



# Variability of Resting Carbon Dioxide Tension in Patients with Intracranial Steno-occlusive Disease

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## Abstract

**Introduction** Controlling the partial pressure of carbon dioxide (PaCO<sub>2</sub>) is an important consideration in patients with intracranial steno-occlusive disease to avoid reductions in critical perfusion from vasoconstriction due to hypocapnia, or reductions in blood flow due to steal physiology during hypercapnia. However, the normal range for resting PCO<sub>2</sub> in this patient population is not known. Therefore, we investigated the variability in resting end-tidal PCO<sub>2</sub> (P<sub>ET</sub>CO<sub>2</sub>) in patients with intracranial steno-occlusive disease and the impact of revascularization on resting P<sub>ET</sub>CO<sub>2</sub> in these patients.

**Setting and Design** Tertiary care center, retrospective chart review

**Materials and Methods** We collected resting P<sub>ET</sub>CO<sub>2</sub> values in adult patients with intracranial steno-occlusive disease who presented to our institution between January 2010 and June 2021. We also explored postrevascularization changes in resting P<sub>ET</sub>CO<sub>2</sub> in a subset of patients.

**Results** Two hundred and twenty-seven patients were included [moyamoya vasculopathy ( $n = 98$ ) and intracranial atherosclerotic disease ( $n = 129$ )]. In the whole cohort, mean  $\pm$  standard deviation resting P<sub>ET</sub>CO<sub>2</sub> was  $37.8 \pm 3.9$  mm Hg (range: 26–47). In patients with moyamoya vasculopathy and intracranial atherosclerotic disease, resting P<sub>ET</sub>CO<sub>2</sub> was  $38.4 \pm 3.6$  mm Hg (range: 28–47) and  $37.4 \pm 4.1$  mm Hg (range: 26–46), respectively. A trend was identified suggesting increasing resting P<sub>ET</sub>CO<sub>2</sub> after revascularization in patients with low preoperative resting P<sub>ET</sub>CO<sub>2</sub> (<38 mm Hg) and decreasing resting P<sub>ET</sub>CO<sub>2</sub> after revascularization in patients with high preoperative resting P<sub>ET</sub>CO<sub>2</sub> (>38 mm Hg).

**Conclusions** This study demonstrates that resting P<sub>ET</sub>CO<sub>2</sub> in patients with intracranial steno-occlusive disease is highly variable. In some patients, there was a change in resting P<sub>ET</sub>CO<sub>2</sub> after a revascularization procedure.

## Keywords

- ▶ resting PCO<sub>2</sub>
- ▶ cerebrovascular reactivity
- ▶ intracranial atherosclerotic disease
- ▶ moyamoya vasculopathy
- ▶ steno-occlusive disease

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## Introduction

Carbon dioxide (CO<sub>2</sub>) is a potent modulator of cerebrovascular tone. Hence, controlling the partial pressure of carbon dioxide (PCO<sub>2</sub>) is an important consideration in perioperative neurosurgical care. Importance of CO<sub>2</sub> in patients with raised intracranial pressure has been well known.<sup>1,2</sup> Although preliminary evidence suggests that CO<sub>2</sub> management plays an important role in patients with intracranial steno-occlusive disease (SOD), researchers have not explicitly considered this in their study. In patients with intracranial SOD, hypocapnia may cause further reductions in perfusion of critical vascular beds due to vasoconstriction and hypercapnia may cause localized vasodilation resulting in steal physiology in vulnerable vascular beds leading to exacerbation of cerebral ischemia.<sup>3,4</sup> Maintaining normocapnia is an important recommendation in patients with intracranial SOD undergoing cerebral revascularization procedures.<sup>5–7</sup> Hence, clinicians need to know the resting CO<sub>2</sub> levels of a patient with SOD undergoing a surgical procedure to avoid cerebral ischemic insults and steal phenomenon.

Traditionally, the normal range of resting PaCO<sub>2</sub> has been considered to be within 35 to 45 mm Hg.<sup>8,9</sup> The reference standard for measuring CO<sub>2</sub> is partial pressure of CO<sub>2</sub> in arterial blood (PaCO<sub>2</sub>), which requires an arterial puncture. However, end-tidal CO<sub>2</sub> (P<sub>ET</sub>CO<sub>2</sub>) is a noninvasive method that is often used to predict PaCO<sub>2</sub> values, especially when the arterial to end-tidal gradient is known.<sup>10</sup>

We and others have observed resting P<sub>ET</sub>CO<sub>2</sub> values outside the normal range (35–45 mm Hg) in patients with SOD presenting for surgical revascularization.<sup>11,12</sup> This is important because maintaining normocapnia based on the traditional range might increase the risk of cerebral ischemia in a patient whose resting CO<sub>2</sub> is outside the normal range. Thus, understanding the variability of CO<sub>2</sub> in patients with intracranial SOD is important for individualized control of CO<sub>2</sub> to improve patient outcomes.

In this study, two research questions were investigated. First, we sought to investigate the variability of resting P<sub>ET</sub>CO<sub>2</sub> in patients with intracranial SOD by examining the distribution of this measurement within our study population. We hypothesized that patients with intracranial SOD would have considerable variability in resting P<sub>ET</sub>CO<sub>2</sub>, extending outside the traditional range of 35 to 40 mm Hg. Second, we explored the impact of a revascularization surgery on resting P<sub>ET</sub>CO<sub>2</sub> in patients with intracranial SOD. Given the exploratory nature of this research question, we adopted no a priori hypothesis.

