Noninvasive monitoring of PaCO$_2$ during one-lung ventilation and minimal access surgery in adults: End-tidal versus transcutaneous techniques

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Abstract

Background: Previous studies have suggested that end-tidal CO$_2$ (ET-CO$_2$) may be inaccurate during one-lung ventilation (OLV). This study was performed to compare the accuracy of the noninvasive monitoring of PCO$_2$ using transcutaneous CO$_2$ (TC-CO$_2$) with ET-CO$_2$ in patients undergoing video-assisted thoracoscopic surgery (VATS) during OLV. Materials and Methods: In adult patients undergoing thoracoscopic surgical procedures, PCO$_2$ was simultaneously measured with TC-CO$_2$ and ET-CO$_2$ devices and compared with PaCO$_2$. Results: The cohort for the study included 15 patients ranging in age from 19 to 71 years and in weight from 76 to 126 kg. During TLV, the difference between the TC-CO$_2$ and the PaCO$_2$ was 3.0 ± 1.8 mmHg and the difference between the ET-CO$_2$ and PaCO$_2$ was 6.2 ± 4.7 mmHg (P=0.02). Linear regression analysis of TC-CO$_2$ vs. PaCO$_2$ resulted in an $r^2$ = 0.6280 and a slope = 0.7650 ± 0.1428, while linear regression analysis of ET-CO$_2$ vs. PaCO$_2$ resulted in an $r^2$ = 0.05528 and a slope = 0.1986 ± 0.1883. During OLV, the difference between the TC-CO$_2$ and PaCO$_2$ was 3.5 ± 1.7 mmHg and the ET-CO$_2$ to PaCO$_2$ difference was 9.6 ± 3.6 mmHg (P=0.03 vs. ET-CO$_2$ to PaCO$_2$ difference during TLV; and $P=0.0001$ vs. TC-CO$_2$ to PaCO$_2$ difference during OLV). In 13 of the 15 patients, the TC-CO$_2$ value was closer to the actual PaCO$_2$ than the ET-CO$_2$ value (P=0.0001). Linear regression analysis of TC-CO$_2$ vs. PaCO$_2$ resulted in an $r^2$ = 0.7827 and a slope = 0.8142 ± 0.07965, while linear regression analysis of ET-CO$_2$ vs. PaCO$_2$ resulted in an $r^2$ = 0.2989 and a slope = 0.3026 ± 0.08605. Conclusions: During OLV, TC-CO$_2$ monitoring provides a better estimate of PaCO$_2$ than ET-CO$_2$ in patients undergoing VATS.

Key words: End-tidal CO$_2$, thoracoscopy, transcutaneous CO$_2$
endotracheal tube, with oxygenation and ventilation supported by the nonoperative lung. Even with effective hypoxic pulmonary vasoconstriction, the technique results in an increase in the shunt fraction and perfusion of the nonventilated lung. Previous studies have demonstrated a significant arterial to ET-CO\(_2\) gradient during one-lung OLV\(^{[4-6]}\) The efficacy of ET-CO\(_2\) monitoring is limited during such procedures, suggesting that alternative noninvasive monitors of PaCO\(_2\) may be needed. Although used predominantly in the neonatal and pediatric population, there is increasing interest in the use of and recent reports of transcutaneous (TC) CO\(_2\) monitoring in the adult population\(^{[5-9]}\). The current study prospectively compares ET-CO\(_2\) and TC-CO\(_2\) monitoring during OLV in adults undergoing video-assisted thoracoscopic surgery.

**MATERIALS AND METHODS**

The study was approval by the Institutional Review Board and the Committee for the Protection of Human Subjects of the University of Missouri. Verbal informed consent was obtained from each patient. The patient population included patients scheduled for minimal access thoracic surgery and OLV, who were 18 years of age or older and in whom intraarterial access was deemed necessary. OLV was provided by either a bronchial blocker or a double lumen endotracheal tube. Effective lung separation was confirmed by clinical auscultation and fiberoptic bronchoscopy prior to the start of the procedure. Intrathoracic CO\(_2\) insufflation was not used during the procedure.

