End-tidal $P_{CO_2}$ Monitoring in Infants and Children Ventilated with Either a Partial Rebreathing or a Non-rebreathing Circuit

J. MICHAEL BADGWEll, M.D.,* JAMES E. HEAVNER, D.V.M., PH.D.,† W. SAM MAY, M.D.,‡ JANE F. GOLDTTHORN, M.D.,§ JERROLD LERMAN, M.D., F.R.C.P.C.¶

End-tidal $P_{CO_2}$ measurements are frequently less accurate in neonates, infants, and small children than in adults.** The difficulty in obtaining accurate measure-

ments in pediatric patients may be attributed to the low ratio of tidal volume to equipment deadspace, rapid ventilatory rates and high fresh gas flows, and high sampling rates required by $CO_2$ analyzers. We believe that these problems are maximal when pediatric patients (particularly neonates and infants) are ventilated with partial rebreathing circuits, which allow fresh gas to flow past the endotracheal tube during expiration, and are minimal when these patients are ventilated with circuits which have non-rebreathing valves that separate the inspiratory and expiratory phases of respiration. To verify this clinical impression, we compared the arterial $P_{CO_2}$ ($Pa_{CO_2}$) with the end-tidal $P_{CO_2}$ ($Pet_{CO_2}$) during ventilation of neonates, infants, and children using a partial rebreathing circuit (Air-Shields Ventimeter* [ASV] and a Mapleson D breathing circuit) or a non-rebreathing circuit (Siemens-Elema "Servo" 900-C® [SES]).

METHODS AND MATERIALS

Fifty children with no known cardiopulmonary disease who were scheduled for general surgery or neurosurgical procedures were studied. The patients varied in age from premature newborn to 9 yr, and in weight from 1.65–23.5 kg. The study was approved by the Institutional Re-
transducer in the expiratory channel (fig. 1, No. 12) measures the $V_T$ and calculates the $V_T$ ($V_T = \frac{V_E}{\text{respiratory rate}}$). Fresh gas flows from the anesthetic machine were connected to the SES at the low pressure inlet (fig. 1, No. 1) and delivered at a flow rate greater than the $V_E$. Positive end-expiratory pressures were avoided when either ventilator was used. All data were obtained after the induction of anesthesia and before incision. All patients were supine and horizontal throughout the study. Rectal temperatures were recorded throughout the study and were maintained between 36 and 37°C.

Respiratory gases were sampled through a side stream connector placed between the endotracheal tube and the breathing circuit, and were measured with a mass spectrometer calibrated each day with dry gas. The spectrometer sample flow rate was 240 ml·min⁻¹, for periods of 20 s, and at intervals of 1 or more min. The sampling line was 40 m in length from the patient to the mass spectrometer. Exhaled gas measurements were corrected for the presence of water vapor, and reflected saturated alveolar levels at ambient barometric pressures.

Arterial blood samples for PAO₂ were obtained from an indwelling arterial catheter (n = 51) via percutaneous puncture (n = 41), or via arterialized heel stick (n = 3). The PAO₂ samples were measured at 37°C with a CO₂ electrode calibrated prior to each sample and uncorrected for body temperatures. The PAO₂ was compared to peak-expiratory or end-tidal PCO₂ values sampled simultaneously. For downsloping plateaus, the peak end-expiratory PCO₂ value was compared to PAO₂, whereas, for flat plateaus, end-tidal PCO₂ was compared to PAO₂. The inspired concentrations of CO₂ (PICO₂) and inspiratory: expiratory time ratios (I:E) were measured and recorded in each patient.

The gradients between PAGO₂ and PETCO₂ values (ΔPAGO₂, PetCO₂) were compared to body weight using non-linear exponential regression analysis and the coefficient of determination ($r^2$). After the study was completed, the subjects were divided into four groups according to their weight and the ventilator(s) used during the study (table 1). Differences in the slopes of the regression lines among the groups were compared using analysis of covariance. Differences in weight, ΔPGO₂ (a-et) values, and PICO₂ values among the groups were compared using one-way ANOVA and the Student-Newman-Keuls test. Statistical significance of $P \leq 0.05$ was accepted.

RESULTS

Ventilation was controlled with an ASV and Mapleson D circuit alone in 32 patients (21 with a Bain circuit and 11 with an Ayre's t-piece), with an SES alone in 10 patients, and with both ventilators in sequence (denoted by * in fig. 1) in 8 patients. When the ASV was used, only

view Board, and informed consent was obtained from the parents.