## Materials and Methods

### Study Design

After Institutional Research Ethics Board (REB # 22-5923, December 22, 2022) approval, we conducted a retrospective chart review of all patients over 18 years old with intracranial SOD who presented to our institution between January 2010 and June 2021. We included patients with symptomatic intracranial SOD who underwent cerebrovascular reactivity

(CVR) assessment as part of their clinical care. We excluded patients with extracranial SOD and those who did not have CVR assessments.

CVR assessment is our standard clinical care for patients who present with intracranial SOD. CVR assessments are done using precisely controlled carbon dioxide [hypercapnia (resting P<sub>ET</sub>CO<sub>2</sub> + 10 mm Hg)] as a vasodilatory stimulus and Blood Oxygen Level Dependent Magnetic Resonance Imaging (BOLD-MRI) serves as a surrogate for cerebral blood flow. CVR is calculated as a ratio of the change in the BOLD signal to the change in P<sub>ET</sub>CO<sub>2</sub>. Based on the patients' CVR assessment, a revascularization surgery (superficial temporal artery to middle cerebral artery bypass) was performed on patients that demonstrated impaired or paradoxical (steal physiology) CVR. After revascularization, patients' CVRs were reassessed at approximately 1 year to determine if the surgery improved steal physiology.

Changes in P<sub>ET</sub>CO<sub>2</sub> were administered by an automated gas blender (RespirAct Thornhill Medical, Toronto, Canada) using sequential gas delivery.<sup>13–15</sup> This system measures the breath-to-breath P<sub>ET</sub>CO<sub>2</sub>, which is used to calculate the gas flow for the subsequent breath to target end-tidal gases. The computer precalculates the required breath-by-breath inspired gas concentrations and adjusts the inspiratory flow accordingly, regardless of the patient's tidal volume or breathing pattern.<sup>15,16</sup> The sequential gas delivery circuit contains an exhaled gas reservoir and uses rebreathed gas as reserve gas for control of end-tidal PCO<sub>2</sub> (more detail provided in Fisher et al 2016<sup>15</sup> and Somogyi et al 2005<sup>14</sup>). P<sub>ET</sub>CO<sub>2</sub> measured by this system has been shown to be equal to PaCO<sub>2</sub>.<sup>10,17,18</sup> The apparatus and technique to control P<sub>ET</sub>CO<sub>2</sub> have been described in greater detail elsewhere.<sup>13,19</sup>

### Data Collection

The data sources used for the present work included the prospective CVR database described above and our institution's electronic patient record (QuadraMed Corporation, Reston, Virginia, United States). Data collected included patient demographics, clinical diagnoses, details of surgical intervention, CVR assessments, and resting P<sub>ET</sub>CO<sub>2</sub> values. Resting P<sub>ET</sub>CO<sub>2</sub> values were collected from preoperative and postoperative CVR assessments. They were measured prior to CVR testing (i.e., before applying hypercapnia) and the measurements were done over a 5 minutes period at rest. In addition, in a subset of patients who underwent revascularization surgery, PaCO<sub>2</sub> values from the preinduction arterial line were collected.

### Statistical Analysis

All analyses were performed using R Statistical Software (v3.5.0; R Core Team 2018). A sample size calculation was not performed due to the exploratory nature of this study. Continuous data are presented as mean ± standard deviation. Variability in resting P<sub>ET</sub>CO<sub>2</sub> values was presented as a range. As a part of the secondary analysis, based on preoperative resting P<sub>ET</sub>CO<sub>2</sub> values, a median split was performed to subset patients into "high" and "low" preoperative values. Paired sample *t*-tests were used to compare preoperative

resting P<sub>ET</sub>CO<sub>2</sub> values with postoperative resting P<sub>ET</sub>CO<sub>2</sub> values. A statistical significance threshold of *p*-value less than 0.05 was used. Finally, a Bland–Altman plot was generated to compare P<sub>ET</sub>CO<sub>2</sub> values from CVR testing with PaCO<sub>2</sub> measurements of arterial blood gas.

**Results**

Two hundred and twenty-seven patients who met the inclusion criteria were included in the study. Ninety-eight patients had moyamoya vasculopathy (MMV) (age: 42.2 ± 15.2 years, 63.3% female) and 129 patients had intracranial atherosclerotic disease (ICAD) (age: 57.8 ± 15.9 years, 51.9% female).

**Preoperative Variability of Resting P<sub>ET</sub>CO<sub>2</sub> in Patients with Steno-occlusive Disease**

In the whole sample, resting P<sub>ET</sub>CO<sub>2</sub> was 37.9 ± 4.0 mm Hg (range: 26–47). Resting P<sub>ET</sub>CO<sub>2</sub> values in MMV disease and ICAD were 38.4 ± 3.7 mm Hg (range: 28–47) and 37.5 ± 4.1 mm Hg (range: 26–46), respectively. A frequency histogram of resting P<sub>ET</sub>CO<sub>2</sub> values across MMV and ICAD groups is shown in ►Fig. 1. In the entire group, the median value for preoperative resting P<sub>ET</sub>CO<sub>2</sub> was 38 mm Hg.

