



ORIGINAL ARTICLE

Capnography in newborns under mechanical ventilation and its relationship with the measurement of CO₂ in blood samples



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KEYWORDS

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Abstract

Introduction: Monitoring the partial pressure of CO₂ (PCO₂) in newborns who require ventilation would allow avoiding hypocapnia and hypercapnia. The measurement of end-tidal carbon dioxide (ETCO₂) is an alternative rarely implemented in this population.

Objective: To evaluate the relationship between ETCO₂ and PCO₂ in newborns.

Methods: Cross-sectional study comparing two PCO₂ measurement methods, the conventional one by analysis of blood samples and the one estimated by ETCO₂. The study included hospitalized newborns that required conventional mechanical ventilation. The ETCO₂ was measured with a Tecme GraphNet[®] neo, a neonatal ventilator with an integrated capnograph, and we obtained the ETCO₂–PCO₂ gradient. We conducted correlation and Bland-Altman plot analyses to estimate the agreement.

Results: A total of 277 samples (ETCO₂ / PCO₂) from 83 newborns were analyzed. The mean values of ETCO₂ and PCO₂ were 41.36 mmHg and 42.04 mmHg. There was a positive and significant correlation between ETCO₂ and PCO₂ in the overall analysis ($r=0.5402$; $P<.001$) and in the analysis of each unit ($P<.001$). The mean difference was 0.68 mmHg (95% CI, -0.68 to 1.95) and was not significant. We observed a positive systematic error (PCO₂ > ETCO₂) in 2 of the units, and a negative difference in the third (PCO₂ < ETCO₂).

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Discussion: The correlation between ETCO₂ and PCO₂ was significant, although the obtained values were not equivalent, with differences ranging from 0.1 mmHg and 20 mmHg. Likewise, we found systematic errors that differed in sign (positive or negative) between institutions. © 2022 Asociación Española de Pediatría. Published by Elsevier España, S.L.U. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

PALABRAS CLAVE

Neonatos;
Ventilación
mecánica;
Capnografía;
Monitorización PCO₂

Capnografía en recién nacidos en ventilación mecánica y su relación con la medición de CO₂ en muestras sanguíneas

Resumen

Introducción: Monitorizar la presión parcial de CO₂ (PCO₂) en los recién nacidos que requieren ventilación permitiría evitar hipocapnia e hipercapnia. La medición de CO₂ espirada (ETCO₂) es una alternativa poco implementada en esta población.

Objetivo: Evaluar la relación entre la ETCO₂ y la PCO₂ en recién nacidos

Métodos: Estudio de corte transversal, comparativo entre dos métodos de medición de PCO₂, el convencional mediante análisis de muestras sanguíneas y el estimado mediante ETCO₂. Se incluyeron recién nacidos internados que requerían ventilación mecánica convencional. La medición de ETCO₂ se realizó mediante un ventilador neonatal Graph Net Neo – TECME®, con capnógrafo incorporado y se obtuvo el gradiente ETCO₂ – PCO₂. Se realizaron análisis de correlación y gráficos de Bland Altman para estimar la concordancia.

Resultados: Se analizaron 277 muestras (ETCO₂ / PCO₂) en 83 recién nacidos. Los valores promedios de ETCO₂ y PCO₂ fueron de 41.36 mmHg y 42.04 mmHg, Hubo correlación positiva y significativa entre ETCO₂ y PCO₂ en el análisis global ($r=0,5402$; $p<0,001$) y en el de cada unidad ($p<0,001$). La media de las diferencias fue de 0,68 mmHg (IC95% - 0,68 a 1,95,) y no resultó significativa. Se observó error sistemático positivo (PCO₂ > ETCO₂) en 2 de las unidades mientras que en la tercera la diferencia fue negativa (PCO₂ < ETCO₂)

Discusión: La correlación entre ETCO₂ y PCO₂ es significativa, si bien los valores obtenidos no resultan equivalentes y la diferencia varía entre 0,1 mmHg a 20 mmHg. Asimismo, observamos errores sistemáticos de signo diferente (positivo o negativo) entre las instituciones.

