RESEARCH ARTICLE

Noninvasive Measurement of Carbon Dioxide during One-Lung Ventilation with Low Tidal Volume for Two Hours: End-Tidal versus Transcutaneous Techniques

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Abstract

Background

There may be significant difference between measurement of end-tidal carbon dioxide partial pressure ($PetCO_2$) and arterial carbon dioxide partial pressure ($PaCO_2$) during one-lung ventilation with low tidal volume for thoracic surgeries. Transcutaneous carbon dioxide partial pressure ($PtcCO_2$) monitoring can be used continuously to evaluate $PaCO_2$ in a noninvasive fashion. In this study, we compared the accuracy between $PetCO_2$ and $PtcCO_2$ in predicting $PaCO_2$ during prolonged one-lung ventilation with low tidal volume for thoracic surgeries.

Methods

Eighteen adult patients who underwent thoracic surgeries with one-lung ventilation longer than two hours were included in this study. Their $PetCO_2$, $PtcCO_2$, and $PaCO_2$ values were collected at five time points before and during one-lung ventilation. Agreement among measures was evaluated by Bland-Altman analysis.

Results

Ninety sample sets were obtained. The bias and precision when $PtcCO_2$ and $PaCO_2$ were compared were 4.1 ± 6.5 mmHg during two-lung ventilation and 2.9 ± 6.1 mmHg during one-lung ventilation. Those when $PetCO_2$ and $PaCO_2$ were compared were -11.8 ± 6.4 mmHg during two-lung ventilation and -11.8 ± 4.9 mmHg during one-lung ventilation. The differences between $PtcCO_2$ and $PaCO_2$ were significantly lower than those between $PetCO_2$ and $PaCO_2$ at all five time-points ($p < 0.05$).

Conclusions

$PtcCO_2$ monitoring was more accurate for predicting $PaCO_2$ levels during prolonged one-lung ventilation with low tidal volume for patients undergoing thoracic surgeries.

Introduction

Arterial carbon dioxide partial pressure ($PaCO_2$) is the gold standard in monitoring ventilation during general anesthesia. End-tidal carbon dioxide partial pressure ($PetCO_2$) reflects $PaCO_2$ and becomes a standard monitoring during surgery. However, various pathologic processes of the cardio-respiratory system such as ventilation-perfusion mismatch or shunt as well as changes in patient positioning have been shown to influence the correlation between $PaCO_2$ and $PetCO_2$ [1]. One-lung ventilation (OLV) and lateral decubitus position during thoracic surgery impair ventilation-perfusion matching and, as a result, the difference between $PaCO_2$ and $PetCO_2$.

Transcutaneous carbon oxide partial pressure ($PtcCO_2$) monitoring provides a noninvasive and continuous estimation of $PaCO_2$ by sampling from arterialized capillary blood and is not influenced by ventilation-perfusion mismatch [2]. Previous studies [3–4] found that during short time OLV (≤ 1 hour) for thoracic surgery, the value of $PtcCO_2$ is closer to $PaCO_2$ than $PetCO_2$.

With the wide-spread use of mini-invasive thoracic surgery and the introduction of lung-protective ventilation strategy during thoracic anesthesia, prolonged hypercapnia originated from low tidal volume OLV in these patients are not uncommon [5–6]. We designed this study to evaluate the accuracy of $PtcCO_2$ in predicting $PaCO_2$ values during prolonged OLV and permissive hypercapnia during mini-invasive thoracic surgery.

Materials and Methods

The study protocol was approved by the Clinical Research Ethics Committee of Peking University First Hospital (2012[504]). Written informed consent was obtained from each patient.

Eighteen adult patients of ASA physical status I or II who were scheduled to undergo mini-invasive thoracic surgery with an expected OLV duration of two hours or more were recruited for this study. Patients with diagnosed cardiovascular disease were excluded.

No premedication was administered. Before the induction of general anesthesia, an epidural puncture was performed between the fifth and eighth thoracic interspace and an epidural catheter was inserted. A test dose of 3 ml 1% lidocaine was administered and no other epidural medication was used during anesthesia.