After induction of general anesthesia with either an intravenous or inhalation induction and endotracheal intubation, ventilation was controlled with: 1) a partial rebreathing circuit (an ASV and Mapleson D circuit [Bain or Jackson-Rees modification of the Ayre's t-piece]), or 2) a non-rebreathing circuit (a SES), or 3) both ASV and SES used in random sequence. When the ASV was used, the initial fresh gas flows were 1000 cc plus 100 cc·kg⁻¹ for infants and children less than 30 kg in body weight and 2000 cc plus 50 cc·kg⁻¹ for children greater than 30 kg.® Thereafter, fresh gas flows were adjusted to maintain PAO₂ or PETCO₂ within an acceptable clinical range for general surgery (34–58 mmHg) and neurosurgery (28–34 mmHg). The respiratory rate was between 30 and 40 breaths per minute (BPM) for newborns and infants, and between 20 and 30 BPM for older infants and children. When the ASV was used, the tidal volume ($V_t$) was approximately 10–15 cc·kg⁻¹ with corresponding peak inspiratory pressures of 20–30 mmHg. When the SES ventilator was used, the expired minute ventilation ($V_E$) was adjusted by varying the $V_t$ and respiratory rate (as indicated above) to maintain PAO₂ or PETCO₂ within the acceptable clinical ranges. In the SES, a flow
TABLE 1. Patients Ventilated with the Air-shields Ventimeter (ASV) and the Siemens-Elema "Servo" 900-C (SES)

<table>
<thead>
<tr>
<th></th>
<th>ASV</th>
<th>SES</th>
<th>Both Ventilators*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;8 kg</td>
<td>28 kg</td>
<td>&lt;8 kg</td>
</tr>
<tr>
<td>Number of patients</td>
<td>17</td>
<td>23</td>
<td>10</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.4 ± 1.8‡</td>
<td>12.9 ± 5.1</td>
<td>4.3 ± 1.8</td>
<td>13.8 ± 6.5</td>
</tr>
</tbody>
</table>
| ΔP<sub>CO₂</sub> (a-et)† (mmHg) | 12.0 ± 7.8‡ | 1.5 ± 2.6 | 5.4 ± 1.5       | 2.8 ± 2.3  | ASV 12.4 ± 8.0§ | 0.6 ± 2.4  
|                |         |         |                   |           | SES     | 2.6 ± 1.0 |
|                |         |         |                   |           |         | 2.2 ± 2.5 |

Data are mean ± SD.
* Patients ventilated in random sequence with both ventilators; the data for these 8 patients are also included in the data from the other 42 patients summarized in the first 4 columns.
† ΔP<sub>CO₂</sub> (a-et) = the difference between P<sub>ACO₂</sub> and Pet<sub>CO₂</sub>.
‡ P < 0.05 compared to 28 kg groups.
§ P < 0.01 compared to the other three groups.

Minimal adjustments in fresh gas flow (± 10%) were required to maintain the P<sub>ACO₂</sub> or Pet<sub>CO₂</sub> within the clinical ranges. The mean weight of the <8 kg ASV group did not differ significantly from that of the <8 kg SES group, and, similarly, the mean weight of the ≥8 kg ASV group did not differ significantly from that of the ≥8 kg SES group (table 1).

A hyperbolic relationship existed between body weight and ΔP<sub>CO₂</sub> (a-et) values in the patients ventilated with an ASV: y = 1 ÷ 49.6(x) - 2.4, (r<sup>2</sup> = 0.67) where y is ΔP<sub>CO₂</sub> (a-et) and x is the patient weight (fig. 2). Since the hyperbolic curve for the partial rebreathing circuit crossed the line for the SES group at approximately 8 kg on the abscissa, the patients in the ASV group were divided into two groups according to weight: <8 kg and ≥8 kg. The relationship between weight and ΔP<sub>CO₂</sub> (a-et) values in the patients ventilated with the SES did not depend significantly on weight: y = 0.05(x) + 2.73 (r<sup>2</sup> = 0.03).

The Pet<sub>CO₂</sub> measurements did not approximate P<sub>ACO₂</sub> measurements in the <8 kg ASV group (fig. 3). However, Pet<sub>CO₂</sub> measurements did approximate P<sub>ACO₂</sub> measurements in the ≥8 kg ASV group and in all patients (< and ≥8 kg) in the SES groups (fig. 4). The mean ΔP<sub>CO₂</sub> (a-et) value was significantly greater in the <8 kg ASV group compared to both the ≥8 kg ASV group and all patients in the SES group (table 1).

Weight and ΔP<sub>CO₂</sub> (a-et) values obtained from the eight patients ventilated in random sequence with both ventilators were similar to those from patients ventilated with only one of the ventilators (table 1).