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Introduction

Monitoring of the arterial partial pressure of carbon dioxide (PaCO₂) in ill newborns, especially those who require ventilation, is important to optimise patient management and prevent complications, since both hypocapnia and hypercapnia are known contributors to periventricular leukomalacia,^{1,2} intracranial haemorrhage³ and bronchopulmonary dysplasia.^{3,4} At the same time, fluctuations in PaCO₂ are associated with poorer neurodevelopmental outcomes.⁵

While arterial blood gas analysis is the gold standard for PaCO₂ monitoring, it requires a painful collection procedure, is expensive and can lead to iatrogenic anaemia⁶ due to repeated collection of samples, thereby increasing the need of transfusion, while only providing information on discrete timepoints.

A possible alternative is transcutaneous monitoring of the partial pressure of CO₂ (TcCO₂), but using this method in young children is complicated due to the immaturity of the skin, the need of repeated calibration and the risk of burns and infections,^{7,8} leaving aside that it is not available in most neonatal intensive care units (NICUs) in Spain.

End-tidal CO₂ (ETCO₂) monitoring is a useful alternative. This method has been applied widely in the fields of surgery and anaesthesia in adult and paediatric patients, where it is used to help confirm the correct positioning of endotracheal tubes and to monitor ventilation and cardiopulmonary status in patients.^{9–11} However, its use in the NICU setting or the delivery room in infants requiring resuscitation has been scarce, probably due to the inconsistent evidence on the correlation between the ETCO₂ and the PaCO₂ in newborns and how the severity of pulmonary illness may affect this correlation.^{12–16}

The gradient between the ETCO₂ and the PaCO₂ may be affected by the severity of respiratory impairment, but this aspect has not been adequately assessed in ventilated infants.^{17,18}

Volumetric capnography can be used to estimate the physiological dead space in adults. Using a modified version of the Bohr formula, it is possible to assess the correlation between the calculated dead space (VD) and the tidal volume (Vt),¹⁸ both inspiratory and expiratory. In adults, the normal range for the dead space to tidal volume ratio (VD/Vt) has been established at 0.20 to 0.35. In adult patients with acute lung injury, this ratio increases to 0.44–0.55, which

is associated with a high mortality.¹⁹ Unfortunately, the possibilities offered by this approach are still limited in newborn infants. The technical problems caused by the apparatus dead space, response times and endotracheal tube leaks are evident limitations in newborn infants, especially those born preterm with very low birth weights.²⁰

Although the correlation between arterial blood gas analysis and non-invasive methods has been studied in newborns, the results reported in the scientific literature have been contradictory and very heterogeneous.²¹ Notwithstanding, the current evidence is promising and may contribute valuable information for future studies, which will be necessary to establish non-invasive methods as a reliable and feasible alternative to arterial blood gas analysis.

The primary objective of our study was to assess and report the correlation between the ETCO₂ and the partial CO₂ pressure (PCO₂) in newborns requiring mechanical ventilation in 3 neonatal intensive care units in Argentina.

Material and methods

We conducted a cross-sectional comparative study of 2 PCO₂ measuring methods: conventional measurement by blood gas analysis in blood samples and estimation by ETCO₂.

The sample consisted of newborns admitted to the NICUs of the Clínica Universitaria Reina Fabiola, Clínica y Maternidad CERHU and Hospital Provincial de Rosario between August 2019 and July 2020 that required conventional mechanical ventilation and/or manual ventilation through an endotracheal tube, with no limitations to inclusion based on birth weight, gestational age or postnatal age. We excluded newborns managed with high-frequency ventilation.

We obtained a convenience sample that was partly determined by the availability of ETCO₂ monitoring devices in each unit.