Intraoperative monitoring included a non-invasive blood pressure, pulse oxygen saturation, an electrocardiogram, nasopharyngeal temperature, urine output, peak airway pressure, and direct arterial blood pressure measurement through a radial artery catheter. General anesthesia was induced with propofol (1–2 mg/kg) and remifentanil (effect site target control infusion at a target of 4–6 ng/ml). And rocuronium (0.6mg/kg) was administered to facilitate endotracheal intubation with a double-lumen tube by direct laryngoscopy. Patients were mechanically ventilated in a volume-controlled manner both in the supine and the lateral decubitus position. During two-lung ventilation (TLV), the fresh gas flow, tidal volume, respiratory rate and inspiratory/expiratory ratio were set at 1 L/min oxygen and 1 L/min air, 6–8 ml/kg, 10–12 breath/min, and 1:2, respectively. Anesthesia was maintained with sevoflurane inhalation (end-tidal anesthetic concentration of 0.8 MAC or above) and remifentanil infusion until the end of the surgery. Sufentanil was administered as a bolus when deemed necessary during surgery and before the end of surgery.

For all patients, the position of the double-lumen endobronchial tube was confirmed under direct vision with a fiberoptic bronchoscope (FOB). The patients were then turned to the lateral decubitus position. The tube position was then checked again with the FOB just before OLV, and the effectiveness of lung collapse during OLV was confirmed by direct observation in the operative field. During OLV, the fresh gas flow, tidal volume, respiratory rate and inspiratory/

expiratory ratio were set at 1 L/min oxygen, 4–6 ml/kg, 10–16 breath/min, and 1:1.5, respectively, to maintain a SpO_2 of 90% or higher and a peak airway pressure lower than 25 cmH_2O. Intravenous ephedrine or phenylephrine or nicardipine was administrated to maintain blood pressure fluctuation within 30% from baseline. Additional doses of rocuronium were administered to maintain muscle relaxation.

$PtcCO_2$ was measured with a TCM3 transcutaneous CO_2/oxygen device (Radiometer, Copenhagen, Denmark). The monitoring technique was standardized by applying the probe to the upper part of the patient's dependent arm in the lateral decubitus position. Before each study, the device was calibrated by using a two-point self-calibration (5% and 10% CO_2) and the working temperature of the electrode was maintained at 42°C to "arterialize" the skin capillary blood flow according to the manufacturer's recommendations. The monitor used an internal adjustment to compensate for the effects of the heated probe on CO_2 tension. It took appropriately 20 minutes for initial stabilization after probe attachment. The end-tidal concentrations of the anesthetics and CO_2 were measured with a AS/5 monitor (Datex-Ohmeda, Helsinki, Finland) which was calibrated in 5% CO_2 and 20.9% oxygen gas before the study. Continuous sampling was obtained from a connector attached to the proximal end of heat moisture exchanger in the respiratory circuit. Arterial blood samples were obtained during TLV, just before the initiation of OLV, and every 30 minutes during OLV until 120 minutes. Arterial blood gas analysis was performed using a GEM premier 3000 analyzer (Instrumentation Laboratory, USA). Data of $PtcCO_2$, $PetCO_2$, and $PaCO_2$ monitoring results were collected simultaneously. The heart rate, mean arterial pressure, pulse oxygen saturation, and nasopharyngeal temperature were also recorded at same time-points.

Quantitative data were presented as means ± standard deviation (SD). Bland-Altman method was used to analyze the agreement between $PaCO_2$ and $PetCO_2$ or between $PaCO_2$ and $PtcCO_2$. The bias (the mean difference between the values) and the precision (the SD of the bias) were calculated. Student's unpaired t-tests were also used to compare the differences between $PaCO_2$ and $PetCO_2$ or between $PaCO_2$ and $PtcCO_2$. A p value of less than 0.05 was regarded as statistically significant. Statistical analysis was conducted using SPSS version 14.0 (Chicago, IL, USA).