**Fig. 2.** Arterial to end-tidal P<sub>CO₂</sub> gradients compared to body weight when the Air-Shields Ventimeter and Siemens-Elema "Servo" 900-C were used to ventilate infants and children (* = ventilators used in sequence in same patient).
There was a trend for the PI\textsubscript{CO\textsubscript{2}} values in the ASV groups with I:E > 1:3.5 (e.g., 1:1, 1:2, and 1:3) to be greater than the PI\textsubscript{CO\textsubscript{2}} values in the SES groups with I:E > 1:3.5 (table 2). The mean PI\textsubscript{CO\textsubscript{2}} value in the >8 kg ASV group with I:E ≤ 1:3.5 was greater than the mean PI\textsubscript{CO\textsubscript{2}} values in all groups with I:E > 1:3.5. In the SES group, PI\textsubscript{CO\textsubscript{2}} was greater in the I:E ≤ 1:3.5 (e.g., 1:4, 1:5, 1:6, and 1:7) groups than in the groups with an I:E ≥ 1:3.5.

Seven of the 50 patients had a Pet\textsubscript{CO\textsubscript{2}} value greater than the Pa\textsubscript{CO\textsubscript{2}} value (negative PI\textsubscript{CO\textsubscript{2}}[a-et]). Of these patients, six were in the ≥8 kg ASV group (mean weight ± SD = 11.4 ± 3.6 kg; mean ΔP\textsubscript{CO\textsubscript{2}}[a-et] ± SD = -1.8 ± 1.3 mmHg), and one was in the ≥8 kg SES group (8.1 kg, ΔP\textsubscript{CO\textsubscript{2}}[a-et] = -0.43 mmHg).

The capnographic waveforms in 15 of 17 patients in the <8 kg ASV group demonstrated either a flat plateau phase, despite a large ΔP\textsubscript{CO\textsubscript{2}} (a-et) value, or failed to achieve a plateau phase on the capnographic waveform (table 3, fig. 5). Furthermore, the capnographic waveforms in 8 of 23 patients in the ≥8 kg ASV group demonstrated decay of the plateau phase (table 2, fig. 6A). In these eight patients, the Pet\textsubscript{CO\textsubscript{2}} measurements were less accurate than the Pet\textsubscript{CO\textsubscript{2}} measurements in the 15 patients who did not demonstrate decay. When the SES was used, decay of the plateau phase was not observed in any of the patients (fig. 6B).

### Table 2. The Effect of Inspiratory:Expiratory Time Ratios (I:E) on the Inspired Concentration of CO\textsubscript{2} (PI\textsubscript{CO\textsubscript{2}}) in Infants and Children Ventilated with the Air-shields Ventilator (ASV) and the Siemens-Elema "Servo" 900-C (SES)

<table>
<thead>
<tr>
<th>I:E</th>
<th>&lt;8 kg</th>
<th>&gt;8 kg</th>
<th>&lt;8 kg</th>
<th>&gt;8 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASV</td>
<td>4.3 ± 4.8 (n = 11)</td>
<td>5.2 ± 5.0 (n = 19)</td>
<td>8.4 ± 5.6 (n = 6)</td>
<td>10.5 ± 4.0* (n = 10)</td>
</tr>
<tr>
<td>SES</td>
<td>2.2 ± 2.0† (n = 3)</td>
<td>1.8 ± 0.9† (n = 4)</td>
<td>8.5 ± 3.2 (n = 6)</td>
<td>7.5 ± 4.3 (n = 5)</td>
</tr>
</tbody>
</table>

Data are mean (PI\textsubscript{CO\textsubscript{2}}) values in mmHg ± SD.
* P < 0.05 compared to all four groups with I:E > 1:3.5.
† P < 0.05 compared to SES groups with I:E ≤ 1:3.5.

### Discussion

The large ΔP\textsubscript{CO\textsubscript{2}} (a-et) values in patients <8 kg who are ventilated with the ASV (a continuous flow, time-cycled ventilator) may be attributed, in part, to the dilution of end-tidal gas by the continuous flow of fresh gas past the sampling site at the top of the endotracheal tube.†† Furthermore, the diluted end-tidal gas samples result in capnographic waveforms, which either fail to achieve a flat plateau phase, or reach a flat plateau which underestimates the Pa\textsubscript{CO\textsubscript{2}}. However, in the SES, an inspiratory valve (fig. 1, No. 10) automatically interrupts the flow of fresh gas at the completion of inspiration thereby allowing undiluted alveolar gas to be sampled during the expiratory phase. Consequently, Pet\textsubscript{CO\textsubscript{2}} measurements in patients ventilated with the SES accurately predict Pa\textsubscript{CO\textsubscript{2}} and produce flat plateaus on the capnographic waveform even in very small infants.