**Transcutaneous and end-tidal carbon dioxide monitoring**

ET-CO\(_2\) was measured using an infrared analyzer with a side stream sampler attached at the elbow between the endotracheal tube and the anesthesia circuit. Prior to use, the ET-CO\(_2\) device was calibrated according to the manufacturer’s recommendations. TC-CO\(_2\) was measured with a commercially available TC-CO\(_2\) device (Sentec AG, Therwil, Switzerland). This device is based on a Stow-Severinghaus-type CO\(_2\) sensor combined with a pulse oximeter and is attached to the patient’s earlobe by a low pressure attachment clip\(^{[10,11]}\). The *in vitro* 90% response time is <50s for the CO\(_2\) electrode. Prior to placement, the sensor was prepared and calibrated according to the manufacturer’s recommendations. The sensor is calibrated *in vitro* by using a one-point dry gas calibration with 7% carbon dioxide. The working temperature of the sensor is 42°C. The sensor was cleaned with alcohol and dried before application. One drop of contact gel was applied to the center of the sensor prior to placement on the patient’s earlobe. Oxygen saturation values are available immediately, while TC-CO\(_2\) values are available after a 2-3 min calibration time.

**Data collection and statistical analysis**

ABG analyses were obtained following endotracheal intubation during two-lung ventilation (TLV) and as clinically indicated during OLV. When an ABG was obtained, the ET-CO\(_2\) and TC-CO\(_2\) were simultaneously recorded on a data sheet. Calculation of the absolute difference between the noninvasive monitor (ET-CO\(_2\) or TC-CO\(_2\)) and the PaCO\(_2\) was performed. Negative numbers were not used because this could artificially lower the mathematical mean of the differences between the noninvasive monitors of CO\(_2\) and the PaCO\(_2\). If multiple ABGs were obtained during OLV, the absolute differences between the PaCO\(_2\) and the noninvasive monitors were averaged and counted as a single data point. This was done to avoid biasing the data by overrepresentation of any one patient as the number of ABGs varied for each patient. The absolute difference between the ET-CO\(_2\) and PaCO\(_2\) was compared to the absolute difference between the TC-CO\(_2\) and the PaCO\(_2\) during TLV and OLV using a non-paired t-test. A contingency table with a Fisher’s exact test was used to compare the times that each of the noninvasive monitors was closest to the actual PaCO\(_2\). Using the raw numbers from all of the individual sample sets (PaCO\(_2\)/ET-CO\(_2\)/TC-CO\(_2\)) obtained during TLV and OLV, linear regression analysis and Bland-Altman analyses were performed.

**RESULTS**

The cohort for the study included 15 patients ranging in age from 19 to 71 years (46.9 ± 17.3 years) and in weight from 76 to 126 kg (93.4 ± 12.4 kg). There were 11 men and 4 women. Nineteen sample sets (PaCO\(_2\)/ET-CO\(_2\)/TC-CO\(_2\)) were obtained during TLV and
27 were obtained during OLV. During TLV, the difference between the TC-CO$_2$ and the PaCO$_2$ was 3.0 ± 1.8 mmHg with a range of 0 to 8 mmHg and the difference between the ET-CO$_2$ and the PaCO$_2$ was 6.2 ± 4.7 mmHg with a range of 2 to 18 mmHg (P=0.02 vs. TC-CO$_2$ to PaCO$_2$ difference) [Table 1]. During TLV, the TC-CO$_2$ value was closer to the actual PaCO$_2$ in 10 patients, the ET-CO$_2$ value was closer in 2 patients and there was no difference in 3 patients (P=NS). During TLV, linear regression analysis of TC-CO$_2$ vs. PaCO$_2$ resulted in an $r^2=0.6280$ and a slope = 0.7650 ± 0.1428 (95% confidence intervals: 0.4367 to 1.066). During TLV, linear regression analysis of ET-CO$_2$ vs. PaCO$_2$ resulted in an $r^2=0.05528$ and a slope = 0.1986 ± 0.1883 (95% confidence intervals: -0.1956 to 0.5928) [Figure 1]. During TLV, Bland-Altman analysis of TC vs. PaCO$_2$ revealed a bias of +2.2 mmHg and a precision of ±3.0 mmHg and analysis of ET vs. PaCO$_2$ revealed a bias of -7.3 mmHg and a precision of ± 5.5 mmHg.