Results

All eighteen patients completed the study protocol. The demographic data were shown in Table 1. Surgical procedures included lobectomy or pneumonectomy for lung cancer, and thymectomy for thymoma. A total of 90 data sets consisting of the simultaneous measurements of $PtcCO_2$, $PetCO_2$ and $PaCO_2$ at five time points were obtained (Table 2). The heart rate and mean arterial pressure did not significantly change from the preoperative values during the study period. The body temperature remained constant between 35.5 and 36.5°C.

Table 1. Demographic data (n = 18).

Variable	Data
Age (yr)	59 ± 13
Sex (M/F)	13/5
Weight (kg)	61 ± 10
Height (cm)	165 ± 5
ASA classification I/II (n)	2/16
Smoking (n)	10

Values are expressed as mean ± standard deviation or number of patients.

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Table 2. Carbon dioxide level in five time points.

Variable	TLV	OLV30	OLV60	OLV90	OLV120
$PaCO_2$ (mmHg)	46.5 ± 6.9	52.2 ± 9.1	52.2 ± 7.0	52.4 ± 6.9	52.2 ± 6.6
$PetCO_2$ (mmHg)	34.7 ± 4.7	39.7 ± 5.6	40.2 ± 4.8	41.2 ± 5.6	40.7 ± 5.5
$PtcCO_2$ (mmHg)	50.6 ± 8.0	56.1 ± 10.5	55.2 ± 8.4	55.0 ± 10.7	54.4 ± 10.0

Values are expressed as mean ± standard deviation. OLV30, OLV60, OLV90 and OLV120 refer to 30, 60, 90 and 120 minutes of OLV, respectively. TLV, two-lung ventilation; OLV, one-lung ventilation.

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When $PtcCO_2$ and $PaCO_2$ were compared, the bias and precision were 4.1 ± 6.5 mmHg during TLV and 2.9 ± 6.1 mmHg during OLV, respectively (Fig 1). When $PetCO_2$ and $PaCO_2$ were compared, the bias and precision were -11.8 ± 6.4 mmHg during TLV and -11.8 ± 4.9 mmHg during OLV, respectively (Fig 2). The values of bias and precision were stable and the difference between $PtcCO_2$ and $PaCO_2$ was significantly lower than that between $PetCO_2$ and $PaCO_2$ throughout the 2-hour period of OLV (Table 3).

Discussion

This study demonstrates that $PtcCO_2$ monitoring is a more accurate estimation of $PaCO_2$ than $PetCO_2$ during OLV of two hours or more with low tidal volume for thoracic surgery. Our results are consistent with previous ones on the accuracy of $PtcCO_2$ monitoring during thoracic surgery of shorter duration [3–4]. Moreover, we find that the $PtcCO_2$ is accurate of in estimating the $PaCO_2$ in the clinical condition of permissive hypercapnia which is not observed in previous studies [3–4].