It has been suggested that the presence of a "flat alveolar phase" on the capnogram ensures that the Pet\textsubscript{CO\textsubscript{2}} closely approximates the alveolar P\textsubscript{CO\textsubscript{2}} (P\textsubscript{ACO\textsubscript{2}}) or Pa\textsubscript{CO\textsubscript{2}} in infants.‡‡ However, in the present study, the presence of large ΔP\textsubscript{CO\textsubscript{2}} (a-et) values in patients with flat plateau phases are consistent with a mathematical model which suggests that, when Pet\textsubscript{CO\textsubscript{2}} is sampled at the proximal end of the endotracheal tube, the "determinants of distortion" (expiratory flow rate and concentration profiles, the sample flow rate, sample tube dimensions, and sample cell volume) may lead to artificially flat plateau phases and Pet\textsubscript{CO\textsubscript{2}} values which underestimate the Pa\textsubscript{CO\textsubscript{2}} values.‡‡ Thus, a flat plateau phase may not always represent the alveolar phase, particularly when sampled proximally.

TABLE 5. Capnographic Waveforms in Patients Ventilated with the Air-Shields Ventimeter

<table>
<thead>
<tr>
<th></th>
<th>&lt;8 kg</th>
<th></th>
<th>≥8 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Patients with a Flat Plateau on</td>
<td>Patients without</td>
<td>Decay of the Capnographic Waveform</td>
</tr>
<tr>
<td></td>
<td>Capnogram Waveform</td>
<td>a Flat Plateau on</td>
<td>Present</td>
</tr>
<tr>
<td></td>
<td>Small ΔPCO₂ (s-et)</td>
<td>Capnogram Waveform</td>
<td>Absent</td>
</tr>
<tr>
<td></td>
<td>Large ΔPCO₂ (s-et)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of patients</td>
<td>4</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>6.5 ± 1.0*</td>
<td>3.8 ± 1.3</td>
<td>11.4 ± 3.5</td>
</tr>
<tr>
<td>ΔP₂CO₂ (a-et)† (mmHg)</td>
<td>2.0 ± 1.0*</td>
<td>15.4 ± 6.3</td>
<td>3.2 ± 2.3†</td>
</tr>
</tbody>
</table>

Data are mean ± SD.
* P < 0.01 compared to the other two <8 kg groups.
† ΔP₂CO₂ (a-et) = the difference between P₂CO₂ and Pet₂CO₂.
‡ P < 0.01 compared to ≥8 kg patients with absence of capnographic waveform decay.

The negative ΔP₂CO₂ (a-et) values in our study are consistent with existing data in adults,\(^6,6\) and may be explained by either calibration errors in the CO₂ electrode or mass spectrometer, the charged membrane hypothesis, or the delayed equilibration theory.\(^6,6\) Since it is currently accepted that P₂CO₂ is equal to PA₂CO₂ in the lung at equilibrium,\(^6\) the small negative or positive ΔP₂CO₂ (a-et) values in our data probably reflect small calibration errors or small ventilation to perfusion mismatches in some patients.

It is not known from these data whether Pet₂CO₂ can be measured accurately in small infants when they are ventilated with a continuous-flow, time-cycled ventilator and a conventional circle system. However, accurate Pet₂CO₂ measurements are obtained in newborn pigs only when additional one-way valves are added to the conventional circle system and when measurements are sampled from the distal end of the endotracheal tube.\(^††\) It is also not known from these data whether Pet₂CO₂ can be measured accurately in the ASV or SES using a flow-through type sampling cell. However, since mixing of end-tidal and fresh gases may still occur, one might speculate that Pet₂CO₂ measurements in patients < 8 kg would be accurate with the SES and inaccurate with the ASV.

These data suggest that when either the ASV or the SES is used, the optimal I:E ratio to prevent rebreathing is > 1:3.5. When the I:E ratios ≤ 1:3.5, the inspiratory time is insufficient to allow adequate removal of exhaled gases and rebreathing occurs even in the SES, a "non-rebreathing" system (fig. 6B).