During OLV, the difference between the TC-CO$_2$ and the PaCO$_2$ was 3.5 ± 1.7 mmHg with a range of 2 to 8 mmHg (P= NS vs. TC-CO$_2$ to PaCO$_2$ difference during TLV). During OLV, the ET-CO$_2$ to PaCO$_2$ difference was 9.6 ± 3.6 mmHg with a range of 2 to 15 mmHg (P=0.03 vs. ET-CO$_2$ to PaCO$_2$ difference during TLV; and P<0.0001 vs. TC-CO$_2$ to PaCO$_2$ difference during OLV) [Table 1]. In 13 of the 15 patients, the TC-CO$_2$ value was closer to the actual PaCO$_2$ than the ET-CO$_2$ value (P= 0.0001). During OLV, linear regression analysis of TC-CO$_2$ vs. PaCO$_2$ resulted in an $r^2=0.7827$ and a slope = 0.8142 ± 0.07965 (95% confidence intervals: 0.6513 to 0.9771). During OLV, linear regression analysis of ET-CO$_2$ vs. PaCO$_2$ resulted in an $r^2=0.2989$ and a slope = 0.3026 ± 0.08605 (95% confidence intervals: 0.1266 to 0.4786) [Figure 2]. During OLV, Bland-Altman analysis of TC vs. PaCO$_2$ revealed a

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![Figure 1](https://www.medknow.com)  
**Figure 1:** Linear regression analysis during two-lung ventilation of TC-CO$_2$ versus PaCO$_2$ (above) and ET-CO$_2$ vs. PaCO$_2$ (below). Analysis of TC-CO$_2$ vs. PaCO$_2$ revealed $r^2=0.6280$ and slope = 0.7650 ± 0.1428 (95% confidence intervals: 0.4367 to 1.066). Analysis of ET-CO$_2$ vs. PaCO$_2$ revealed of $r^2=0.05528$ and slope = 0.1986 ± 0.1883 (95% confidence intervals: -0.1956 to 0.5928)

![Figure 2](https://www.medknow.com)  
**Figure 2:** Linear regression analysis during one-lung ventilation of TC-CO$_2$ versus PaCO$_2$ (above) and ET-CO$_2$ vs. PaCO$_2$ (below). Analysis of TC-CO$_2$ vs. PaCO$_2$ revealed $r^2=0.7827$ and slope = 0.8142 ± 0.07965 (95% confidence intervals: 0.6513 to 0.9771). Analysis of ET-CO$_2$ vs. PaCO$_2$ revealed $r^2=0.2989$ and slope = 0.3026 ± 0.08605 (95% confidence intervals: 0.1266 to 0.4786).

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### Table 1: End-tidal and transthoracic differences vs. PaCO$_2$ during one-lung ventilation and two-lung ventilation

<table>
<thead>
<tr>
<th></th>
<th>TC-CO$_2$ to PaCO$_2$ difference (mmHg)</th>
<th>ET-CO$_2$ to PaCO$_2$ difference (mmHg)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-lung ventilation</td>
<td>3.0 ± 1.8</td>
<td>6.2 ± 4.7</td>
<td>0.02</td>
</tr>
<tr>
<td>One-lung ventilation</td>
<td>3.5 ± 1.7</td>
<td>9.6 ± 3.6</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>
bias of $\pm 2.9$ mmHg and a precision of $\pm 2.5$ mmHg and analysis of ET vs. PaCO$_2$ revealed a bias of $-10.5$ mmHg and a precision of $\pm 6.2$ mmHg.

No problems occurred with ET-CO$_2$ monitoring during the study period. In two patients, the TC-CO$_2$ electrode had to be repositioned after the initial placement to obtain an effective value. No blistering, erythema or skin changes were noted on the earlobe following use of the TC-CO$_2$ device.

**DISCUSSION**

The current study demonstrates that noninvasive monitoring of PaCO$_2$ using ET-CO$_2$ devices may be inaccurate during minimal access thoracoscopic surgery and OLV in adults. In our cohort of 15 patients, TC-CO$_2$ monitoring was more accurate than ET-CO$_2$ monitoring (difference of $3.0 \pm 1.8$ mmHg vs. $6.2 \pm 4.7$ mmHg) during the baseline state using TLV. Although no significant change was noted in the TC-CO$_2$ to PaCO$_2$ gradient during OLV ($3.5 \pm 1.7$ mmHg), the ET-CO$_2$ to PaCO$_2$ difference increased to $9.6 \pm 3.6$ mmHg. In 13 of 15 patients, the TC-CO$_2$ was closer to the actual PaCO$_2$ than the ET-CO$_2$ during OLV.

