**P**<sub>ET</sub>CO<sub>2</sub> measured by a new lightweight mainstream capnometer with very low dead space volume offers accurate and reliable noninvasive estimation of PaCO<sub>2</sub>

**Objective:** Although capnometers are widely used in adult and pediatric intensive care units, they are not widely used in neonatal intensive care units due to issues such as the weight of sensors, dead space, and leakage from tracheal intubation tubes. These authors developed a light and low dead space airway adaptor of end-tidal carbon dioxide pressure (P<sub>ET</sub>CO<sub>2</sub>) and evaluated the correlations between P<sub>ET</sub>CO<sub>2</sub> and partial CO<sub>2</sub> pressure (PaCO<sub>2</sub>) in rabbits while changing tidal volume and leakage volume.

**Methods:** Firstly, Japanese rabbits weighing 2 kg were divided into three tidal volumes (6 mL/kg, 10 mL/kg, or 15 mL/kg), and P<sub>ET</sub>CO<sub>2</sub> and PaCO<sub>2</sub> were measured. Secondly, the respiratory apparatus was set to a tidal volume/body weight ratio of 10 mL/kg, leakage rates were divided into seven groups, and P<sub>ET</sub>CO<sub>2</sub> and PaCO<sub>2</sub> were measured.

**Results:** P<sub>ET</sub>CO<sub>2</sub> and PaCO<sub>2</sub> were significantly correlated (r<sup>2</sup> = 0.9099, P < 0.0001) when there was no leakage in the tracheal intubation tubes. No significant differences were observed between PaCO<sub>2</sub> and P<sub>ET</sub>CO<sub>2</sub> in the three tidal volume/body weight groups or for groups in which leakage rate was <60%, but significant deviations in P<sub>ET</sub>CO<sub>2</sub> were noted in groups with leakage rate 60%.

**Conclusion:** There was a strong correlation between P<sub>ET</sub>CO<sub>2</sub> and PaCO<sub>2</sub> when tidal volume/body weight ratio was 6–15 mL/kg with leakage rate <60%. Lightweight mainstream capnometer with a low amount of dead space airway adaptor might be useful in very low birth weight infants with small tidal volume.

**Keywords:** capnography, mainstream, neonate

**Introduction**

Advancements in the treatment of neonatal respiratory failure, including exogenous surfactant, inhaled nitric oxide, and a growing repertoire of assisted ventilation strategies, have decreased morbidity and mortality rates. Patient monitoring has played a critical role in the safe and effective application of these advanced therapies.

Maintaining partial carbon dioxide pressure (PaCO<sub>2</sub>) within the desired range by frequent arterial sampling can increase the need for multiple transfusions in the neonatal intensive care unit, so methods for continuous noninvasive monitoring of CO<sub>2</sub> levels would prove extremely useful. Both hypocarbia and hypercarbia are detrimental to extremely low birth weight infants and have been implicated as causative factors in periventricular leukomalacia, intraventricular hemorrhage, and chronic lung disease. Critical event analyses have documented hypoxemia secondary to depressed
research activity as a principal risk factor for near misses and death.10,11

Capnography, which displays the level and waveform of CO₂ in exhaled air, provides information on cell metabolism, blood perfusion, and alveolar ventilation12 with noninvasive indirect methods. Use of end-tidal CO₂ pressure (ṖĖCO₂) for monitoring and as a tool for verifying endotracheal tube position is a common practice in the operating room and in adult and pediatric intensive care units.13 However, so far capnometers are not used widely in neonates due to issues such as the weight of sensors and water droplets within circuits, dead space, and leakage from tracheal intubation tubes.

These authors developed a new light (6 g) and low dead space (1 mL) airway adapter (YG-213T; Nihon-Kohden Corporation, Tokyo, Japan) for mainstream capnography (Cap-ONE TG-970P; Nihon-Kohden). The objective of this study was to evaluate the correlations between ṖĖCO₂ and PaCO₂ in rabbits while changing tidal volume (TV) and leakage volume with this device.