$PtcCO_2$ monitoring used in the present study is a non-invasive method for continuous measurement of transcutaneous CO_2 partial pressure. It uses skin electrodes to quantify the amount of CO_2 that diffuses to the electrode on the surface of the skin. Local heating is required in order to increase the local blood circulation in the capillary bed below the sensor. The accuracy of $PtcCO_2$ monitoring is influenced by several factors including methodological limitations (e.g., stabilization time, reaction time, periodic repositioning of the sensor, the need for membrane restoration, and baseline calibration), technical mistakes (e.g., improper
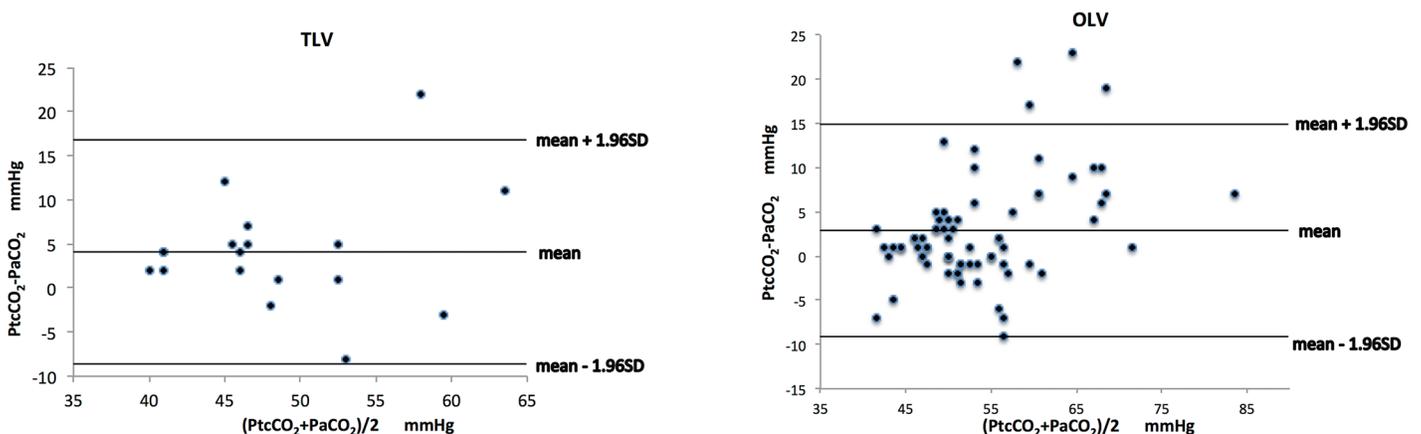

Fig 1. Agreement between transcutaneous CO_2 ($PtcCO_2$) and arterial CO_2 ($PaCO_2$). Bland-Altman analysis of $PtcCO_2$ versus $PaCO_2$ during two-lung ventilation (TLV) and one-lung ventilation (OLV). Bias was labeled. The 95% limits of agreement of the average $PtcCO_2$ –$PaCO_2$ difference during TLV and OLV were 4.1 ± 6.5 mmHg and 2.9 ± 6.1 mmHg (mean ± 1.96 standard deviation), respectively.

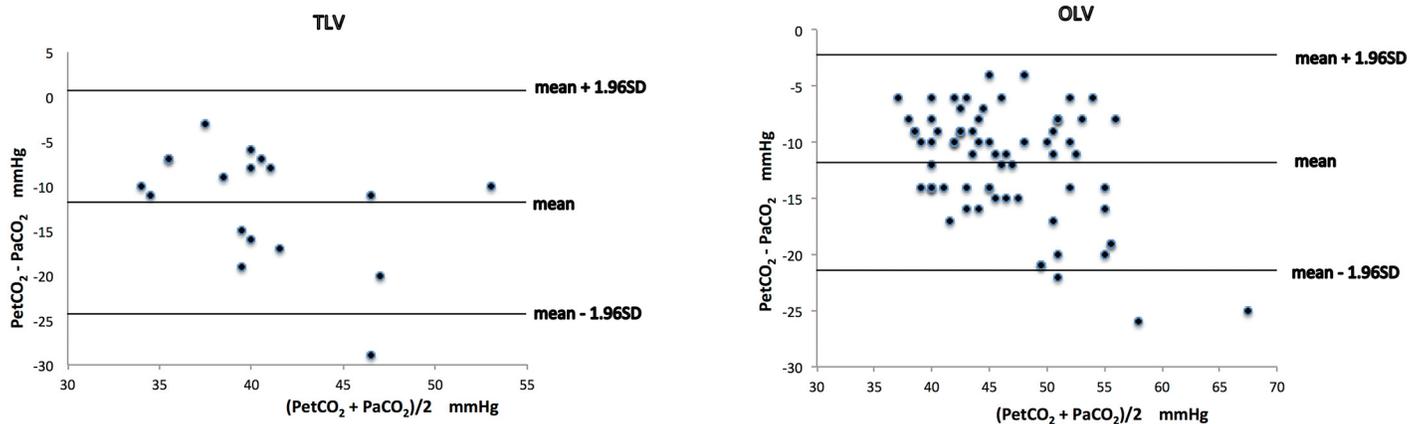doi:10.1371/journal.pone.0138912.g001

Fig 2. Agreement between end-tidal CO$_2$ (PetCO$_2$) and arterial CO$_2$ (PaCO$_2$). Bland-Altman analysis of PetCO$_2$ versus PaCO$_2$ during two-lung ventilation (TLV) and one-lung ventilation (OLV). Bias was labeled. The 95% limits of agreement of the average PetCO$_2$ –PaCO$_2$ difference during TLV and OLV were -11.8 ± 6.4 mmHg and -11.8 ± 4.9 mmHg (mean ± 1.96 standard deviation), respectively.

