# Fresh gas formulae do not accurately predict end-tidal $PCO_2$ in paediatric patients

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*To determine the fresh gas flow (FGF) requirements in paediatric patients, we measured the FGFs needed to maintain distal end–tidal $PCO_2$ ($PETCO_2$) values at 30 and 38 mmHg in patients weighing between 3.8 and 20 kg ventilated with either a Sechrist Infant Ventilator IV–100B® or an Air-Shields Ventimeter® and a Mapleson D circuit. The FGF requirement was 500 $ml \cdot kg^{-1} \cdot min^{-1}$ to maintain a $PETCO_2$ of 30 mmHg and 250 $ml \cdot kg^{-1} \cdot min^{-1}$ to maintain a $PETCO_2$ of 38 mmHg when minute ventilation ≥ FGF. When these formulae were used in a subsequent group of similar patients, a wide variation in $PETCO_2$ measurements were obtained. We conclude that the safest and most accurate approach to determine the FGF requirement of paediatric patients is to continuously monitor the $PETCO_2$ in each patient and to adjust the FGF accordingly.*

Since the introduction of the earliest of the Mapleson D breathing circuits, the Ayre's t-piece in 1937[1] and the Jackson-Rees modification in 1950,[2] there has been controversy regarding the optimal fresh gas flow (FGF) and ventilatory requirements in paediatric patients. Previous recommendations for fresh gas flow requirements (FGFRs) in Mapleson D circuits have been based on (1) end–expired $PCO_2$ sampled from the proximal end of the endotracheal tube[3,4] or (2) measurements of arterial $PCO_2$ ($PaCO_2$) and estimations of $CO_2$ production ($\dot{V}CO_2$) using measurements of the mixed expired $CO_2$ fraction ($F\bar{E}CO_2$) sampled from the expiratory limb.[5–7] However, when two of the formulae derived from the data were assessed in subsequent groups of patients, wide variations in $PaCO_2$ values were obtained.[6,7] It is not known whether the use of a formula derived from continuous measurements of end–tidal $PCO_2$ ($PETCO_2$) from the distal end of the endotracheal tube will predict $PaCO_2$ or $PETCO_2$ values more accurately than previous formulae.

We reported previously that distal $PETCO_2$ measurements approximated $PaCO_2$ measurements in paediatric patients during general anaesthesia and controlled ventilation.[8] In the present study, we first determined the formulae for FGFR for $PETCO_2$ values of 30 and 38 mmHg in paediatric patients weighing ≤ 20 kg and then applied these formulae to a second group of similar patients to determine their accuracy in predicting the $PETCO_2$.

**Key Words**
ANAESTHESIA, GENERAL: breathing circuits, monitoring, paediatric; CARBON DIOXIDE: end–tidal.

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## Methods

This study was approved by the local Human Review Committee. It was performed in two parts: in Part A, the FGFRs were determined by continuous measurements of $PETCO_2$ as described below; in Part B, the observed and predicted $PETCO_2$ values were compared when FGF was delivered to patients according to the formulae derived in Part A.

*Part A*

Thirty-five unpremedicated healthy patients weighing ≤20 kg and scheduled for elective surgery were studied. Patients with cardiopulmonary or metabolic disease and those scheduled for thoracic or upper abdominal surgery were excluded. All patients were monitored with a precordial stethoscope, ECG, Doppler probe over the radial artery, blood pressure cuff, and rectal temperature probe. Patients were included in the study only if their temperature was maintained between 36.5° and 37.5° C. All patients were supine and horizontal throughout the study period. After induction of anaesthesia and the insertion of an endotracheal tube, ventilation was controlled with a Sechrist Infant Ventilator IV–100B® and a Mapleson D breathing circuit (Jackson-Rees modification of the Ayre's t-piece). There was no audible air leak around the endotracheal tube at 30 cm $H_2O$ pressure. In

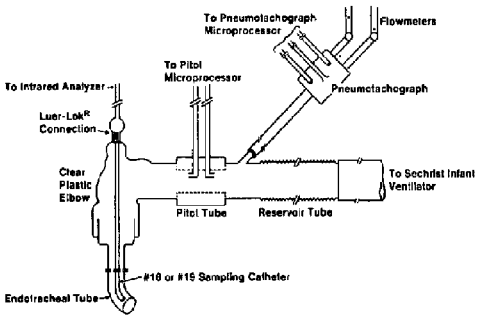


FIGURE 1 Components of the breathing circuit and measuring apparatus used in this study.