End-tidal CO₂ monitoring was performed with a TECME Graph Net neo neonatal ventilator (Córdoba, Argentina) with an integrated mainstream dual wavelength end-tidal CO₂ sensor (Respironics Capnostat 5).

The PCO₂ was measured in samples of arterial blood (PaCO₂), capillary blood (PcCO₂) or venous blood (PvCO₂), collected according to the judgment of the physician in charge of the patient. In this observational study, samples were not ever collected for research purposes, and we only included measurements for samples obtained in the context of clinical care.

To standardise the sample collection procedure, all staff members who performed this task in each unit were given specific directions on how to collect the samples and submit them to the laboratory for processing.

The blood gas analysis procedure depended on the equipment available in the laboratories of each hospital: Cobas b 121 (Roche), Cobas b 221 (Roche) and Epop Reader (Epopal).

After collecting the blood sample ordered in each case, the ETCO₂ was recorded and compared with the value obtained in the laboratory (arterial, venous or capillary PCO₂) to calculate the ETCO₂-PCO₂ gradient.

Although the units of analysis were the comparative measurements, variables related to the infant, the infant's condition and the type of blood sample were also doc-

umented in each case. We recorded the birth weight, gestational age (GA), postnatal age, illness that required mechanical ventilation, fraction of inspired oxygen (F_iO₂) and site of blood extraction.

Carbon dioxide measurements obtained with the ETCO₂ monitor were not used in clinical decision-making.

In the descriptive analysis, we calculated measures of central tendency and dispersion, including the range, mean, median, mode, standard deviation (SD), proportions or percentages and confidence intervals (CIs). Comparisons were made using analysis of variance (ANOVA), the Student *t* test and the χ^2 test with the Fisher and Yates correction, as applicable, having assessed the normality of the distribution in every case using graphical and statistical methods (Kolmogorov–Smirnov test). We calculated the Pearson correlation coefficient for the total sample and for the data obtained in each of the 3 participating units. In addition, we generated Bland–Altman plots to estimate the concordance between the measurement methods and calculated the measurement bias. The statistical analysis was performed with the InfoStat software (Universidad Nacional de Córdoba, Argentina) and the level of significance was 5% in every test.

The study was approved by the research ethics committees of each participating institution, and since it did not require modifying the care of the newborns and ETCO₂ monitoring is a standard non-invasive method used in intensive care, the respective ethics committees determined that the study was exempt from informed consent.

All the procedures adhered to good clinical research practice in humans, the Declaration of Helsinki and the corresponding provincial laws. Confidentiality was safeguarded in accordance with the Personal Data Protection Act (25326/2000).

Results

We analysed 277 comparative samples (ETCO₂/PCO₂) in 83 newborns.

The mean weight of the assessed newborns was 2017 g (SD, 853 g; range, 660–4220 g) and the mean GA was 32 weeks (SD, 4). The sex distribution of the sample was 52.4% male and 47.6% female.

Table 1 presents the distribution of patients and samples per centre (centres identified as A, B and C).

Table 2 compares the 3 institutions in terms of GA, birth weight, the frequency of FiO₂ values under 30% and the site of blood extraction, showing that the GAs and birth weights of the newborns were greater in centre B, while the frequency of arterial blood samples was higher in centre C. We found no significant differences in the need of supplemental oxygen when we compared the measurements in the 3 centres.

The most frequent diagnosis during the measurements was respiratory distress syndrome (RDS), documented in 60% of the cases (166 observations).

The mean ETCO₂ and PCO₂ values were 41.36 mmHg and 42.04 mmHg, respectively (Table 3).

We found a significant positive correlation between the ETCO₂ and PCO₂ in both the overall analysis of the samples, with a correlation coefficient of 0.5402 ($P < .001$), and

Table 1 Frequency distribution of patients and samples by centre.

Centre A		Centre B		Centre C	
Newborns (n)	Samples (n)	Newborns (n)	Samples (n)	Newborns (n)	Samples (n)
28	51	18	112	37	114

Table 2 Characteristics of the infants and samples (n) by centre.