In the whole patient sample, 41.4% (94/227) had resting P<sub>ET</sub>CO<sub>2</sub> values outside the range of 35 to 40 mm Hg; 38.8% (38/98) of patients with MMV and 43.4% (56/129) of patients

with ICAD had resting P<sub>ET</sub>CO<sub>2</sub> values outside the range of 35 to 40 mm Hg.

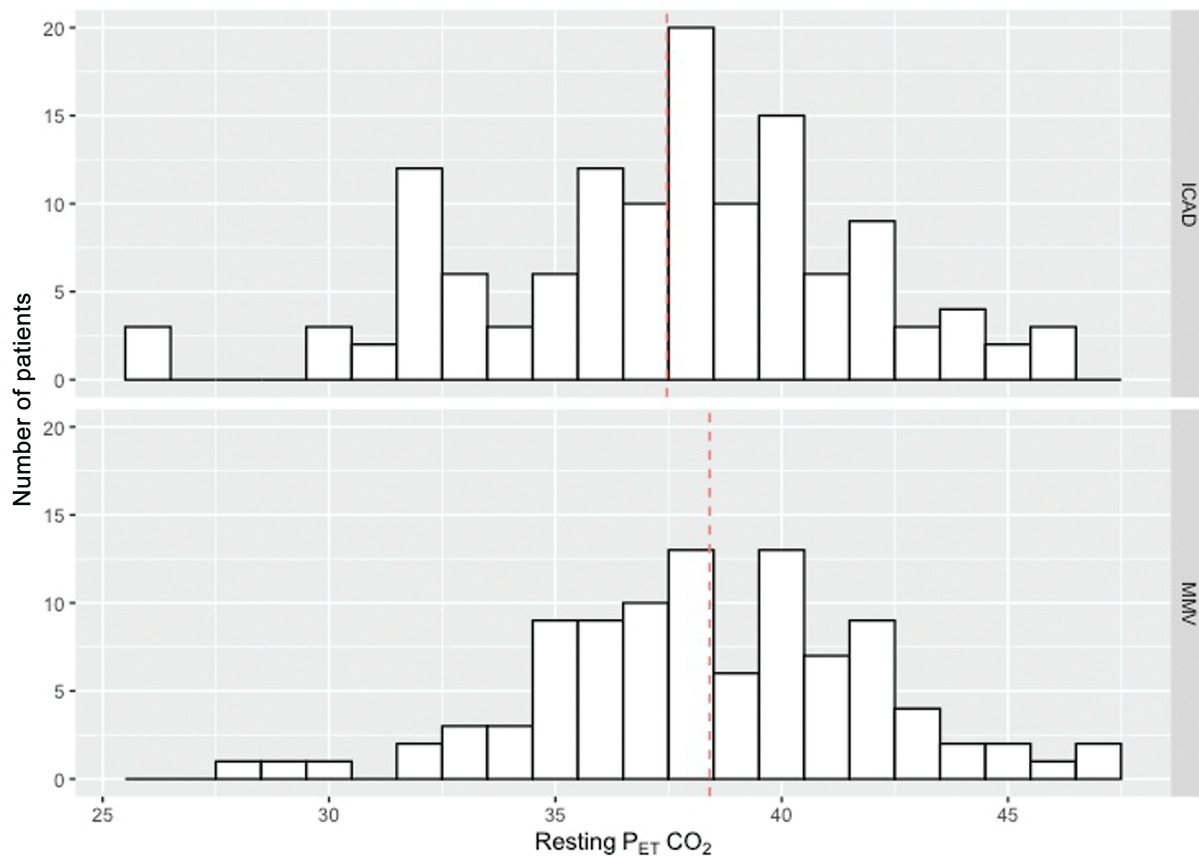
**Effect of Surgical Revascularization on Resting P<sub>ET</sub>CO<sub>2</sub> in Patients with Steno-occlusive Disease**

Out of 227 patients with intracranial SOD, 50 patients underwent successful surgical revascularization (i.e., CVR improved at 1 year and they were clinically asymptomatic). Within this cohort, we compared preoperative and postoperative resting P<sub>ET</sub>CO<sub>2</sub> and found no statistically significant differences (*t* = 0.10, *p* = 0.92).