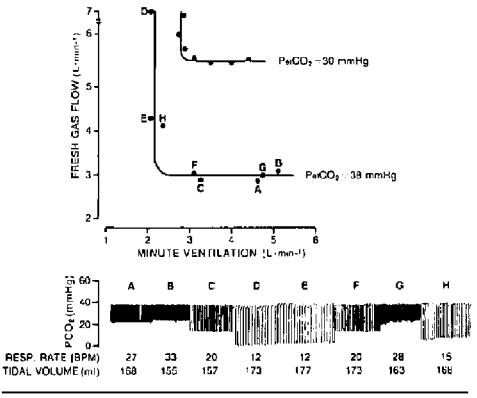


FIGURE 2 The isopleths for $P_{ET}CO_2$ of 30 and 38 mmHg and capnographic waveform for $P_{ET}CO_2$ of 38 mmHg in a 9.5 kg, one-year-old infant. The letters (A-H) on the capnographic waveform correspond to the lettered points (A-H) on the isopleth.

six patients, an Air-Shields Ventimeter® was used in sequence with the Sechrist ventilator. One of two Ohmeda anaesthesia machines was used in each patient. The FGFs were measured continuously with a heated Fleish pneumotachograph (Hewlett Packard®)[9] placed between the fresh gas outlet of the anaesthesia machine and the fresh gas tubing (Figure 1). The pneumotachograph was calibrated before use with 65 per cent $N_2O$/35 per cent $O_2$. Anaesthesia was maintained with 65 per cent $N_2O$/35 per cent $O_2$, halothane (0.5–1.5 per cent inspired), and fentanyl (0.5–2 $\mu \cdot kg^{-1}$). Twitch depression was monitored and maintained at approximately 95 per cent throughout the study using d-tubocurarine (0.4 $mg \cdot kg^{-1}$ initial dose and 0.1 $mg \cdot kg^{-1}$ subsequent doses) or atracurium (0.4 $mg \cdot kg^{-1}$ initial dose and 0.1 $mg \cdot kg^{-1}$ subsequent doses).

Gas for measurement of end-tidal and inspired $PCO_2$ was continuously sampled from the distal end of the endotracheal tube[8] using a Puritan-Bennett Datex infrared analyzer calibrated before each study (Figure 1). Gas for analysis was sampled at a rate of 150 $ml \cdot min^{-1}$ and was corrected for ambient barometric pressure and $N_2O$. Gas was sampled using a #16 or #19 Deseret Intracath® (#19 was used for endotracheal tubes $\leq$ 3.0 mm ID) inserted through a Luer-Lok® connection in the elbow of the anaesthetic circuit to within 5 mm of the distal end of the endotracheal tube. The hub of the Intracath® was then secured to the Luer-Lok® connector of a 1.5 meter sampling line attached to the infrared analyzer.

The Sechrist ventilator delivered an I: E ratio of 1: 2, peak inspiratory/postive end-expiratory pressures of 15–25/0–2 mmHg, and expired tidal volumes ($V_T$) of 10–15 $ml \cdot kg^{-1}$. The pressure pattern of the Sechrist ventilator was a modified square wave set to factory specifications. The anaesthetic machine fresh gas flow was adjusted to be > 10 per cent of the Sechrist gas flow to prevent contamination of anaesthetic fresh gas flow.[10] $V_T$ was measured with a modified Pitot tube (dead space = 1.5 ml), a device that derives $V_T$ from measurements of gas velocity and time.[9] The modified Pitot tube estimates velocity from the dynamic pressure (total pressure minus static pressure) of gas flowing past sampling tubes in a cylinder. The minute ventilation ($\dot{V}_E$) was calculated as the product of $V_T$ and respiratory rate. FGF and $\dot{V}_E$ were then adjusted to produce $P_{ET}CO_2$ values of 30 and 38 mmHg. Isopleths were produced as a result of maintaining constant $P_{ET}CO_2$ values and varying the FGF and $\dot{V}_E$ (Figure 2). $\dot{V}_E$ was varied by changing the respiratory rate in approximately 5 $breaths \cdot min^{-1}$ increments and decrements. In order to provide steady state conditions, a minimum of 15 minutes was allowed between ventilatory changes. $V_T$ was maintained at a constant volume. We defined FGFR as the lowest FGF required to maintain the horizontal segment of the 30 or 38 mmHg isopleth. A volume of 150 $ml \cdot min^{-1}$ was subtracted from the FGFR in order to account for the gas sampled for $CO_2$ analysis.