Several factors may be responsible for discrepancies between ET-CO$_2$ and PaCO$_2$, including technical issues with the monitor; and patient-related factors, including ventilation-perfusion mismatch, dead space and true shunt.\cite{12,13} Whitesell et al demonstrated that patients with underlying lung disease had a significantly greater ET-CO$_2$ to PaCO$_2$ gradient when compared with patients with normal baseline pulmonary function ($3.3 \pm 0.6$ mmHg versus $0.8 \pm 0.3$ mmHg).\cite{13} Patient positioning has also been shown to have an impact on the accuracy of ET-CO$_2$ monitoring.\cite{2,3} With patients undergoing renal or upper ureteral surgery in the supine position, Pansard et al reported that the ET-CO$_2$ to PaCO$_2$ difference was $4.8 \pm 3.9$ mmHg 10 min after induction and increased to $7.9 \pm 3.5$ mmHg ($P<0.01$) 5 min after placement of the patients into the lateral decubitus ‘kidney rest’ position. Similar results were reported by Grenier et al in a cohort of patients undergoing neurosurgical procedures in the lateral decubitus position.\cite{3}

In addition to these factors, the significant physiologic alterations induced by OLV can be expected to alter the relationship between ET-CO$_2$ and PaCO$_2$ values. Ip Yam et al evaluated the accuracy of ET-CO$_2$ during OLV in a cohort of 22 adults undergoing thoracotomy.\cite{4} During TLV, the ET-CO$_2$ to PaCO$_2$ difference was $1.3 \pm 0.6$ kPa (1 kPa = 7.5 mmHg) and it was $1.2 \pm 0.7$ kPa during OLV. Even if the difference for subsequent ABG analysis was corrected by subtracting the gradient from the first ABG analysis, the ET-CO$_2$ to PaCO$_2$ difference varied from -1.3 to 1.7 kPa. The authors concluded that the efficacy of ET-CO$_2$ monitoring during OLV even when using corrected values remains questionable.

Two previous studies have evaluated noninvasive PCO$_2$ monitoring during OLV using both TC-CO$_2$ and ET-CO$_2$ devices in patients undergoing open thoracotomy,\cite{5,6} while there are no previous reports of using such monitoring in patients undergoing minimal access surgery. Oshibuchi et al compared the accuracy of TC-CO$_2$ and ET-CO$_2$ monitoring in a cohort of 26 adult patients undergoing OLV for open thoracotomy and pneumonectomy. The transcutaneous device (TCM3 transcutaneous CO$_2$/oxygen device, Radiometer, Copenhagen, Denmark) was applied to the upper part of the patient’s dependent arm. Evaluation of the TC-CO$_2$ to PaCO$_2$ difference revealed a bias of $-0.4$ mmHg and a precision of $\pm 2.5$ mmHg during TLV and a bias of $1.4$ mmHg and a precision of $\pm 4.3$ mmHg during OLV. Evaluation of the ET-CO$_2$ to PaCO$_2$ difference revealed a bias of $-5.8$ mmHg and a precision of $\pm 4.1$ mmHg during TLV and a bias of $-7.1$ mmHg and a precision of $\pm 4.6$ mmHg during OLV. The authors concluded that TC-CO$_2$ monitoring was an accurate means of evaluating PaCO$_2$ during OLV. Tobias et al used the same transcutaneous device in their study of 15 young adult and pediatric patients (14.1 ± 6.1 years, range - 5 to 28 years) undergoing open thoracotomy.\cite{5} During TLV, the TC-CO$_2$ to PaCO$_2$ difference was $2.5 \pm 0.8$ mmHg, while the ET-CO$_2$ to PaCO$_2$ difference was $3.9 \pm 1.6$ mmHg ($P=0.0049$). There was a significant increase in the ET-CO$_2$ to PaCO$_2$ gradient during OLV (5.8 ± 2.3 mmHg), while no change was noted in the TC-CO$_2$ to PaCO$_2$ difference (2.7 ± 1.4 mmHg).
The previously reviewed studies of Oshibuchi et al. and Tobias, along with the data from the current cohort of adult patients, demonstrate the inaccuracy of ET-CO₂ monitoring during OLV and suggest that TC-CO₂ monitoring is an effective alternative or adjunct. Until recently, transcutaneous CO₂ monitoring was used most commonly in the neonatal and occasionally in the pediatric ICU population; however, there is growing experience with its use in adult patients in both the operating room and the ICU setting. These studies have demonstrated that TC-CO₂ is more accurate than ET-CO₂ in situations where the continuous monitoring of PaCO₂ is vital.

TC-CO₂ monitoring may be of particular benefit when the ventilation-perfusion properties of the respiratory system are altered. ET-CO₂ measures a sample of gas that contains a mixture of gas exhaled from several areas of the airway and alveoli. Regions with a high ventilation-perfusion ratio (dead space) do not participate in gas exchange and therefore the partial pressure of CO₂ is low or absent. During exhalation, the gas from regions of dead space mixes with the gas from areas of normal ventilation-perfusion ratios, resulting in dilution of the ET-CO₂ sample and a widening of the ET-CO₂ to PaCO₂ difference. Alternatively, areas of low ventilation-perfusion ratios (shunt) result in ineffective gas exchange and the addition of blood with a high partial pressure of CO₂ to the arterial circulation contributing to the increased ET-CO₂ to PaCO₂ gradient.