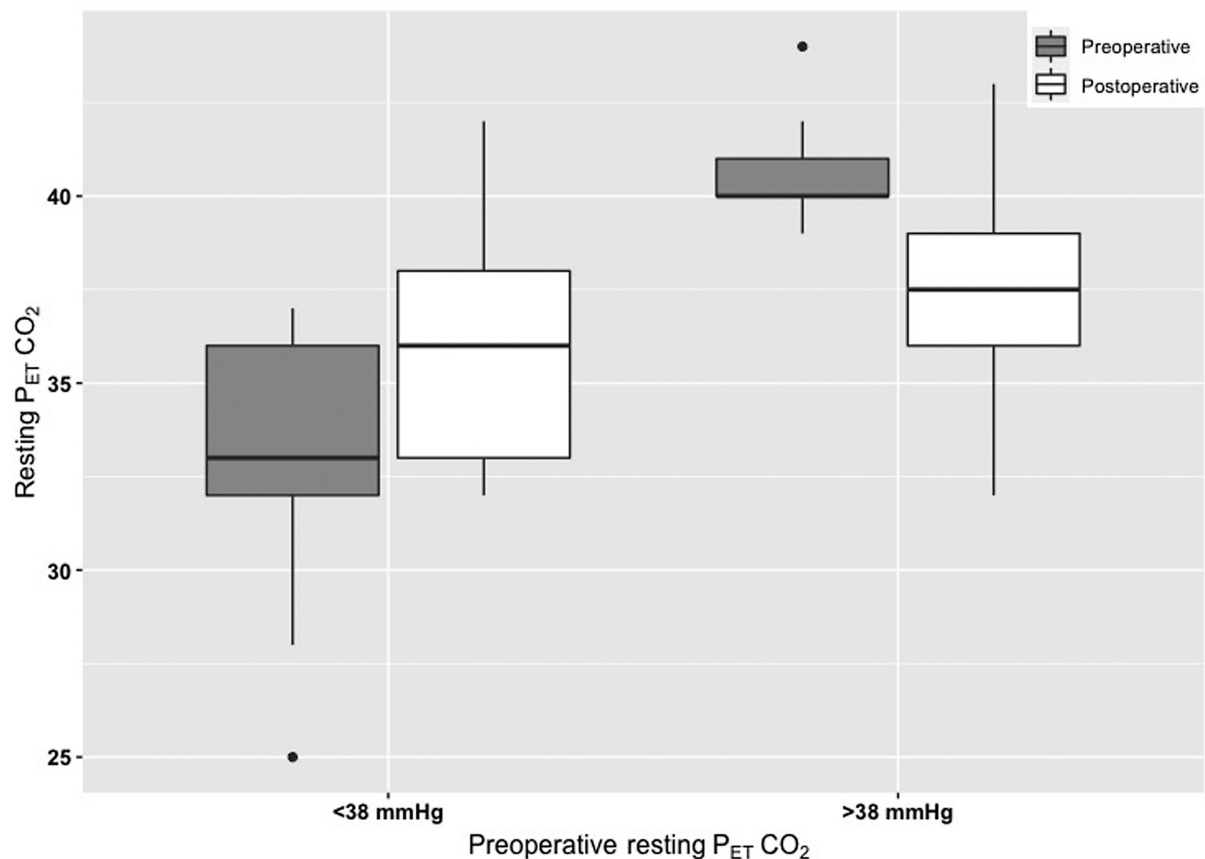
In patients with a preoperative resting P<sub>ET</sub>CO<sub>2</sub> more than 38 mm Hg (*n* = 22), revascularization led to a reduction in the postoperative resting P<sub>ET</sub>CO<sub>2</sub> (*t* = 5.28, *p* < 0.001). In patients with a preoperative resting P<sub>ET</sub>CO<sub>2</sub> less than 38 mm Hg (*n* = 21), following revascularization there was an increase in postoperative resting P<sub>ET</sub>CO<sub>2</sub> (*t* = 2.74, *p* = 0.013; ►Fig. 2).

**Comparing Resting P<sub>ET</sub>CO<sub>2</sub> and PaCO<sub>2</sub>**

In 20 patients that underwent surgical revascularization, PaCO<sub>2</sub> was measured from their preinduction arterial line while they were awake and without any sedation. Within this cohort, we compared resting PaCO<sub>2</sub> with P<sub>ET</sub>CO<sub>2</sub> from preoperative CVR assessments. Resting PaCO<sub>2</sub> was 33.8 ± 4.6 mm Hg (range: 26–41) and P<sub>ET</sub>CO<sub>2</sub> was 34.0 ± 4.7 mm Hg (range: 25–42). A Bland–Altman graph comparing resting P<sub>ET</sub>CO<sub>2</sub> with PaCO<sub>2</sub> demonstrates the



**Fig. 1** Number of patients with resting P<sub>ET</sub>CO<sub>2</sub> values within the total sample. ICAD, intracranial atherosclerotic disease; MMV, Moyamoya vasculopathy; P<sub>ET</sub>CO<sub>2</sub>, End-tidal partial pressure of carbon dioxide. The dotted vertical line illustrates the mean value.



**Fig. 2** Preoperative and postoperative resting P<sub>ET</sub>CO<sub>2</sub> following revascularization in a subset of the whole sample, split by those with preoperative resting P<sub>ET</sub>CO<sub>2</sub> values below 38 mmHg and those above 38 mmHg. P<sub>ET</sub>CO<sub>2</sub>, End-tidal partial pressure of carbon dioxide.

minimal discrepancy between these measures across the full range of average measurements (►Fig. 3); the difference between PaCO<sub>2</sub> and P<sub>ET</sub>CO<sub>2</sub> values was less than or equal to 2 mm Hg in 95% (19/20) of patients.