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application of the sensor, trapped air bubbles in the electrolyte solution, damage to the sensor membrane, improper calibration) and hypoperfusion (e.g., vasoconstriction, hypothermia, shock, low cardiac output or local edema) [7].

Since its introduction into clinical practice, PtcCO$_2$ monitoring has received great attention in neonates [8–9]. Later on, with the improvement of technology and increasing knowledge of this monitoring modality, its use has been increasing in pediatric patient [10–11], in adult patients undergoing thoracic [3–4] and laparoscopic surgery [12–15] and in patients after surgery [16–17]. The accuracy of PtcCO$_2$ monitoring has been confirmed by these studies. However, some others reported that PtcCO$_2$ monitoring cannot precisely predict PaCO$_2$ in preterm infants during in their first 24 hours [18] and in some patients receiving artificial ventilation during general anesthesia [19], possibly because of the aforementioned reasons. Considering the relative high price and the failure possibility, appropriate indication should be considered in chosing this monitoring method. One suitable clinical condition for PtcCO$_2$ monitoring is OLV during thoracic surgery.

OLV is essential for the success of mini-invasive thoracic surgery. Advances in this technique have enabled more complex intrathoracic procedures being performed. Protective ventilation strategy [5–6] is now widely used during OLV and consists of small tidal volumes, low inspired oxygen fraction, low airway pressures, permissive hypercapnia, and positive end expiratory pressure. Our results demonstrated the applicability of PtcCO$_2$ during a 2-hour period of OLV with hypercapnia for thoracic surgery. The study of Oshibuchi et al. [3] found that PtcCO$_2$ monitoring provides a more accurate estimation of PaCO$_2$ than PetCO$_2$ during an

Table 3. Bland-Altman analysis at different time points.

Variable	TLV	OLV30	OLV60	OLV90	OLV120
PtcCO$_2$-PaCO$_2$ difference (mmHg)	4.1 ± 6.5*	3.8 ± 5.8*	2.9 ± 5.1*	2.6 ± 6.7*	2.2 ± 7.2*
PetCO$_2$-PaCO$_2$ difference (mmHg)	-11.8 ± 6.4	-12.5 ± 5.0	-12.0 ± 5.2	-11.3 ± 4.5	-11.5 ± 5.1

Values are expressed as bias ± precision. OLV30, OLV60, OLV90 and OLV120 refer to 30, 60, 90 and 120 minutes of OLV, respectively. TLV, two-lung ventilation; OLV, one-lung ventilation.

* Significantly different from PetCO$_2$, PaCO$_2$ differences (p < 0.05).

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1-hour period of OLV with normocapnia ($PaCO_2$ in the range of 30–50 mmHg) for thoracic surgery. In another study, Kelly et al. [20] reported that the agreement between $PtcCO_2$ and $PaCO_2$ deteriorated at high $PaCO_2$ levels (>60 mmHg). Our results extrapolate these ranges, i.e., a 2-hour period of OLV with hypercapnia ($PaCO_2$ in the range of 35–70 mmHg) during thoracic surgery. Long time $PtcCO_2$ monitoring (longer than 2 hours) was only observed in nonsurgical patients in previous studies [21–22].

A difference of 5 mmHg or less between $PaCO_2$ and other carbon dioxide measurement was a clinically acceptable discrepancy [4,13]. Our results found that the bias between $PtcCO_2$ and $PaCO_2$ was less than 5 mmHg during either TLV or OLV, whereas the bias between $PetCO_2$ and $PaCO_2$ was lower than -11 mmHg during either TLV or OLV. In the scatter diagram of $PetCO_2$ and $PaCO_2$, 3 of 90 points were outside of the limits of agreement during OLV and all 3 points were beyond 22 mmHg. Whereas in the scatter diagram of $PtcCO_2$ and $PaCO_2$, 4 of 90 points were outside of the limits but only 1 point was beyond 22 mmHg. These also indicated the superiority of $PtcCO_2$ in predicting $PaCO_2$.