TC-CO₂ monitoring avoids the effect of sampling gas that may be subject to ventilation-perfusion mismatch. Transcutaneous monitoring relies on cutaneous respiration of the diffusion of gases across the skin. The transcutaneous monitor measures the CO₂ that is produced by local tissue metabolism and the CO₂ released from the blood as it flows through the capillaries near the skin surface. The latter is in direct equilibrium with the capillary CO₂ which is in equilibrium with the arterial CO₂. Warming of the skin to 42°C by the sensor increases blood flow and CO₂ solubility, resulting in an even greater diffusion of CO₂ into the skin and equilibration with capillary and arterial PCO₂ values. The TC-CO₂ monitor measures the PCO₂ at the epidermis by using an infrared sensor, pH electrode or a Clark-type electrode. Unlike ET-CO₂, which typically underestimates actual CO₂, the transcutaneous method typically overestimates actual CO₂ by 5.2-6.4 mmHg due to the increased CO₂ production from local metabolism induced by heating to 42°C. The currently available TC-CO₂ devices have an internal correction/calibration factor to correct for the heat-induced changes in CO₂ production. TC-CO₂ monitoring requires specific training in calibration, preparation, placement and maintenance of the device. Errors in any one of these steps may give false readings. When compared with ET-CO₂ monitoring, currently available TC-CO₂ monitors require a longer preparation time, including a 5-min calibration period and then an additional 5-10 min equilibration time after placement on the patient. Although not an issue with the TC-CO₂ monitor used in the current study, other TC-CO₂ monitors may require heating the skin to 44-45°C to ensure accuracy. When this is done, there are occasional reports of superficial burns and skin blistering. Technical and patient-related factors may affect the accuracy of TC-CO₂ monitoring. Improper membrane placement on the sensor or damage to the membrane may affect its accuracy. Patient factors, including skin thickness, skin edema and hypoperfusion (decreased cardiac output, hypovolemia or vasoconstriction), may also alter the diffusion of CO₂ to the sensor and result in inaccurate readings. As no continuous noninvasive monitor can be expected to be 100% accurate, periodic calibration with an arterial sample may be indicated.

CONCLUSION

The current study adds to the growing body of knowledge demonstrating the efficacy of TC-CO₂ monitoring in the adult population. This study is the first to evaluate the use of TC-CO₂ vs. ET-CO₂ during OLV in minimal access surgery. The continuous monitoring of PaCO₂ may be particularly important during minimal access surgery. In addition to OLV, CO₂ insufflation, to facilitate surgical visualization, places patients at a higher risk of hypercarbia than those undergoing open procedures. The combination of increased CO₂ from systemic absorption of the insufflated CO₂ with alterations in tidal volume
imposed by decreasing minute ventilation during OLV makes accurately and continuously monitoring PaCO₂ vital during minimal access surgery. TC-CO₂ monitoring is not meant to replace ET-CO₂ monitoring. Rather, the devices should be used to complement one another, especially in the OR setting. Although our data further demonstrate that TC-CO₂ monitoring is more accurate than ET-CO₂ monitoring, ET-CO₂ remains the standard of care in the OR to document the intratracheal position of the endotracheal tube, to serve as an additional ventilator disconnect monitor and to provide a capnograph for waveform analysis.

REFERENCES


Announcement

Dr. J. C. Patel Birth Centenary Celebration Committee

The year 2008 is the Birth Centenary Year of Dr. J. C. Patel. Some of his students/admirers felt that it would be a good idea to celebrate this Centenary Year by organizing CMEs, Orations/Lectures, Conferences, etc. during the year. He was associated with many professional bodies, which meet regularly every year; during these annual meetings/conferences, a lecture/symposium, etc. can be organized as a part of Centenary celebrations. We would like to form a Dr. J. C. Patel Birth Centenary Celebrations Committee. All his past students/admirers are invited to join the committee (without any financial commitment). Kindly communicate your name, designation, postal address, telephone number and E-mail ID to Dr. B. C. Mehta at Flat 504, Prachi Society, Juhu-Versova Link Road, Andheri (W0, Mumbai - 400053 (drmehta.bc@gmail.com).