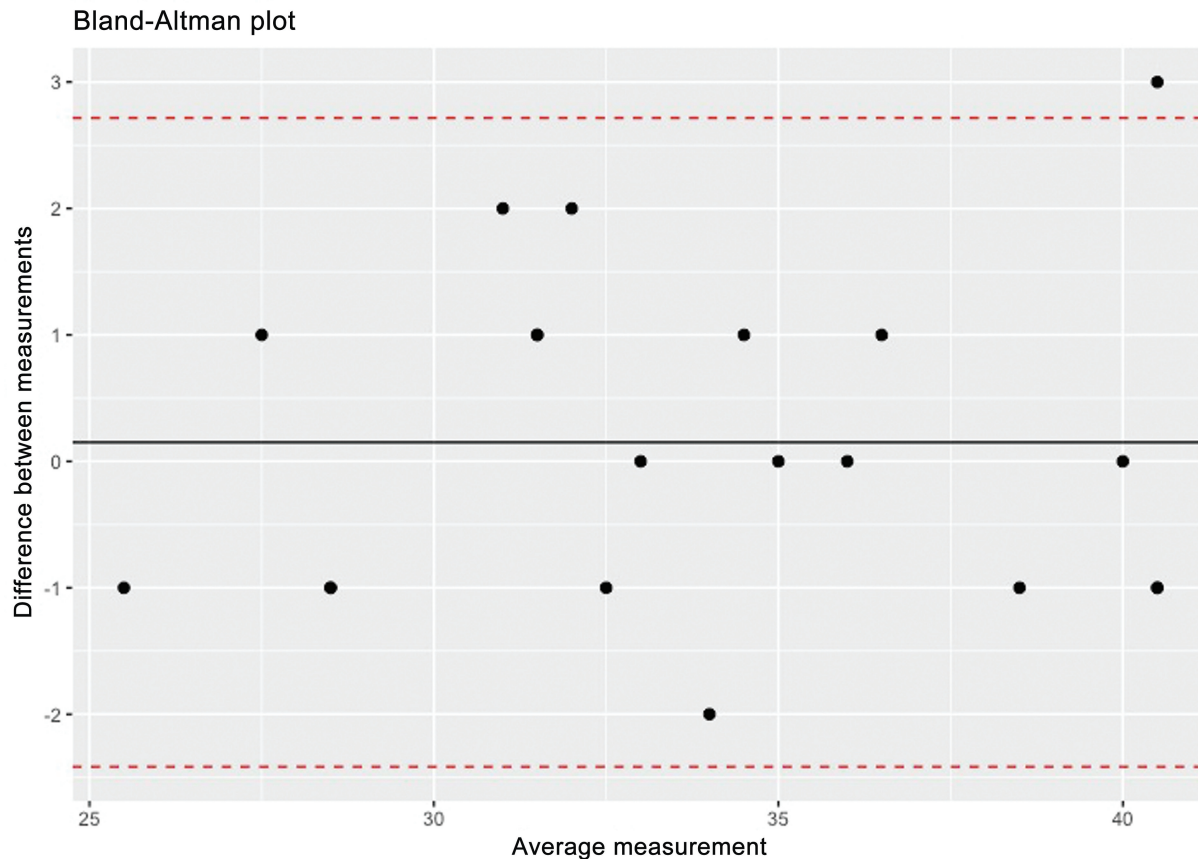
## Discussion

To the best of our knowledge, this is the first investigation to examine the variability of resting P<sub>ET</sub>CO<sub>2</sub> in patients with intracranial SOD. Our study demonstrates that resting P<sub>ET</sub>CO<sub>2</sub> varies considerably between individual patients. Although the mean value of P<sub>ET</sub>CO<sub>2</sub> in our studied group was around 38 mm Hg, many individuals had P<sub>ET</sub>CO<sub>2</sub> values lower or higher than the normal range of 35 to 40 mm Hg. Indeed, 41.4% (94/227) of patients had resting P<sub>ET</sub>CO<sub>2</sub> values outside this range. Further, in some patients, there was a change in resting P<sub>ET</sub>CO<sub>2</sub> subsequent to revascularization procedures. These findings suggest a role for resting PaCO<sub>2</sub> in the regulation of cerebral blood flow in patients with disrupted CVR and steal phenomenon.

CO<sub>2</sub> is a potent vasoactive stimulus and an important driver of cerebral blood flow. Hence, PaCO<sub>2</sub> plays an important role in patients with SOD. In patients with intracranial SOD, a global vasodilatory stimulus such as hypercapnia can lead to a paradoxical decrease in blood flow in the regions distal to stenosis as the blood flow is redistributed from more affected to lesser affected vessels. This phenomenon is known as

“vascular steal,” arising from redistribution of blood flow away from an area with exhausted vascular reserve to vascular beds with intact reserve and thus an ability to lower flow resistance. Intracerebral steal is a strong marker for the risk of cerebral ischemia.<sup>3</sup> Kurehara et al studied the effect of hypercapnia on cortical blood flow in patients with moyamoya disease (MMD) using a laser-doppler method.<sup>20</sup> They showed a decrease in regional cortical blood flow with hypercapnia and confirmed that the normal cortical blood flow response to hypercapnia was impaired during surgery. Using positron emission tomography, another study showed that patients with MMD had severely decreased cerebrovascular responses to hypercapnia over the cerebral cortex.<sup>21</sup> There have been similar findings reported in children suffering from MMD.<sup>22</sup>

Hypocapnia, on the other hand, causes cerebral vasoconstriction and puts patients with MMD more at risk of cerebral ischemia.<sup>23</sup> Using positron emission tomography and single photon emission computed tomography, another study on patients with MMD has demonstrated that the reduced CVR to hypocapnia with hyperventilation preoperatively preoperatively is associated with the development of cerebral hyperperfusion syndrome after cerebral revascularization surgery.<sup>24</sup> Additionally, transient ischemic attack has been observed in children with MMD who have experienced hyperventilation due to crying or exercise.<sup>25-27</sup> In a study using 133-Xe inhalation methods, Tagawa et al have shown that hyperventilation (PaCO<sub>2</sub> < 29 mm Hg) decreased