$PetCO_2$ monitoring is still the most convenient method in CO_2 measurement and has a unique role in judging the position of artificial airway and ventilation status. The difference between $PaCO_2$ and $PetCO_2$ increases with age, pulmonary disorders, pulmonary embolism, reduced cardiac output, hypervolemia, anesthesia, and other conditions that increase the ventilation-perfusion mismatch. In the present study, the mean difference between $PetCO_2$ and $PaCO_2$ during either TLV or OLV was higher than the previously reported ones in similar patients [3–4]. This is perhaps because the tidal volume settings during TLV (6–8 ml/kg) and OLV (4–6ml/kg) were lower in our study than in previous one (10 ml/kg throughout the operation) [3]. According to respiratory physiology, the ratio of dead space to tidal volume determines the gradient between $PaCO_2$ and $PetCO_2$ assuming that the $PaCO_2$ remains constant. The higher difference between $PetCO_2$ and $PaCO_2$ in our study supports the use of $PtcCO_2$ monitoring during prolonged OLV with lung-protective strategy of low tidal volume ventilation.

Conclusions

In conclusion, our study demonstrated that $PtcCO_2$ is more accurate than $PetCO_2$ in estimating $PaCO_2$ during prolonged OLV with low tidal volume ventilation for thoracic surgery.

Supporting Information

S1 Dataset. Data for analysis.
(XLSX)

Acknowledgments

Author Contributions

Conceived and designed the experiments: HZ DXW. Performed the experiments: HZ. Analyzed the data: HZ. Contributed reagents/materials/analysis tools: HZ. Wrote the paper: HZ DXW.

References

1. Whitesell R, Asiddao C, Gollman D, Jablonski J. Relationship between arterial and peak expired carbon dioxide pressure during anesthesia and factors influencing the difference. Anesth Analg 1981; 60:508–12. PMID: 6787952

2. Huttmann SE, Windisch W, Storre JH. Techniques for the measurement and monitoring of carbon dioxide in the blood. Ann Am Thorac Soc 2014; 11:645–52. doi: 10.1513/AnnalsATS.201311-387FR PMID: 24701974

3. Oshibuchi M, Cho S, Hara T, Tomiyasu S, Makita T, Sumikawa K. A comparative evaluation of transcutaneous and end-tidal measurements of CO_2 in thoracic anesthesia. Anesth Analg 2003; 97:776–9. PMID: 12933401

4. Tobias JD. Noninvasive carbon dioxide monitoring during one-lung ventilation: End-Tidal versus transcutaneous techniques. J Cardiothorac Vasc Anesth 2003; 17:306–8. PMID: 12827576

5. Kilpatrick B, Slinger P. Lung protective strategies in anaesthesia. Br J Anaesth 2010; 105 Suppl 1: i108–16. doi: 10.1093/bja/aeq299 PMID: 21148650

6. Brassard CL, Lohser J, Donati F, Bussieres JS. Step-by-step clinical management of one-lung ventilation: continuing professional development. Can J Anesth 2014; 61:1103–21. doi: 10.1007/s12630-014-0246-2 PMID: 25389025

7. Eberhard P. The design, use, and results of transcutaneous carbon dioxide analysis: Current and future directions. Anesth Analg 2007; 105(6 Suppl):S48–52. PMID: 18048898

8. Binder N, Atherton H, Thorkelsson T, Hoath SB. Measurement of transcutaneous carbon dioxide in low birthweight infants during the first two weeks of life. Am J Perinatol 1994; 11:237–41. PMID: 8048993