The FGFRs to produce $P_{ET}CO_2$ values of 30 and 38 mmHg were compared with body weight using linear regression analysis and the coefficient of determination ($r^2$). The coefficient of determination is that proportion of the total variation in the y-variable that is explained by the fitted regression (i.e., the x-variable). The slopes of the two regression lines were compared with slope = 0 using Student's t test. The FGFs required to produce $P_{ET}CO_2$ of 30 and 38 mmHg were compared for patients weighing < 10 kg and $\geq$ 10 kg, using Student's t test for unpaired data. Statistical significance was accepted if $p \leq 0.05$.

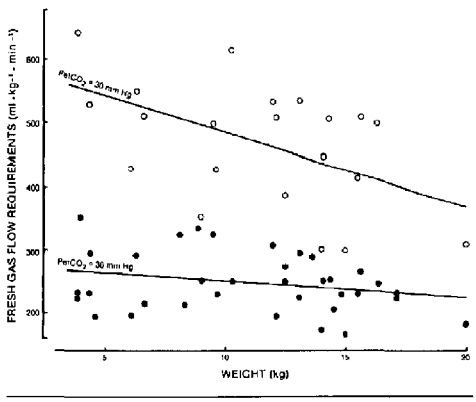


FIGURE 3 The relationship between body weight and fresh gas flow requirements to produce $PETCO_2$ of 30 mmHg (open circles, $y = -11.67X + 602.31$, $r^2 = 0.26$, $p < 0.05$) and $PETCO_2$ of 38 mmHg (closed circles, $y = -2.80X + 278.24$, $r^2 = 0.07$, $p$ = NS).

*Part B*

Sixty-five unpremedicated patients without cardiopulmonary disease, weighing ≤ 20 kg, and scheduled for elective surgery were studied. The conditions of anaesthesia in these patients were the same as for patients in Part A except that isoflurane (1–2 per cent inspired) was used in some patients. Ventilation was controlled with either a Sechrist Infant Ventilator® (n = 11) or an Air-Shields Ventimeter® (n = 54) and a Mapleson D breathing circuit (Jackson-Rees modification of the Ayre's t-piece).

End-tidal $PCO_2$ was measured as described in Part A. The $PETCO_2$ values were measured during steady state (no surgical stimuli, body temperature in the range of 36.5 to 37.5° C, constant level of anaesthesia and 95 per cent twitch depression). In order to reproduce the usual clinical situation, FGFs and VT in Part B were measured by means other than pneumotachography and Pitot tube. The FGFs were measured by flowmeter and were delivered at rates derived in Part A that were expected to produce $PETCO_2$ values of 30 and 38 mmHg. An additional 150 $ml \cdot min^{-1}$ of gas was delivered to compensate for sampling loss. VT was assumed to be 10–15 $ml \cdot kg^{-1}$ when inspiratory pressure equaled 20–30 $cmH_2O$. The $\dot{V}E$ was calculated from the product of VT and respiratory rate. In order to ensure that FGF was indeed minimal (i.e., to ensure that FGF and $\dot{V}E$ were on the horizontal segment of the isopleth): (1) $\dot{V}E$ was adjusted to equal approximately 1.5 times the FGF and (2) evidence of rebreathing (inspired $PCO_2 \geq 5$ mmHg) was present on the capnographic waveform of each patient.

The observed $PETCO_2$ values in patients < 10 kg and ≥ 10 kg were compared using one-way ANOVA and Student-Newman-Keuls test. Statistical significance was accepted if $p \leq 0.05$.

## Results

*Part A*

The mean (±SD) age and weight for the 35 patients were 1.9 ± 1.6 years (range = 4 weeks to 5.5 years) and 11.4 ± 4.3 kg (range = 3.8 to 20 kg). Isopleths and FGFRs for a $PETCO_2$ of 30 mmHg were obtained in 21 of the 35 patients and for a $PETCO_2$ of 38 mmHg in all 35 patients.

At a $PETCO_2$ of 30 mmHg, there was an inverse linear relationship between body weight and FGFRs (Figure 3). In contrast, at a $PETCO_2$ of 38 mmHg, there was no significant relationship between weight and FGFRs. The FGFR values (mean ± SD) were 469 ± 98 $ml \cdot kg^{-1} \cdot min^{-1}$ for a $PETCO_2$ of 30 mmHg and 247 ± 47 $ml \cdot kg^{-1} \cdot min^{-1}$ for a $PETCO_2$ of 38 mmHg. The FGFR values did not differ significantly between the < 10 kg and ≥ 10 kg patients for either a $PETCO_2$ of 30 or 38 mmHg (Table).