In a previous study using a lung model, two different sample flow rates (200 and 500 ml·min⁻¹) did not significantly effect the accuracy of Pet₂CO₂ measurements.†‡ In the present study, we used similar sample flow rates (240 ml·min⁻¹) and obtained accurate Pet₂CO₂ measurements in all patients ventilated with the SES and patients ≥ 8 kg ventilated with the ASV. Since the same sample flow rate was used in both the <8 kg SES and <8 kg ASV patients, perhaps the sample flow rate is not an important

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**Fig. 5.** The capnographic waveform for a 4.1 kg infant ventilated with an Air-Shields Ventimeter and Bain circuit with a fresh gas flow of 1.4 l·min⁻¹ (resp. rate = 32 and I:E ratio = 1:2.33) P₂CO₂ = 40.3 mmHg; Pet₂CO₂ = 31.0 mmHg; ΔP₂CO₂ (a-et) = 9.3 mmHg; PI₂CO₂ = 7.5 mmHg.

**Fig. 6.** A. The capnographic waveform for an 8 kg child ventilated with an Air-Shields Ventimeter and 1-piece circuit with a fresh gas flow of 2 l·min⁻¹ (resp. rate = 30 and I:E ratio = 1:1.5) P₂CO₂ = 33.9 mmHg; Pet₂CO₂ = 31.0 mmHg; ΔP₂CO₂ (a-et) = 2.9 mmHg; PI₂CO₂ = 8.1 mmHg. B. Same child (as in A) ventilated with a Siemens-Elema "Servo" 900-C Ventilator with an expired minute ventilation of 2 l (resp. rate = 25 and I:E ratio = 1:6.6) P₂CO₂ = 30.6 mmHg; Pet₂CO₂ = 31.0 mmHg; ΔP₂CO₂ (a-et) = -0.4 mmHg; PI₂CO₂ = 7.3 mmHg.
factor in preventing accurate $\text{PetCO}_2$ measurements in patients <8 kg ventilated with an ASV. In summary, we have shown that $\text{PetCO}_2$ measurements sampled from the proximal end of the endotracheal tube do not accurately predict $\text{PaCO}_2$ measurements in patients weighing less than 8 kg who are ventilated with a continuous-flow, time-cycled ventilator and a Mapleson D partial rebreathing circuit. By contrast, $\text{PetCO}_2$ measurements sampled from proximal sites accurately predict the $\text{PaCO}_2$ in patients more than 8 kg in weight who are ventilated with this circuit and in all patients (<8 and ≥8 kg) ventilated with the Siemens-Elema "Servo" 900-C* Ventilator. This study indicates the need to develop an accurate technique to sample $\text{PetCO}_2$ when continuous flow ventilators and Mapleson D circuits are used in small infants. Meanwhile, the Siemens-Elema "Servo" 900-C remains a very useful ventilator when accurate end-tidal $\text{PCO}_2$ monitoring is important in small infants.

The authors thank Ms. Terri Cain, Ouidalee Rucker, and Carolyn Barnes for their secretarial assistance, Craig Flinders, Rita Prichett, and Jamie Castillo for their technical assistance, and Susan Johnston for her assistance with the artwork. This paper was prepared with the assistance of the Medical Publications Department, The Hospital for Sick Children, Toronto.

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Anesthetic Management for Cesarean Section of a Patient with Charcot-Marie-Tooth Disease

JOHNNY E. BRIAN, JR., M.D., * GERALD D. BOYLES, M.D.,† J. GERALD QUIRK, JR., M.D., PH.D.,‡ RICHARD B. CLARK, M.D.§

Charcot-Marie-Tooth disease, a rare degenerative disease of the peripheral nervous system has been recognized as a clinical entity since 1886.¶** Described separately by Charcot and Marie in France and Tooth in England, the disease usually follows an autosomal dominant mode of inheritance. The hallmark of the disease process is peroneal muscle atrophy, reflecting the tendency for involvement of distal limb musculature. High pedal arches or club feet are common; mildly affected patients may demonstrate only foot deformities. Nerve conduction velocities and sural nerve biopsies permit differentiation into two subtypes. Type I usually has an onset in the first or second decade of life with foot drop and steppage gait. Sensory impairment occurs in a stocking and glove distribution. Later in life, atrophy of intrinsic hand muscles occurs. Tendon reflexes are diminished in affected areas, and foot deformities are common. Type II usually appears in adulthood, with symptoms similar to type I. Either subtype may present at any age, however. Foot deformities may be evident for many years prior to the appearance of muscular atrophy. Progression of type I is slow, and type II, very slow. Incapacitation is very rare, and death usually occurs from other causes.¶

We recently encountered a patient with Charcot-Marie-Tooth disease who had experienced a severe exacerbation of her disease process during pregnancy. Such occurrences have been rarely reported.¶‡ Anesthesia management of such a patient has never been described, although anes-