	Centre A		Centre B		Centre C	
	n	%	n	%	n	%
GA > 32 wk	23	45.1	90	80.4	63	55.3
Birth weight > 1500 g	31	60.7	95	84.8	68	59.6
FiO ₂ > 30%	15	29.4	28	25.0	30	26.3
Arterial blood sample	16	31.4	22	19.6	87	76.3

FiO₂, fraction of inspired oxygen; GA, gestational age; wk, week.

Table 3 Summary of ETCO₂ and PCO₂ values in the 277 samples.

	Mean (mmHg)	Standard deviation (mmHg)	Minimum (mmHg)	Maximum (mmHg)
PCO ₂	42.04	10.85	17.8	76
ETCO ₂	41.36	11.24	11	74

ETCO₂, end-tidal carbon dioxide; PCO₂, partial pressure of carbon dioxide;

the analysis of the samples of each of the 3 institutions ($P < .001$). The highest correlation coefficient corresponded to centre C ($r = 0.6319$), followed by centre B ($r = 0.6234$) and centre A ($r = 0.5703$) (Fig. 1).

We used the Bland-Altman method to assess the concordance between the PCO₂ and ETCO₂ values (Fig. 2). For the overall sample, the mean difference was of 0.68 mmHg with a 95% CI of -0.68 to 1.95, meaning that it was not significant ($P = .289$). However, when we analysed the samples of each institution separately, we did find some differences: in centres A and B, we found a positive difference or systematic error (PCO₂ > ETCO₂), and in centre C a negative difference or systematic error (PCO₂ < ETCO₂). Table 4 presents the differences between the PCO₂ and ETCO₂ values with the respective 95% CIs for each institution and in the overall sample.

Lastly, for each unit, we calculated the frequency of values without differences or bias (PCO₂ = ETCO₂) and the frequency of negative bias (PCO₂ < ETCO₂) or positive bias (PCO₂ > ETCO₂) based on the magnitude of the values and analysed in intervals that we established arbitrarily. Table 5 presents these results. In centres A and B, the percentages of ETCO₂ values that exceeded the PCO₂ values were 16% and 35%, respectively, but in centre C these differences were found in 70% of the observations. With a different approach, if we considered measurement differences of less than 5 mmHg, only 103 of the 277 observations (37%) would be in the acceptable difference range.

In a preliminary analysis, we explored the effect of gestational age, birth weight and the site of blood extraction (arterial vs capillary or venous) on the association between the PCO₂ and the ETCO₂.

We found a weaker correlation in infants born at or before 32 weeks of gestation ($r = 0.5445$) compared to those born after 32 weeks ($r = 0.5681$); there were no significant differences based on birth weight.

The correlation was also stronger in infants with a FiO₂ of 30% or greater ($r = 0.6100$) compared to those with a FiO₂ of less than 30% ($r = 0.5533$), although both were statistically significant ($P = .0177$). When it came to the effect of CO₂ values on the correlation, we did not find statistically significant differences when we separated the observations into those with CO₂ values of less than 45 mmHg or equal or greater than 45 mmHg. We also found that the site of extraction had a significant effect on the strength of the correlation ($P < .0001$), with a stronger correlation in the group of arterial samples ($r = 0.6471$) compared to the group of venous or capillary samples ($r = 0.5684$).