### Material and methods

Ten adult Japanese rabbits weighing 2 kg were anesthetized by intramuscular injection of ketamine at 10 mg/kg and xylazine at 5 mg/kg, and a 24 G catheter (JELCO, Smiths Medical Italia Srl, Mirano, Italy) was placed in the ear vein for continuous intravenous infusion of anesthetic agents. Rabbits were placed in a supine position throughout the experiment. After tracheotomy, an endotracheal tube (internal diameter, 2.5 mm; Mallinkrodt, Inc, St Louis, MO) was inserted. A 24 G catheter was placed in the internal carotid artery to allow collection of samples for blood gas analysis and to monitor arterial blood pressure and heart rate using biomedical research system (LEG-1000; Nihon-Kohden). Anesthesia was provided by continuous intravenous infusion of anesthetic agents. Animals were administered a mixture of 0.45% sterile saline and 10% glucose solution at 3 mL/kg/hour during the experiment. Body temperature was continuously monitored and maintained at 38.5°C–39.5°C using a heating pad.

Rabbits were ventilated mechanically with a time-cycled pressure-limited ventilator (Humming II; Metran Co, Ltd, Saitama, Japan) adjusted to: fraction of inhaled oxygen at 0.6; inspiratory time at 0.6 seconds; and positive end-expiratory pressure at 5 cmH₂O. Peak inspiratory pressure was settled at the TV maintained at TV/body weight (BW) ratios of 6 mL/kg, 7 mL/kg, 10 mL/kg, and 15 mL/kg, as measured by pneumotachography (ARFEL-VR; Avision Corporation, Tokyo, Japan). Respiratory rate was adjusted to a level at which normocapnia was maintained (41.6 ± 3.8 mmHg). In the investigation of the effects on TV/BW, TV/BW was divided into three groups (6 mL/kg, 10 mL/kg, and 15 mL/kg), and ṖĖCO₂ and PaCO₂ were measured.

ṖĖCO₂ was monitored in intubated rabbits by mainstream capnography (Cap-One TG-970P; Nihon-Kohden). Mainstream ṖĖCO₂ was measured via a capnograph connected to the proximal end of the endotracheal tube. Before each blood sampling, an adequate reading of ṖĖCO₂ and a reliable waveform on the mainstream capnograph (continuous steady waveform of expired CO₂ throughout the ventilatory cycle) was taken. Data was continuously recorded on a laptop computer using the software programmed by LabVIEW (National Instruments Corporation, Austin, TX) for each rabbit. PaCO₂ was measured from samples withdrawn intermittently from intraarterial lines indwelling in the internal carotid artery (ABL700; Radiometer Medical ApS, Bronshoj, Denmark). The amount of leakage was adjusted by fixation of the tracheal intubation tubes. The leakage ratio was calculated using the following equation:

\[
\text{Leakage ratio} = \frac{\text{inspiratory TV} - \text{expiratory TV}}{\text{inspiratory TV} \times 100}
\]

The end-tidal volume was measured by mainstream capnography (CO2SMO 8100, Fukuda Denshi, Tokyo, Japan) and also leakage rate was calculated with CO2SMO 8100. The respiratory apparatus was set to a TV/BW ratio of 10 mL/kg, then leakage rates were divided into seven groups (0%–10%, 10%–30%, 30%–50%, 50%–60%, 60%–70%, 70%–80%, and 80%–100%), and ṖĖCO₂ and PaCO₂ were measured.

PaCO₂ was measured with the additional dead space caused by attachment of a CO₂ sensor and additional dead space in the setting of TV/BW ratios of 6 mL/kg, 7 mL/kg, and 10 mL/kg.