A typical set of isopleths and capnographic waveforms are shown in Figure 2. In this 9.5 kg infant, the FGFR for a $PETCO_2$ of 38 mmHg was 498 $ml \cdot kg^{-1} \cdot min^{-1}$ and for a $PETCO_2$ of 38 mmHg it was 325 $ml \cdot kg^{-1} \cdot min^{-1}$. Typical of patterns in all patients, rebreathing was maximal at the right side of the isopleth (Figure 2, B, G), approached zero at the elbow of the isopleth, and was minimal (Figure 2, E, H) or nonexistent (Figure 2, D) on the vertical segment. Data points from patients ventilated with both Sechrist and Air-Shields ventilators (mean ± SD weight = 11.7 ± 2.2 kg) closely followed the curve of the isopleth (Figure 4).

*Part B*

The mean (±SD) age and weight for the 65 patients were 1.8 ± 1.7 years (range = newborn to four years) and 10.7 ± 4.7 kg (range = 2.8 to 19.1 kg). For use in Part B, the formulae derived from Part A were approximately 500 $ml \cdot kg^{-1} \cdot min^{-1}$ to produce a $PETCO_2$ of 30 mmHg and 250 $ml \cdot kg^{-1} \cdot min^{-1}$ to produce a $PETCO_2$ of 38 mmHg when $\dot{V}E \geq 1.0 \times FGF$. When the $PETCO_2$ was set for 30 mmHg, the observed mean (±SD) value was 30.0 ± 3.8 mmHg for patients weighing < 10 kg and 27.6 ± 3.1 mmHg for patients weighing ≥ 10 kg (Figure 4). When the $PETCO_2$ was set for 38 mmHg, the observed mean value was 38.5 ± 4.0 mmHg for patients weighing < 10 kg and 37.3 ± 3.3 mmHg for patients weighing > 10 kg (Figure 4). The observed $PETCO_2$ values did not differ significantly between the < 10 and ≥ 10 kg patients for either a $PETCO_2$ of 30 or 38 mmHg.

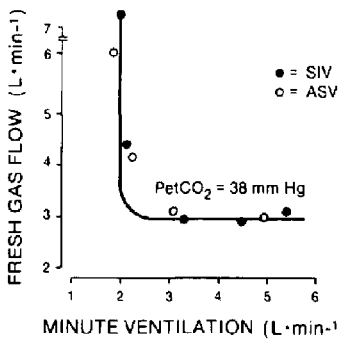


FIGURE 4 The isopleth for $P_{ET}CO_2$ of 38 mmHg in a 14.5 kg, two-year-old child who was ventilated in sequence with both a Sechrist Infant Ventilator IV–100B® (SIV, closed circles) and an Air-Shields Ventimeter® (ASV, open circles).

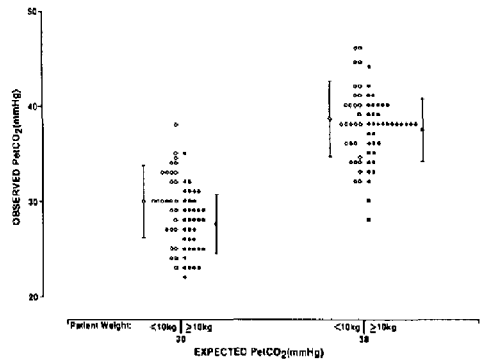


FIGURE 5 The relationship between observed $P_{ET}CO_2$ values compared to expected $P_{ET}CO_2$ values in patients weighing < 10 kg (open circles) and ≥ 10 kg (closed circles) using fresh gas flows of 500 ml·kg$^{-1}$·min$^{-1}$ to produce a $P_{ET}CO_2$ of 30 mmHg and 250 ml·kg$^{-1}$·min$^{-1}$ to produce a $P_{ET}CO_2$ of 38 mmHg. The symbols with vertical bars are mean (± SD) $P_{ET}CO_2$ values.