9. Bernet V, Döll C, Cannizzaro V, Ersch J, Frey B, Weiss M. Longtime performance and reliability of two different $ptcCO_2$ and $spOO_2$ sensors in neonates. Paediatr Anaesth 2008; 18:872–7. doi: 10.1111/j.1460-9592.2008.02661.x PMID: 18768047

10. Dullenkopf A, Bernardo SD, Berger F, Fasnacht M, Gerber AC, Weiss M. Evaluation of a new combined $spOO_2$/$ptcCO_2$ sensor in anaesthetized paediatic patients. Paediatr Anaesth 2003; 13:777–84. PMID: 14617118

11. Tobias JD. Transcutaneous carbon dioxide monitoring in infants and children. Paediatr Anaesth 2009; 19:434–44. doi: 10.1111/j.1460-9592.2009.02930.x PMID: 19236597

12. Bhavani-Shankar K, Steinbrook RA, Mushlin PS, Freiberger D. Transcutaneous PCO_2 monitoring during laparoscopic cholecystectomy in pregnancy. Canadian Journal of Anaesthesia 1998; 45:164–9 PMID: 9512853

13. Xue Q, Wu X, Jin J, Yu B, Zheng M. Transcutaneous carbon dioxide monitoring accurately predicts arterial carbon dioxide partial pressure in patients undergoing prolonged laparoscopic surgery. Anesth Analg 2010; 111:417–20 doi: 10.1213/ANE.0b013e3181e30b54 PMID: 20584872

14. Liu S, Sun J, Chen X, Yu Y, Liu X, Liu C. The application of transcutaneous CO_2 pressure monitoring in the anesthesia of obese patients undergoing laparoscopic bariatric surgery. PLoS One 2014; 9(4): e91563. doi: 10.1371/journal.pone.0091563 PMID: 24699267

15. De Oliveira GS, Ahmad S, Fitzgerald PC, McCarthy RJ. Detection of hypoventilation during deep sedation in patients undergoing ambulatory gynaecological hysteroscopy: A comparison between transcutaneous and nasal end-tidal carbon dioxide measurements. Br J Anaesth 2010; 104:774–8. doi: 10.1093/bja/aeq092 PMID: 20418266

16. Hirabayashi M, Fujiwara C, Ohtani N, Kagawa S, Kamide M. Transcutaneous PCO_2 monitors are more accurate than end-tidal PCO_2 monitors. J Anesth 2009; 23:198–202. doi: 10.1007/s00540-008-0734-z PMID: 19444557

17. Roediger R, Beck-Schimmer B, Theusinger OM, Rusch D, Seifert B, Spahn DR, et al. The revised digital transcutaneous PCO_2/$spOO_2$ ear sensor is a reliable noninvasive monitoring tool in patients after cardiac surgery. J Cardiothorac Vasc Anesth 2011; 25:243–9. doi: 10.1053/j.jvca.2010.06.021 PMID: 20851636

18. Aliwalas LL, Noble L, Nesbitt K, Fallah S, Shah V, Shah PS. Agreement of carbon dioxide levels measured by arterial, transcutaneous and end tidal methods in preterm infants < or = 28 weeks gestation. J Perinatol 2005; 25:26–9. PMID: 15496874

19. Nishiyama T, Nakamura S, Yamashita K. Effects of the electrode temperature of a new monitor, TCM4, on the measurement of transcutaneous oxygen and carbon dioxide tension. J Anesth 2006; 20:331–4. PMID: 17072703

20. Kelly AM, Klim S. Agreement between arterial and transcutaneous PCO_2 in patients undergoing noninvasive ventilation. Respir Med 2011; 105:226–9. doi: 10.1016/j.rmed.2010.11.010 PMID: 21131188

21. Storre JH, Steurer B, Kabitz HJ, Dreher M, Windisch W. Transcutaneous PCO_2 monitoring during initiation of noninvasive ventilation. Chest 2007; 132:1810–6. PMID: 18079217

22. Janssens JP, Laszlo A, Uldry C, Titelion V, Picaud C, Michel JP. Non-invasive (transcutaneous) monitoring of PCO_2 ($tcpCO_2$) in older adults. Gerontology 2005; 51:174–8. PMID: 15832044