Discussion

Our findings, like other studies in the past, found a significant correlation between the ETCO₂ and the PCO₂. The correlation coefficients obtained in the 3 units under study ($r = 0.54$) were somewhat lower compared to the previous literature, in which reported values have ranged from 0.70 to 0.80.²¹⁻²⁴ Most recent reviews highlight the broad heterogeneity of the published results.^{25,26}

In our multicentre study, we found that the correlation between the ETCO₂ and the PCO₂ differed between centres. The concordance analyses found positive biases in 2 centres and a negative bias in the other. While we cannot ascertain the cause of these variations, they could be due to the equipment used to process blood samples or the greater

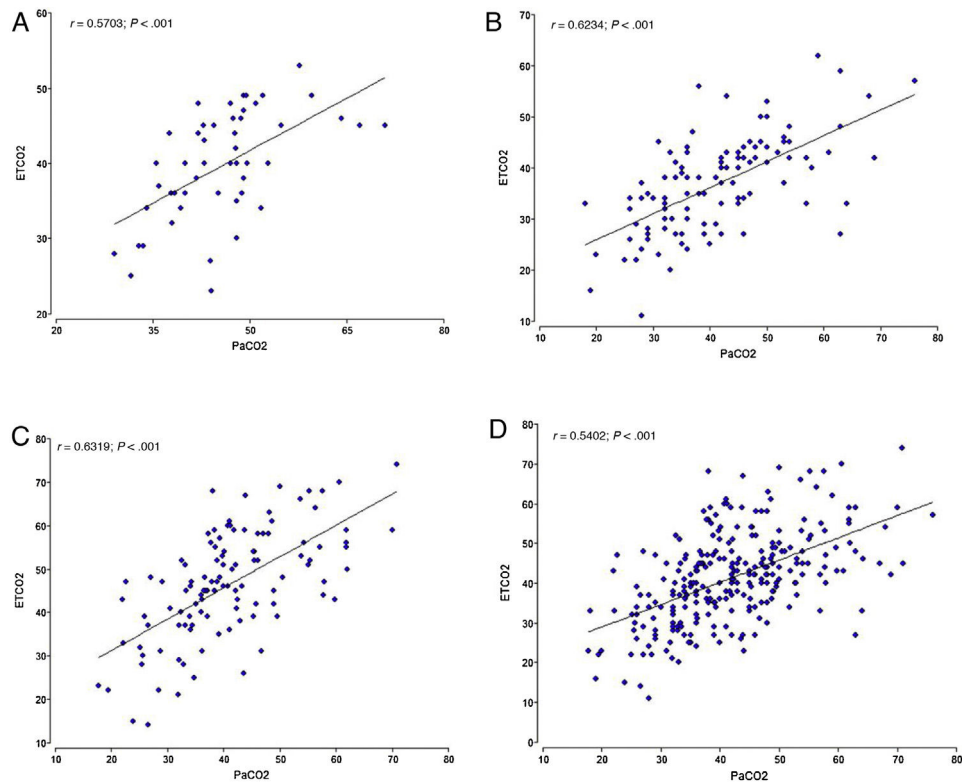


Figure 1 Scatter plots of the association of ETCO₂ and PCO₂ values in each participating centre (A, B, and C) and for the overall sample (D).

Table 4 Mean difference, standard deviation and confidence interval in the measurement of CO₂ (PCO₂ vs ETCO₂).

	Difference between PCO ₂ and ETCO ₂				
	mean	standard deviation	95% CI, LL	IC 95%, UL	P
Centre A	6.14	7.41	4.06	8.22	<.001
Centre B	4.49	9.21	2.73	6.24	<.001
Centre C	-5.42	10.06	-7.29	-3.54	<.001
Global	0.68	10.6	-0.68	1.95	.2892

CI, confidence interval; ETCO₂, end-tidal carbon dioxide; LL, lower limit; PCO₂, partial pressure of carbon dioxide; UL, upper limit.

percentage of arterial blood samples in the San Luis centre. There is evidence that the type of sample affects the correlation,²⁷ and in our study, 68% and 80% of the samples in the 2 institutions with a positive bias were venous or capillary blood samples.

The only parameter of severity or greater respiratory compromise that we analysed in our sample was requiring a FiO₂ of 30% or greater. In this regard, the correlation observed in infants with FiO₂ of 30% or greater was slightly stronger, contrary to what has been previously described.²⁷ We did not find variations in the strength of the correlation based on CO₂ values.