**Fig. 3** Bland-Altman plot comparing resting  $P_{ET}CO_2$  with  $PaCO_2$  in patients with the intracranial steno-occlusive disease.  $P_{ET}CO_2$  was measured using the RespirAct machine, whereas  $PaCO_2$  values were obtained from pre-induction arterial lines. The observed discrepancy between  $P_{ET}CO_2$  with  $PaCO_2$  is minimal across the full range of average measurements.

regional cerebral blood flow in children with MMD.<sup>28</sup> Hence, one of the important goals in patients with intracranial SOD undergoing cerebral revascularization is to maintain normocapnia and avoidance of hypotension.<sup>11,29,30</sup>

The published literature describes a normal resting  $PaCO_2$  range of 35 to 45 mm Hg.<sup>8,9,31</sup> However, variability in the resting  $PaCO_2$  has been observed both in healthy subjects and in patients with intracranial SOD.<sup>1,12,31</sup> Crosby and Robbins observed within-subject, between-day variability, and between-subject variations in the level of  $PaCO_2$ .<sup>31</sup> They observed within-subject, between-day  $PaCO_2$  differences of 4 mm Hg. Recently, Song et al explored the association between  $P_{ET}CO_2$  levels and neurological outcomes in patients undergoing revascularization for MMD.<sup>11</sup> In their study, 60.7% of patients were hypocapnic (< 35 mm Hg) and the mean  $P_{ET}CO_2$  level was  $33.63 \pm 3.54$ . In our study, 41.4% (94/227) of patients had resting  $P_{ET}CO_2$  values outside the traditional normal range (35–40 mm Hg), emphasizing the importance of identifying the baseline  $PaCO_2$  immediately prior to induction using the arterial blood gas sample to then titrate the intraoperative  $PCO_2$  near baseline.

Maintaining normocapnia based on the traditional range might increase the risk of cerebral ischemia in a patient whose resting  $CO_2$  is outside the normal range. For example, a patient with a resting  $PaCO_2$  of 26 mm Hg will be at a high risk of cerebral ischemia due to intracerebral steal phenom-

enon if intraoperative  $PaCO_2$  is kept within the traditional range of 35 to 40 mm Hg. Conversely, hypocapnia can lead to severe vasoconstriction in a patient with a resting  $PaCO_2$  of 46 mm Hg. Thus, understanding the variability of  $CO_2$  in patients with intracranial SOD is important for individualized control of  $CO_2$  to improve patient outcomes.

The reason for the variability in resting  $P_{ET}CO_2$  in patients with intracranial SOD is not known. We postulate that the low resting  $P_{ET}CO_2$  in this patient population may be to minimize the steal phenomenon associated with hypercapnia. Conversely, a high resting  $P_{ET}CO_2$  may be a compensatory mechanism in some patients to facilitate collateral flow. For example, MMV is often a bilateral disease; hence, these patients may have higher than normal  $PCO_2$  at rest to maintain cerebral blood flow. Hence, resting  $PaCO_2$  might play a role in the regulation of cerebral blood flow in patients with disrupted CVR and steal phenomenon. While an increase in blood pressure is a well-established compensatory mechanism for cerebral ischemia, it is possible that changes in resting  $PaCO_2$  can similarly be a compensatory mechanism in patients with intracranial SOD to prevent cerebral ischemia.<sup>32–34</sup> We speculate that blood flow changes to the central chemoreceptors may be causing the resting  $PaCO_2$  changes.

As a part of an exploratory secondary analysis, we also compared preoperative and postoperative resting  $P_{ET}CO_2$  in a subset of patients who underwent successful revascularization

to test the hypothesis if the change in ischemic burden can lead to a change in resting P<sub>ET</sub>CO<sub>2</sub>. Though there were no significant differences between preoperative and postoperative resting P<sub>ET</sub>CO<sub>2</sub> values overall, a trend was identified suggesting increasing resting P<sub>ET</sub>CO<sub>2</sub> after revascularization in patients with low preoperative resting P<sub>ET</sub>CO<sub>2</sub> and decreasing resting P<sub>ET</sub>CO<sub>2</sub> after revascularization in patients with high preoperative resting P<sub>ET</sub>CO<sub>2</sub>.

The reference standard for measuring PCO<sub>2</sub> is PaCO<sub>2</sub>, which requires an arterial puncture. However, P<sub>ET</sub>CO<sub>2</sub> is a noninvasive method that is often used to predict PaCO<sub>2</sub> values, especially when the arterial to end-tidal gradient is known.<sup>10</sup> The normal PaCO<sub>2</sub>-P<sub>ET</sub>CO<sub>2</sub> gradient is considered to be 2 to 5 mm Hg.<sup>35</sup> This difference in healthy individuals is related to the alveolar dead space, where alveoli that are ventilated but not perfused lead to the dilution of P<sub>ET</sub>CO<sub>2</sub> and the creation of the gradient. In our study, resting P<sub>ET</sub>CO<sub>2</sub> was measured using the sequential gas delivery method and P<sub>ET</sub>CO<sub>2</sub> measured by this system has been shown to be equal to PaCO<sub>2</sub>.<sup>17,18</sup> We also confirmed this finding in our study.