Statistical analyses were conducted using SPSS Statistics version 17.0 software (SPSS, Inc, Chicago, IL). To determine whether ṖĖCO₂ values were representative of PaCO₂, the relationship between ṖĖCO₂ and PaCO₂ was analyzed by simple linear regression. Bland–Altman plots, representing a visual assessment of agreement between two methods of measurement, were created to assess the measurement of ṖĖCO₂. Bland–Altman plots demonstrate “good agreement” not only when differences between methods are consistent across all measurements but also when the differences are small. In a situation in which difference between the two measurements is expected to change based on a third
variable, Bland–Altman plots lose importance. The precision of \( P_{\text{ET}} \text{CO}_2 \) measurements and agreement between \( P_{\text{ET}} \text{CO}_2 \) and \( \text{PaCO}_2 \) values were assessed by bias \((\text{PaCO}_2 - P_{\text{ET}} \text{CO}_2)\), standard deviation, and 95% confidence interval (CI) for the bias. One-factor analysis of variance and the Mann–Whitney U test were used to compare differences between subgroups of TV/BW and leakage ratio. Values of \( P < 0.05 \) were considered significant. The present study was conducted with the approval of the Institutional Animal Care and Use Committee of Nagano Children’s Hospital, Nagano, Japan.

**Results**

A total of 43 measurements of \( P_{\text{ET}} \text{CO}_2 \) and \( \text{PaCO}_2 \) were analyzed. Under conditions of no leakages in the tracheal intubation tubes, \( P_{\text{ET}} \text{CO}_2 \) and \( \text{PaCO}_2 \) were significantly correlated \( (r^2 = 0.9099, P < 0.0001; \text{Figure 1}) \) and the Bland–Altman plot test showed a mean difference (bias) for \( P_{\text{ET}} \text{CO}_2 \) of \(-0.876 \text{ mmHg} \) (Figure 2). The 95% CI for this bias was \(-1.80–0.04 \text{ mmHg} \). The 95% CI of limits of agreement was \(-6.74–4.99 \text{ mmHg} \).

In the comparison of differences between \( \text{PaCO}_2 \) and \( P_{\text{ET}} \text{CO}_2 \), when setting the TV/BW to 6 mL/kg, 10 mL/kg or 15 mL/kg, no significant differences were observed between the three groups (Figure 3).

Figure 4 shows the effects of additional dead space on \( \text{PaCO}_2 \) under TV conditions of 12 mL, 14 mL, or 20 mL. Under TV conditions of 12 mL and 14 mL (6 mL/kg and 7 mL/kg, respectively), \( \text{PaCO}_2 \) was significantly increased by a dead space increase of only 1 mL, but under TV conditions of 20 mL (10 mL/kg), a dead space increase of 1 mL did not significantly increase \( \text{PaCO}_2 \). \( \text{PaCO}_2 \) thus seemed to be increased by dead space increases representing 7% of TV.

Figure 5 shows the effects of leakage rate on \( \text{PaCO}_2 \) compared to the group with a leakage rate of 0%–10%. However, groups with leakage rate 60% showed significant deviations between \( \text{PaCO}_2 \) and \( P_{\text{ET}} \text{CO}_2 \).

Regarding the expiratory plateau phase, a relatively constant PCO2 was maintained when alveolar mixed gas was expired, as shown by the capnogram for 10 mL/kg TV/BW and leakage ratio <60% (Figure 6).

**Discussion**

It was found that \( P_{\text{ET}} \text{CO}_2 \) measured by mainstream capnography cap-ONE was an accurate and reliable noninvasive method for estimating \( \text{PaCO}_2 \), showing a good correlation with \( \text{PaCO}_2 \) \( (r^2 = 0.9099, P < 0.0001) \), and there is no bias in the measurement \((95\% \text{ CI: } -1.80–0.04 \text{ mmHg})\).

\( P_{\text{ET}} \text{CO}_2 \) can be feasibly measured by mainstream or sidestream capnography. Measuring \( P_{\text{ET}} \text{CO}_2 \) reportedly underestimates alveolar \( \text{CO}_2 \) due to the relatively low TVs and rapid respiratory rates of newborns.\(^{13,14}\) The \( \text{CO}_2 \) waveform (capnogram) has been characterized for adult patients with normal and abnormal pulmonary function.\(^{15,16}\) In newborns,
The leakage rate (%) of PaCO2/PETCO2 when leakage rate was 60% did not significantly increase PaCO2. However, the leakage rate of 60% showed significant deviations between PaCO2 and PETCO2.