Beyond our findings and their statistical significance, the question we may want to ask from a clinical standpoint is whether it is possible to rely on ETCO₂ values as safe estimates of laboratory PCO₂ values to adequately guide clinical decision-making in ventilated newborns, thus preventing hypocapnia and hypercapnia without the need of

frequent blood extractions. In this sense, it was staggering to find that the values, at least in isolated measurements, were rarely equivalent, and that the difference between the two could range from 0.1 mmHg to more than 20 mmHg. However, in this study we did not analyse trends in serial values in each individual newborn, which could be useful in clinical practice by evincing a decrease or increase of the values relative to the baseline.

The PaCO₂ is an important parameter in critically ill and ventilated patients. The current alternatives available to reduce the number of invasive procedures or to monitor PaCO₂ more continuously are capnography or transcutaneous monitoring. Each of them have advantages and limitations. Capnography provides a measurement of PCO₂ at the end of expiration and has the advantage of being non-invasive and allowing continuous monitoring, although in patients with pulmonary illness it can often diverge, as occurred in our study. Transcutaneous PCO₂ measurement can be reli-

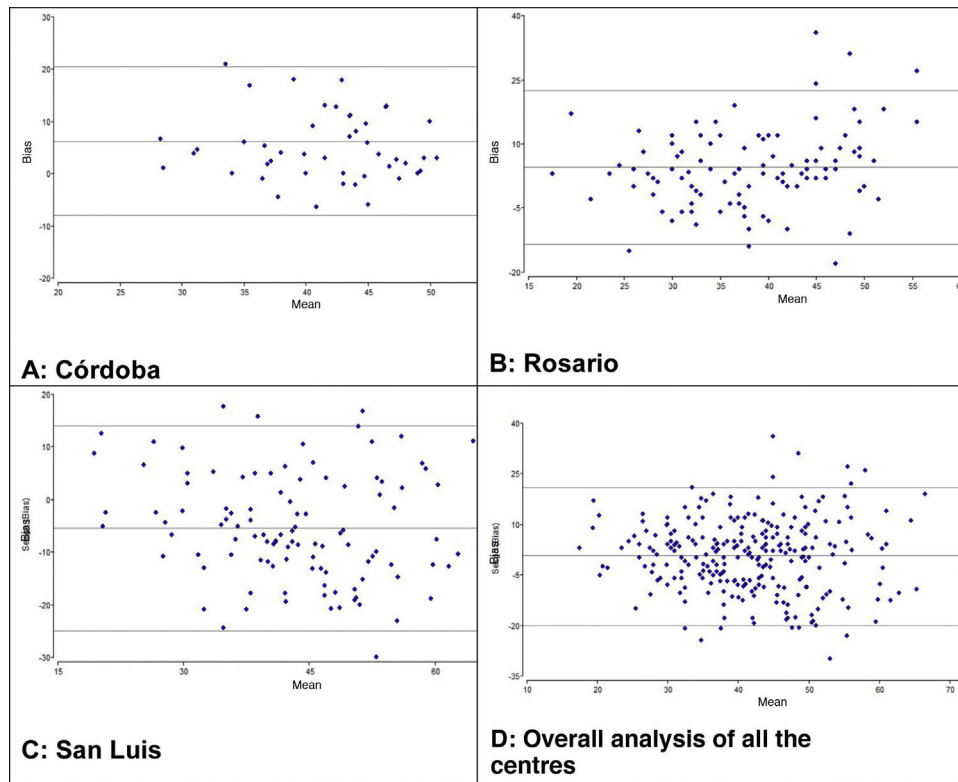


Figure 2 Bland–Altman plots of the association between ETCO₂ and PCO₂ values in each participating centre (A, B, and C) and for the overall sample (D).

Table 5 Distribution of differences between PCO₂ and ETCO₂ values in participating centres.

