaCO_2$ and $P_{TC}CO_2$ was $<$ 5 mmHg throughout the period of capnoperitoneum. The scatter diagram of $P_{ET}CO_2$ and $PaCO_2$ on a Bland–Altman plot also showed many data points outside the acceptable range, indicating poor agreement between $PaCO_2$ and $P_{ET}CO_2$.

Table 3 Bias and Mean Absolute Difference Between $PaCO_2$ and Noninvasive Measurements

	Pre-Capnoperitoneum in the Supine Position	During Capnoperitoneum in the Steep Trendelenburg Position			20 min After CO_2 Deflation and Resumption of Supine Position
		0.5 h	1.5 h	2.5 h	
$PaCO_2$ and $P_{TC}CO_2$ (mmHg)					
Bias[a,b]	0.20 (−0.81–1.22)	−0.14 (−2.42–4.80)	−0.33 (−3.67–7.16)	−0.82 (−11.66–10.01)	−0.27 (−4.72–9.38)
Mean absolute difference[a,c]	0.30 (0.20–0.50)	1.50 (0.70–2.73)	2.60 (0.55–4.60)	2.2 (0.93–4.00)	2.65 (0.98–4.38)
$PaCO_2$ and $P_{ET}CO_2$ (mmHg)					
Bias[a,b]	2.38 (−3.43–8.19)	3.47 (−3.57–10.51)	5.65 (−3.08–14.37)	7.29 (−0.63–15.21)	6.45 (−1.63–14.53)
Mean absolute difference[a,c]	3.05 (1.70–4.50)	3.60 (2.05–5.43)	5.50 (2.80–9.20)	7.2 (4.40–10.08)	5.95 (4.08–8.43)

Notes: [a]$P < 0.001$; The two-tailed Wilcoxon signed-rank test was used to compare pairs. [b]Values are expressed as bias (95% limits of agreement), [c]Values are expressed as the median (interquartile range).
Abbreviation: h, hour or hours.

The bias in the $PaCO_2$ and $P_{TC}CO_2$ in our study was much smaller than reported in previous studies.[15] This was likely to be because none of our patients experienced severe hypercapnia and acidosis, which were avoided by the meticulous adjustments that were made based on both $P_{TC}CO_2$ and $P_{ET}CO_2$ monitoring, with the exception of a single case of subcutaneous emphysema. The respiratory rate was adjusted in 45% of the cases based on the $P_{TC}CO_2$ values compared to 19% based on $P_{ET}CO_2$ values, highlighting that the additional use of $P_{TC}CO_2$ monitoring can compensate for the deficiencies of $P_{ET}CO_2$ monitoring. Considering previous reports of an increasing difference between $PaCO_2$ and $P_{TC}CO_2$ along with an increase of $PaCO_2$ levels,[16,17] the relatively small change in the $PaCO_2$ levels of our patients may account for the discrepancy. In addition, the stable cardiovascular function of the patients, the exclusion of those with severe lung diseases, and the maintenance of a constant body temperature during surgery may have reduced the bias in the $PaCO_2$ and $P_{TC}CO_2$ values in this study.

Previous studies raised concerns about the limitations of $P_{TC}CO_2$ measurements, such as the relatively slow response time, difficulty maintaining good contact between the patient's skin and the sensor, and the long warm-up time needed for the sensor to reach its final operating temperature. In addition, the variability in skin thickness at the sensor attachment site may affect the accuracy of the $P_{TC}CO_2$ measurements. Nishiyama et al[18,19] reported that the $PaCO_2$ was more precisely measured by attaching the electrode to the chest rather than to the upper arm, forearm, or earlobe. In our

Table 4 $PaCO_2$, $P_{ET}CO_2$ and $P_{TC}CO_2$ in a Patient with Subcutaneous Emphysema

	Supine Position	2 min	30 min	60 min	120 min	20 min After CO_2 Deflation and Resumption of the Supine Position
		After Capnoperitoneum and the Steep Trendelenburg Position				
pH	7.431	7.381	7.186	7.178	7.179	7.299
$PaCO_2$ (mmHg)	37.5	44.6	65.7	66.1	64.1	40.8
$P_{ET}CO_2$ (mmHg)	33	40	55	49	52	36
$P_{TC}CO_2$ (mmHg)	37	46	78	72	89	64

Notes: subcutaneous emphysema was detected just after CO_2 insufflation. Note the earlier increase in the $P_{TC}CO_2$ along with an increase in $PaCO_2$. The highest value of $P_{ET}CO_2$ was 55 mmHg, although the $PaCO_2$ had increased to 65.7 mmHg.
Abbreviation: min, minutes.