**Figure 5** Effects of leakage rate on end-tidal carbon dioxide pressure (PaCO2) and partial CO2 pressure (PETCO2). When leakage rate was <60%, no significant differences were seen between PaCO2 and PETCO2 compared to the group in which the leakage rate was 0–10%. However, groups with leakage rate 60% showed significant deviations between PaCO2 and PETCO2.

**Figure 6** Regarding the expiratory plateau phase, when alveolar mixed gas was expired, a relatively constant partial CO2 pressure (PaCO2) was maintained, as shown by the capnogram for the 6 mL/kg tidal volume/body weight (TV/BW) group.

**Figure 4** Effects of additional dead space on partial carbon dioxide pressure (PaCO2) under conditions of 12 mL or 20 mL of tidal volume (TV). Under conditions of 12 mL of TV (6 mL/kg), PaCO2 was significantly increased by a dead space increase of only 1 mL. Under conditions of 20 mL of TV (10 mL/kg), even a dead space increase of 1 mL did not significantly increase PaCO2. PaCO2 appears to be affected by a dead space increase of >7% of TV.

**Figure 4** shows the effects of additional dead space on PaCO2. Under conditions of 6 mL/kg of TV, PaCO2 was significantly increased by a dead space increase of only 1 mL, representing >7% of TV. Figureas et al reported that the introduction of the pneumotachometer, which has a dead space of 1.6 mL for 10 minutes, led to a transcutaneous PCO2 increase of 5.40 ± 2.66 mmHg, from 39.76 ± 8.69 mmHg to 45.17 ± 9.22 mmHg (P = 0.0000) in newborn infants. However, they did not measure PaCO2 directly, nor they did change the amount of dead space when measuring transcutaneous PCO2.
With respect to lung injury, too high volumes/pressures and/or too low positive end expiratory pressure promotes degradation of the lungs, so-called ventilator-induced lung injury, and is associated with high mortality. Such injuries are known to result in local alterations in lung compliance and pulmonary edema secondary to capillary leakage and are important contributing factors to the pathogenesis of chronic lung disease in neonates.

To the best of the authors’ knowledge, no studies have described the effects of endotracheal tube leakage on $P_{ET \ CO_2}$. Leakage is more of a problem in children than in adults because of the use of uncuffed endotracheal tubes. Capnography offers direct monitoring of the inhaled and exhaled concentrations or partial pressure of CO$_2$. The amount of endotracheal tube leakage around an uncuffed endotracheal tube is thus larger, and significant differences between PaCO$_2$ and $P_{ET \ CO_2}$ might arise.

No significant differences were found between PaCO$_2$ and $P_{ET \ CO_2}$ when the leakage rate was <60%, similar to the group in which leakage rate was 0%–10%. However, in groups with a leakage rate 60%, significant deviations were seen between PaCO$_2$ and $P_{ET \ CO_2}$.

Also, regarding the expiratory plateau phase, a relatively constant PCO$_2$ was maintained, as shown by the capnogram for 10 mL/kg TV/BW and leakage ratio <60% (Figure 6).

This analysis of rabbits weighing 2 kg revealed good correlation and agreement between PaCO$_2$ and $P_{ET \ CO_2}$. However, only deep anesthetized rabbits weighing 2 kg were used. In addition, $P_{ET \ CO_2}$ was measured in rabbits using the setting of limited mechanical ventilation. Further studies using different conditions are warranted to further elucidate this area.

Conclusion
A strong correlation was obtained and there was no bias between $P_{ET \ CO_2}$ and PaCO$_2$ when TV/BW was 6–15 mL/kg and the leakage rate was <60%. Lightweight and low amounts of dead space capnometer may be used in very low birth weight infants with small TV.

Disclosure
The authors report no conflicts of interest in this work.

References
20. Bhat R, Kim WD, Shukla A, Vidyasagar D. Simultaneous tissue pH and/or too low positive end expiratory pressure promotes degradation of the lungs, so-called ventilator-induced lung injury, and is associated with high mortality. Such injuries are known to result in local alterations in lung compliance and pulmonary edema secondary to capillary leakage and are important contributing factors to the pathogenesis of chronic lung disease in neonates.