	Difference between values	Centre A, 51 samples	Centre B, 112 samples	Centre C, 114 samples
PCO₂ < ETCO₂	< -20 mmHg	0	1 (1%)	7 (6%)
	from -10.1 to -20 mmHg	0	9 (8%)	31 (27%)
	from -5.1 to -10 mmHg	2 (4%)	13 (12%)	27 (24%)
	from -0.1 to -5 mmHg	6 (12%)	16 (15%)	15 (13%)
	Total	8 (16%)	39 (35%)	80 (70%)
PaCO₂ = ETCO₂	0	3 (6%)	8 (7%)	0
PCO₂ > ETCO₂	from 0.1 to 5 mmHg	17 (33%)	26	12
	from 5.1 to 10 mmHg	9 (18%)	17	8
	from 10.1 to 20 mmHg	11 (21%)	19	9
	> 20	3 (6%)	3	0.9
	Total	40 (78%)	65 (58%)	34 (30%)

able, but its use is limited due to the damage to the skin of newborns resulting from the heat.

There are limitations to our study due to the limited number of isolated observations made in 3 neonatal units. Nevertheless, it contributes new data to add to the contributions of previous authors and warns of the possibility of unpredictable variations, as observed in the participating centres, between which the correlations of the values obtained by the two methods differed. This may suggest that, for the time being, each centre should validate the use of these monitors before assuming that correlation values found in other studies apply to their units. It also underscores the need to continue exploring or identifying the causes of these variations.

Additional studies are still required to establish non-invasive methods as a reliable and feasible alternative to arterial blood gas analysis. Investing in new technologies that allow informed clinical decision-making and improve safety in the care of critically ill newborns also continues to be crucial.

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Conflicts of interest

The authors have no conflicts of interest to declare.