This study has a number of major limitations, including its retrospective design. First, preoperative resting P<sub>ET</sub>CO<sub>2</sub> was measured with the RespirAct during CVR testing and PaCO<sub>2</sub> was measured from the awake pre-induction arterial blood gas on the day of surgery, resulting in a time gap of approximately 3 months. Second, we did not investigate changes in resting P<sub>ET</sub>CO<sub>2</sub> in patients who underwent intracranial stenting procedures, which may have produced different results. Finally, despite a sample size calculation not being performed a priori, the effect sizes observed in the current work within the median split analyses investigating the impact of revascularization procedures on patients with “high” and “low” preoperative values (“high” 1.13 and “low” 0.59) would require 9 and 25 participants, respectively, at an alpha probability of 0.05 and power of 0.8 in a two-tailed investigation.

## Conclusion

In conclusion, patients with intracranial SOD displayed considerable variability in resting P<sub>ET</sub>CO<sub>2</sub>. Further, in some patients, there was a change in resting P<sub>ET</sub>CO<sub>2</sub> subsequent to a revascularization procedure. Future work is necessitated to replicate these findings using matched controls and controlling for possible confounding factors.

### Note

Controlling the partial pressure of carbon dioxide is an important consideration in perioperative neurosurgical care, as both hypocapnia and hypercapnia may lead to complications. This study shows that the resting (i.e., baseline) partial pressure of carbon dioxide in patients with intracranial steno-occlusive disease is highly variable and may be impacted by revascularization procedures. Further research is necessitated to improve our understanding of this phenomenon.

### Previous Presentation

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Place: Quebec City, Quebec, Canada

Date: June 10<sup>th</sup>, 2023

### Authors' Contributions

E.P. contributed to conceptualization, experimental studies, data acquisition, and provided guarantee. L.V. helped in experimental studies. S.A. was involved in conceptualization, designing, literature search, clinical studies, experimental studies, data acquisition, statistical analysis, and provided guarantee. V.R., T.C., O.S., and E.S.S. contributed to conceptualization, designing, literature search, clinical studies, experimental studies, data analysis, statistical analysis, and provided guarantee. J.P., J.D., D.M., and J.F. helped in literature search and experimental studies and provided guarantee.

### Ethical Approval

UHN REB # 22-5923, December 22, 2022

### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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This study was funded in part by a grant from MSH-UHN AMO AFP Innovation fund 2013-15.

### Conflict of Interest

RespirAct is currently a noncommercial research tool assembled and made available by Thornhill Research Inc. (TRI), a spin-off company from the University Health Network to research institutions to enable CVR studies. J.F. is the Chief Scientist and J.D. is the Senior Scientist at TRI, and J.P., O.S., and D.M. have contributed to the development of RespirAct and have received payments from, or shares in, TRI.

## References

- 1 Akça O. Optimizing the intraoperative management of carbon dioxide concentration. *Curr Opin Anaesthesiol* 2006;19(01):19–25
- 2 Brian JE Jr. Carbon dioxide and the cerebral circulation. *Anesthesiology* 1998;88(05):1365–1386
- 3 Sobczyk O, Battisti-Charbonney A, Fierstra J, et al. A conceptual model for CO<sub>2</sub>-induced redistribution of cerebral blood flow with experimental confirmation using BOLD MRI. *Neuroimage* 2014;92:56–68
- 4 Arteaga DF, Strother MK, Faraco CC, et al. The vascular steal phenomenon is an incomplete contributor to negative cerebrovascular reactivity in patients with symptomatic intracranial stenosis. *J Cereb Blood Flow Metab* 2014;34(09):1453–1462
- 5 Zipfel GJ, Fox DJ Jr, Rivet DJ. Moyamoya disease in adults: the role of cerebral revascularization. *Skull Base* 2005;15(01):27–41
- 6 Kim SH, Choi JU, Yang KH, Kim TG, Kim DS. Risk factors for postoperative ischemic complications in patients with moyamoya disease. *J Neurosurg* 2005;103(05, suppl):433–438
- 7 Michenfelder JD. Anesthesia for cerebral surgery. In: Stanley TH, Petty WC, eds. *New Anesthetic Agents, Devices and Monitoring*. 1st ed. New York: Springer-Verlag; 1983:45–49