## Discussion

Several investigators have determined the FGF requirements for infants and children during controlled ventilation with a Mapleson D breathing circuit. Nightingale recommended 220 ml·kg$^{-1}$·min$^{-1}$ FGF with a minimum flow of 3 L·min$^{-1}$ based on the amount of FGF required to maintain end–expired $CO_2$ below 5.8 vol per cent in patients weighing > 8.2 kg.[3] Bain and Spoerel determined that 200 ml·kg$^{-1}$·min$^{-1}$ (minimal flow = 2.0 L·min$^{-1}$) for patients weighing < 10 kg and 100 ml·kg$^{-1}$·min (minimal flow = 3.5 L·min$^{-1}$) for patients ≥ 10 kg would provide adequate FGF to remove $\dot{V}CO_2$.[5] Rayburn and Graves determined that 2500 ml·m$^{-2}$·min$^{-1}$ would provide adequate ventilation for patients weighing ≥ 7.5 kg if the $\dot{V}_E$ equalled three times the alveolar ventilation.[6] From measurements of $PaCO_2$, FGF, $VCO_2$ and $\dot{V}_E$, Rose and Froese derived optimal formulae for FGF and ventilation to achieve desired $PaCO_2$ values for patients weighing ≥10 kg .[7] Hatch *et al.* recommended that FGF equal 1.5 $\dot{V}_E$ when the $\dot{V}_E$ is 200 × kg + 1000 to avoid hypercapnoea during controlled ventilation in patients weighing between 3.5 and 21.8 kg.[4] Our formulae, based on continuous measurements of distal $P_{ET}CO_2$ and isopleths of constant $P_{ET}CO_2$ values in patients weighing between 3.8 and 20 kg, indicate that approximately 500 ml·kg$^{-1}$·min$^{-1}$ is required to maintain the $P_{ET}CO_2$ at 30 mmHg and approximately 250 ml·kg$^{-1}$·min$^{-1}$ to maintain the $P_{ET}CO_2$ at 38 mmHg.

Previous studies recommend that $\dot{V}_E$ should equal 2 × FGF[7] or 3 × FGF[6] or that FGF should equal 1.5 × $\dot{V}_E$[4] in order to deliver adequate ventilation. Our data, however, would indicate that adequate ventilation ($P_{ET}CO_2$ of 38 mmHg) is delivered when $\dot{V}_E$ equals or slightly exceeds the FGF. According to the data in Figure 2, there is no advantage to values of $\dot{V}_E$ far in excess of FGF or vice versa. In fact, marked rebreathing occurs when $\dot{V}_E$ ≥ 1.5 × FGF and rebreathing ceases when FGF approximates $\dot{V}_E$. With the development of accurate end–tidal $PCO_2$ measurements[8,10,11] and the modified Pitot tube,[9] adequate $\dot{V}_E$ may be accurately delivered and monitored.

Since all of the previous formulae predicted wide variations in $PaCO_2$ and $P_{ET}CO_2$, these formulae only approximate the FGF requirement for paediatric patients. Rayburn and Graves found that the 90 per cent confidence level for $PaCO_2$ using their formula ranged from 32 to 49 mmHg.[5] Likewise, Rose and Froese found a wide variation of measured $PaCO_2$ values when they assessed their formulae (the observed ranges of $PaCO_2$ were 27–40

TABLE Fresh gas flow requirements (FGFR) (mean ± SD)

| | $P_{ET}CO_2$ = 30 mmHg | | | $P_{ET}CO_2$ = 38 mmHg | | |
|---|---|---|---|---|---|---|
| Weight (kg) | < 10 | ≥10 | <20 | < 10 | ≥10 | < 20 |
| FGFR | 496±88 | 451±103 | 469±98 | 261±55 | 237±38 | 247*±47 |

*$p < 0.05$ (compared with < 20 kg, $P_{ET}CO_2$ = mmHg).

mmHg when $PaCO_2$ of 30 mmHg was expected and 30–48 mmHg when $PaCO_2$ of 37 mmHg was expected).[7] Despite the use of formulae based on accurate measurements of tidal volume, fresh gas flows, and continuous end-tidal $PCO_2$, the variability in $PETCO_2$ values in Part B of the present study is similar to previous data.

The large variability in $PaCO_2$ and $PETCO_2$ may be attributed to patient and equipment variables. Patient variables include changes in $\dot{V}CO_2$, the heterogeneity of the population studied, preoperative medication, differences in the depth of anaesthesia, differences in the degree of muscle relaxation, and variations in body temperature. Equipment variables include inaccurate flowmeters and difficulty in judging VT from peak inspiratory pressure. Part B of this study was designed to validate these FGF requirements under the same conditions that anaesthetists in practice would encounter. Therefore, we minimized only three of five patient variables (preoperative medication, muscle relaxation, and body temperature) and neither of the equipment variables.