References

- McEvedy BA, McLeod ME, Kirpalani H, Volgyesi GH, Lerman J. End-tidal carbon dioxide measurements in critically ill neonates: a comparison of side-stream and mainstream capnometers. *Can J Anaesth*. 1990;37:322–6.
- Kirpalani H, Kechagias S, Lerman J. Technical and clinical aspects of capnography in neonates. *J Med Eng Tech*. 1991;15:154–61.
- Fujimoto S, Togari H, Yamaguchi N, Mizutani F, Suzuki S, Sobajima H. Hypocarbica and cystic periventricular leukomalacia in premature infants. *Arch Dis Child Fetal Neonatal Ed*. 1994;71:F107–10.
- Garland JS, Buck RK, Allred EN, Leviton A. Hypocarbica before surfactant therapy appears to increase bronchopulmonary dysplasia risk in infants with distress syndrome. *Arch Pediatr Adolesc Med*. 1995;149:617–22.
- Rozycki HJ, Sysyn GD, Marshal MK, Malloy R, Wiswell TE. Mainstream end-tidal carbon dioxide monitoring in the neonatal intensive care unit. *Pediatrics*. 1998;101:648–53.
- Colman Y, Krauss B. Microstream capnography technology: a new approach to an old problem. *J Clin Monit*. 1999;15:403–9.
- 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, 28 weeks gestation. *J Perinatol*. 2005;25:26–9.
- Tingay DG, Stewart MJ, Morley CJ. End-tidal carbon dioxide and transcutaneous carbon dioxide monitoring during neonatal transport. *Arch Dis Child Fetal Neonatal Ed*. 2005;90:F523–6.
- Repetto JE, Donohue PA-CPK, Baker SF, Kelly L, Noguee LM. Use of capnography in the delivery room for assessment of endotracheal tube placement. *J Perinatol*. 2001;21:284–7.
- Tingay DG, Mun KS, Perkins EJ. End tidal carbon dioxide is as reliable as transcutaneous monitoring in ventilated postsurgical neonates. *Arch Dis Child Fetal Neonatal Ed*. 2013;98(2):F161–4.
- Kamlin CO, O'Donnell CP, Davis PG, Morley CJ. Colorimetric end-tidal carbon dioxide detectors in the delivery room: strengths and limitations. A case report. *J Pediatr*. 2005;147:547–8.
- Hsieh KS, Lee CL, Lin CC, Wu SN, Ko FY, Huang YF, et al. Quantitative analysis of end-tidal carbon dioxide during mechanical and spontaneous ventilation in infants and young children. *Pediatr Pulmonol*. 2001;32:453–8.
- Hagerty JJ, Kleinman ME, Zurakowski D, Lyons AC, Krauss B. Accuracy of a new low-flow sidestream capnography technology in newborns: a pilot study. *J Perinatol*. 2002;22:219–25.
- Wu CH, Chou HC, Hsieh WS, Chen WK, Huang PY, Tsao PN. Good estimation of arterial carbon dioxide by end-tidal carbon dioxide monitoring in the neonatal intensive care unit. *Pediatr Pulmonol*. 2003;35:292–5.
- Molloy EJ, Deakins K. Are carbon dioxide detectors useful in neonates? *Arch Dis Child Fetal Neonatal Ed*. 2006;91:F295–8.
- Lopez E, Grabar S, Barbier A, Krauss B, Jarreau PH, Moriette G. Detection of carbon dioxide thresholds using low-flow sidestream capnography in ventilated preterm infants. *Intensive Care Med*. 2009;35(11):1942.
- Tusman G, Sipmann FS, Bohm SH. Rationale of dead space measurement by volumetric capnography. *Anesth Analg*. 2012;114(4):866–74.
- Lin HJ, Huang CT, Hsiao HF, Chiang MC, Jeng MJ. End-tidal carbon dioxide measurement in preterm infants with low birth weight. *PLoS One*. 2017;12(10).
- McSwain SD, Hamel DS, Smith PB, Gentile MA, Srinivasan S, Meliones JN, et al. End-tidal and arterial carbon dioxide measurements correlate across all levels of physiologic dead space. *Respir Care*. 2010;55(3):288–93.
- Schmalisch G. Current methodological and technical limitations of time and volumetric capnography in newborns. *Biomed Eng Online*. 2016;15:104.
- Trevisanuto D, Giuliotto S, Cavallin F, Doglioni N, Toniazzo S, Zanardo V. End-tidal carbon dioxide monitoring in very low birth weight infants: correlation and agreement with arterial carbon dioxide. *Pediatr Pulmonol*. 2012;47(4):367–72.
- Singh BS, Gilbert U, Singh S, Govindaswami B. Sidestream microstream end tidal carbon dioxide measurements and blood gas correlations in neonatal intensive care unit. *Pediatr Pulmonol*. 2013;48(3):250–6.
- Kugelman A, Golan A, Riskin A, Shoris I, Ronen M, Qumqam N, et al. Impact of continuous capnography in ventilated neonates: a randomized, multicenter study. *J Pediatr*. 2016;168:56–61, <http://dx.doi.org/10.1016/j.jpeds.2015.09.051>, e2.
- Williams E, Dassios T, Greenough A. Assessment of sidestream end-tidal capnography in ventilated infants on the neonatal unit. *Pediatr Pulmonol*. 2020;55:1468–73.
- Williams E, Dassios T, O'Reilly N, Walsh A, Greenough A. End-tidal capnography monitoring in infants ventilated on the neonatal intensive care unit. *J Perinatol*. 2021;1:1–7.
- Martins IPM, Nakato AM, Hemberger PK, Ioshii SO, Nohama P. Correlation of end-tidal carbon dioxide with arterial carbon dioxide in mechanically ventilated neonates: a scoping review. *Glob Pediatr Health*. 2021;17:8, 2333794X211016790.
- Nassar BS, Schmidt GA. Estimating arterial partial pressure of carbon dioxide in ventilated patients: how valid are surrogate measures? *Ann Am Thorac Soc*. 2017;14(6):1005–14.