- 8 Deng RM, Liu YC, Li JQ, Xu JG, Chen G. The role of carbon dioxide in acute brain injury. *Med Gas Res* 2020;10(02):81–84
- 9 Messina Z, Patrick H Partial Pressure of Carbon Dioxide. 2022 Sep 26. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2024 Jan. PMID: 31869112
- 10 Ito S, Mardimae A, Han J, et al. Non-invasive prospective targeting of arterial P(CO<sub>2</sub>) in subjects at rest. *J Physiol* 2008;586(15):3675–3682
- 11 Song T, Liu X, Han R, Huang L, Zhang J, Xu H. Effects of end-tidal carbon dioxide levels in patients undergoing direct revascularization for Moyamoya disease and risk factors associated with postoperative complications. *Medicine (Baltimore)* 2021;100(07):e24527
- 12 Raghavan V, Sobczyk O, Sayin ES, et al. Assessment of cerebrovascular reactivity using CO<sub>2</sub>-BOLD MRI: a 15-year, single center experience. *J Magn Reson Imaging* 2023;•••. Doi: 10.1002/jmri.29176
- 13 Slessarev M, Han J, Mardimae A, et al. Prospective targeting and control of end-tidal CO<sub>2</sub> and O<sub>2</sub> concentrations. *J Physiol* 2007; 581(Pt 3):1207–1219
- 14 Somogyi RB, Vesely AE, Preiss D, et al. Precise control of end-tidal carbon dioxide levels using sequential rebreathing circuits. *Anaesth Intensive Care* 2005;33(06):726–732
- 15 Fisher JA, Iscoe S, Duffin J. Sequential gas delivery provides precise control of alveolar gas exchange. *Respir Physiol Neurobiol* 2016; 225:60–69
- 16 Sobczyk O, Battisti-Charbonney A, Poulblanc J, et al. Assessing cerebrovascular reactivity abnormality by comparison to a reference atlas. *J Cereb Blood Flow Metab* 2015;35(02):213–220
- 17 Fierstra J, Winter JD, Machina M, et al. Non-invasive accurate measurement of arterial PCO<sub>2</sub> in a pediatric animal model. *J Clin Monit Comput* 2013;27(02):147–155
- 18 Fierstra J, Machina M, Battisti-Charbonney A, Duffin J, Fisher JA, Minkovich L. End-inspiratory rebreathing reduces the end-tidal to arterial PCO<sub>2</sub> gradient in mechanically ventilated pigs. *Intensive Care Med* 2011;37(09):1543–1550
- 19 Fisher JA. The CO<sub>2</sub> stimulus for cerebrovascular reactivity: fixing inspired concentrations vs. targeting end-tidal partial pressures. *J Cereb Blood Flow Metab* 2016;36(06):1004–1011
- 20 Kurehara K, Ohnishi H, Touho H, Furuya H, Okuda T. Cortical blood flow response to hypercapnia during anaesthesia in Moyamoya disease. *Can J Anaesth* 1993;40(08):709–713
- 21 Kuwabara Y, Ichiya Y, Sasaki M, et al. Response to hypercapnia in moyamoya disease. Cerebrovascular response to hypercapnia in pediatric and adult patients with moyamoya disease. *Stroke* 1997;28(04):701–707
- 22 Ogawa A, Nakamura N, Yoshimoto T, Suzuki J. Cerebral blood flow in moyamoya disease. Part 2: Autoregulation and CO<sub>2</sub> response. *Acta Neurochir (Wien)* 1990;105(3–4):107–111
- 23 Iwama T, Hashimoto N, Yonekawa Y. The relevance of hemodynamic factors to perioperative ischemic complications in childhood moyamoya disease. *Neurosurgery* 1996;38(06):1120–1125, discussion 1125–1126
- 24 Sato S, Kojima D, Shimada Y, et al. Preoperatively reduced cerebrovascular contractile reactivity to hypocapnia by hyperventilation is associated with cerebral hyperperfusion syndrome after arterial bypass surgery for adult patients with cerebral misery perfusion due to ischemic moyamoya disease. *J Cereb Blood Flow Metab* 2018;38(06):1021–1031
- 25 Fukuyama Y, Umezumi R. Clinical and cerebral angiographic evolutions of “idiopathic progressive occlusive disease of the circle of Willis (moyamoya” disease) in children. *Brain Dev* 1985;7(01): 21–37
- 26 Baykan N, Ozgen S, Ustalar ZS, Dagçınar A, Ozek MM. Moyamoya disease and anesthesia. *Paediatr Anaesth* 2005;15(12):1111–1115
- 27 Nomura S, Kashiwagi S, Uetsuka S, Uchida T, Kubota H, Ito H. Perioperative management protocols for children with moyamoya disease. *Childs Nerv Syst* 2001;17(4–5):270–274
- 28 Tagawa T, Naritomi H, Mimaki T, Yabuuchi H, Sawada T. Regional cerebral blood flow, clinical manifestations, and age in children with moyamoya disease. *Stroke* 1987;18(05):906–910
- 29 Chiu D, Shedden P, Bratina P, Grotta JC. Clinical features of moyamoya disease in the United States. *Stroke* 1998;29(07): 1347–1351
- 30 Parray T, Martin TW, Siddiqui S. Moyamoya disease: a review of the disease and anesthetic management. *J Neurosurg Anesthesiol* 2011;23(02):100–109
- 31 Crosby A, Robbins PA. Variability in end-tidal PCO<sub>2</sub> and blood gas values in humans. *Exp Physiol* 2003;88(05):603–610
- 32 Salinet ASM, Minhas JS, Panerai RB, Bor-Seng-Shu E, Robinson TG. Do acute stroke patients develop hypocapnia? A systematic review and meta-analysis. *J Neurol Sci* 2019;402:30–39
- 33 Lee J, Kim SK, Kang HG, et al. High prevalence of systemic hypertension in pediatric patients with moyamoya disease years after surgical treatment. *J Neurosurg Pediatr* 2019;•••:1–7
- 34 Wallace JD, Levy LL. Blood pressure after stroke. *JAMA* 1981;246(19):2177–2180
- 35 McSwain SD, Hamel DS, Smith PB, et al. End-tidal and arterial carbon dioxide measurements correlate across all levels of physiologic dead space. *Respir Care* 2010;55(03):288–293