patients, the electrode was attached to the upper left area of the chest, where adherence of the disc to the skin could be checked by the anesthesiologist even when the patient was in the steep Trendelenburg position during RARP. Skin tissue perfusion is one of the most important factors determining the accuracy and precision of $P_{TC}CO_2$. A low environmental temperature causes vascular contraction in the skin, reducing blood flow. Bladder irrigation, which is frequently performed during urological surgery, may also cause a drop in the patient's body temperature. In our patients, efforts were therefore made to maintain their body temperature, such as by using heated breathing circuits, an intravenous fluid warmer, and a forced-air warming system and by maintaining the temperature of the operating room above 23°C. The accuracy of $P_{TC}CO_2$ monitoring in patients administered vasoconstrictors is a matter of debate. Rodriguez et al[20] reported that catecholamine support did not affect the accuracy $P_{TC}CO_2$ monitoring, but other studies came to the opposite conclusion.[12,14,16,21] In our study, two patients who needed a vasoconstrictor to increase their intraoperative blood pressure were excluded from the final analysis, to eliminate a possible confounder.

In the aforementioned patient with subcutaneous emphysema, $P_{TC}CO_2$ increased more rapidly than $P_{ET}CO_2$ because the former was measured in an area of subcutaneous emphysema. Likewise, the $P_{TC}CO_2$ decreased slowly because of the accumulated CO_2 at that site. Because the development of subcutaneous emphysema in the chest area is common during robotic surgery with the patient in the Trendelenburg position, the attachment of a sensor to the chest area would allow the rapid detection of subcutaneous emphysema. However, once the $P_{TC}CO_2$ increases, it would overestimate the $PaCO_2$ due to the accumulation of CO_2 in the subcutaneous layer.

We initially attempted to compare the decreasing trends in $P_{ET}CO_2$ and $P_{TC}CO_2$ with the decrease in $PaCO_2$ during CO_2 elimination. However, the brief time (< 30 minutes) from the end of capnoperitoneum to extubation was insufficient for the cutaneous capillary and systemic $PaCO_2$ to reach equilibrium, thus ruling out a comparison. Nonetheless, our results showed that the superiority of $P_{TC}CO_2$ over $P_{ET}CO_2$ was maintained even during the CO_2 elimination period after CO_2 insufflation was ended. Further studies are needed to determine whether the good correlation between $P_{TC}CO_2$ and $PaCO_2$ is retained after CO_2 elimination.

The limitations to our study include the following. First, only healthy male patients without significant co-morbidities were enrolled, such that our findings may not be generalizable to patients with severe coexisting conditions. In addition, patients treated with vasoactive drugs were excluded from our study, although transcutaneous monitoring might be advantageous for sedated patients in the intensive care unit who often need vasoactive drugs.

Conclusion

In conclusion, $P_{TC}CO_2$ monitoring was more accurate than $P_{ET}CO_2$ monitoring for measuring $PaCO_2$ and was better able to detect hypercapnia in surgery requiring prolonged capnoperitoneum and the steep Trendelenburg position. Because capnography enables the detection of acute life-threatening events, such as apnea, airway obstruction, ventilator disconnection, or esophageal intubation, $P_{TC}CO_2$ cannot substitute for $P_{ET}CO_2$. Nonetheless, it is valuable as an adjunct method in situations in which ventilation–perfusion mismatch interferes with the gradient between $P_{ET}CO_2$ and $PaCO_2$.

Abbreviations

$P_{ET}CO_2$, end-tidal carbon dioxide partial pressure; $P_{TC}CO_2$, transcutaneous carbon dioxide partial pressure; RARP, robot-assisted radical prostatectomy; $PaCO_2$, arterial carbon dioxide partial pressure; AUC, area under the curve; ABG, arterial blood gases; IAP, intra-abdominal pressure; SD, standard deviation; IQR, interquartile range; CI, confidence interval; COPD, chronic obstructive pulmonary disease.

Data Sharing Statement

The individual deidentified raw data that support the study findings are available from the corresponding author upon reasonable request.

Ethics Approval and Consent for Publication

This study was approved by the Ethics Committee of Ewha Womans University, Seoul, South Korea (SEUMC 2019–10–013–002). This study was registered with the Clinical Trial Registry of Korea (registration identifier: KCT0004680, cris.nih.go.kr) before patient recruitment. The written informed consent was obtained from all patients. It was also obtained for publication of case details with unidentifiable information. This study was conducted in accordance with the Declaration of Helsinki.

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Disclosure

All authors report no conflicts of interest arising from this work.

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