It is well known that $\dot{V}CO_2$ per kg in paediatric patients under anaesthesia is inversely proportional to body weight.[5] This relationship is reflected in the present study by the inverse linear relationship between FGFR to produce $PETCO_2$ of 30 mmHg and body weight (Figure 3). If this inverse relationship between $\dot{V}CO_2$ per kg and body weight were the only factor explaining the variation in $PETCO_2$ in Part B, we would expect that larger patients (i.e., $\geq$ 10 kg) would have lower $PETCO_2$ values when subjected to the formulae. However, we did not observe significantly lower $PETCO_2$ values in the patients $\geq$ 10 kg compared with the patients weighing $<$ 10 kg. Therefore, we ascribe the variation in $PETCO_2$ values in Part B of this study to the patient and equipment variables described above.

Theoretically, the FGF formulae derived in this study may be more accurate than those reported previously since ours are based on *in vivo* $PETCO_2$ isopleths that agree with *in vitro* $PETCO_2$ isopleths in their ability to predict minimal FGF requirements.[7] As with previous formulae, however, our formulae do not predict $PaCO_2$ and $PETCO_2$. Because of the patient and equipment variables, it may be impossible to determine FGFR formulae that will precisely predict $PaCO_2$ and $PETCO_2$ in paediatrics. Therefore, the safest and most accurate approach to the delivery of FGF to paediatric patients is to continuously measure the $PETCO_2$[8,10,11] and to adjust the FGF to meet the patient's requirements.

Although the healthy patient may tolerate a wide range of $CO_2$ tensions, many patients, such as neurosurgical and cardiac patients, require the arterial $CO_2$ tension to be maintained within a narrow range. However, considering the potentially detrimental effects of hypocarbia on the cerebral blood flow and myocardial function, and that hypercarbia may reflect inadequate ventilation, it seems prudent to maintain the $CO_2$ tensions of all patients in a narrow range. When standardized FGFR formulae are used in small infants, two errors may occur: (1) very low FGFs delivered strictly by formula may be hazardous since vaporizers and flowmeters may be inaccurate at low flows, and (2) "minimal flows" recommended by some authors[3–5,7] may induce hypocapnia in small infants.

Since ventilation with either a Sechrist Infant Ventilator IV–100B® or an Air-Shields Ventimeter® produced similar results, it is suggested that our FGFRs will apply to all time-cycled continuous-flow ventilators with Mapleson D circuits. Further studies are needed to determine whether our FGFRs will produce similar results in Mapleson D breathing circuits and other types of ventilators.

In summary, we determined the FGFR formulae that estimate the $PETCO_2$ of 30 mmHg (500 ml·kg$^{-1}$·min$^{-1}$, $\dot{V}E \geq$ FGF) and $PETCO_2$ of 38 mmHg (250 ml·kg$^{-1}$·min$^{-1}$, $\dot{V}E \geq$ FGF) in paediatric patients ventilated with a time-cycled, continuous-flow ventilator and a Mapleson D circuit. When we tested these formulae in a similar group of paediatric patients, we observed great variability in the $PETCO_2$ values. Therefore, we conclude that although FGF formulae may be used as rough guidelines to determine the gas flows, for accurate arterial $CO_2$ tensions continuous $PETCO_2$ monitoring is recommended.

**Acknowledgments**

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Résumé

*Afin de déterminer la quantité de gas frais (FGF) requise en pédiatrie, on a mesuré les FGFs nécessaires afin de maintenir une $PCO_2$ en fin d'expiration ($P_{ET}CO_2$) entre 30 et 38 mmHg chez des patients pesant entre 3.8 et 20 kg ventilés soit avec le ventilateur pédiatrique Sechrist IV 100B® ou un Air-Shields Ventimeter® et un circuit Mapleson D. Le FGF était de 500 $ml \cdot kg^{-1} \cdot min^{-1}$ afin de maintenir une $P_{ET}CO_2$ à 30 mmHg et 250 $ml \cdot kg^{-1} \cdot min^{-1}$ afin de maintenir une $P_{ET}CO_2$ de 38 mmHg quand la ventilation minute était ≥ au FGF. Quand ces formules ont été utilisées subséquemment pour un groupe similaire de patients une grande variation dans la mesure de la $P_{ET}CO_2$ fut obtenue. On conclut que l'approche la plus sécuritaire est la plus exacte afin de déterminer le FGF chez les patients pédiatriques est de continuer à surveiller la $P_{ET}CO_2$ chez chaque patient et d'ajuster la FGF en conséquence.*