Carbon Dioxide Elimination during Total Cardiopulmonary Bypass in Infants and Children

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The authors measured the rate of carbon dioxide elimination (V\textsubscript{CO}_2) in 25 pediatric patients (age 2 days to 9 yr) during total cardiopulmonary bypass at average venous blood temperatures ranging from 19.5 to 35.9° C. A multiplexed mass spectrometer was connected to the gas inlet and exhaust points of the bubble oxygenator, and the gas-phase Fick principle was used to determine V\textsubscript{CO}_2. A curvilinear relationship was found between log V\textsubscript{CO}_2 and venous blood temperature, and a quadratic regression equation (r\textsuperscript{2} = 0.74) was fit to the data. Q\textsubscript{10} (the ratio of V\textsubscript{CO}_2 before and after a 10° C temperature change) was estimated to be 2.7 or 3.0, depending on the analytic method used. Venous blood temperature as a predictor variable explained a greater proportion of the variability of log V\textsubscript{CO}_2 than did nasopharyngeal or rectal temperatures. Analysis of covariance revealed that total circulatory arrest during bypass (utilized in 10 patients for 34 ± 4 min, mean ± SEM) affected the relationship of venous blood temperature with log V\textsubscript{CO}_2, by increasing the y-intercept (P = .008) but not the slope. These data, with associated 95% prediction intervals, define the expected CO\textsubscript{2} elimination rates at various temperatures during standard bypass conditions in our patients. Real-time measurement of V\textsubscript{CO}_2 using mass spectrometry can be a useful routine monitor during CPB that may help to assess patient metabolic function, adequacy of perfusion, and oxygenator performance. (Key words: Carbon dioxide elimination. Cardiopulmonary bypass. Hypothermia. Measurement techniques: mass spectroscopy. Metabolism. Monitoring: carbon dioxide.)

An important goal in the conduct of cardiopulmonary bypass (CPB) is to match body metabolic requirements with the amount of oxygen supplied directly to the tissues. When perfusion is successful, aerobic metabolism should proceed at the normal rate for a given temperature. Clinical indices commonly used to detect global oxygen supply/demand mismatch during CPB include metabolic acid/base status, and oxygen tension (P\textsubscript{O}_2) or saturation (S\textsubscript{O}_2) of mixed venous blood.\textsuperscript{1, 2} The ease and frequency of use of these indices for monitoring adequacy of perfusion have increased with recent technological advances. While very low P\textsubscript{O}_2 or S\textsubscript{O}_2 values usually reflect inadequate tissue oxygenation, the utility of mixed venous oxygenation monitoring is limited, because increases in P\textsubscript{O}_2 or S\textsubscript{O}_2 may reflect arterial-to-venous shunting of blood rather than improved tissue perfusion.\textsuperscript{5} The latter point is most extreme in vascular beds that are completely without blood flow, and which neither contribute the metabolic acid and CO\textsubscript{2} that they produce nor extract oxygen from the blood; such beds will not affect arterial blood pH or venous blood oxygenation.

In theory, the steady-state carbon dioxide elimination rate (V\textsubscript{CO}_2) from the pump oxygenator during total CPB reflects global aerobic metabolic activity, tissue perfusion, and oxygenator function. Of these factors, the metabolic rate dependence may be predominant. Importantly, when non-perfused vascular beds are present, a diminution in measured V\textsubscript{CO}_2 (compared with normal rates) should occur, permitting detection of inadequate perfusion even when arterial blood pH, lactate, and P\textsubscript{O}_2 are normal.

As part of an investigation into the use of gas-phase measurement of V\textsubscript{CO}_2 during clinical CPB, we sought to define the normal temperature dependence of V\textsubscript{CO}_2 in pediatric patients using the technology of multiplexed mass spectrometry.

Materials and Methods

After obtaining approval from our Institutional Review Board, we studied 25 pediatric patients undergoing repair of congenital heart defects using CPB. Table 1 shows the demographic data for the patient population as a whole, and divides patients into groups who did or did not undergo total circulatory arrest ("TCA group" and "No-TCA group," respectively).

Anesthetic Management

Premedication was given to 20 of the 25 patients, consisting of intramuscular morphine (n = 20), scopolamine (n = 19), and/or pentobarbital (n = 11). Prior to CPB, the only anesthetic or adjuvant drugs given: halothane (n = 24), fentanyl (n = 22), isoflurane (n = 1), thiopental (n = 6), N\textsubscript{2}O (n = 12), pancuronium (n
TABLE 1. Patient Characteristics and Bypass Data

<table>
<thead>
<tr>
<th>Variable</th>
<th>All Patients</th>
<th>No-TCA Group (n = 15)</th>
<th>TCA Group (n = 10)</th>
<th>p*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (months)</td>
<td>30.9 ± 5.5</td>
<td>47.0 ± 6.1‡</td>
<td>6.7 ± 1.6§</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>12 ± 1.2</td>
<td>14.4 ± 1.2</td>
<td>5.8 ± 0.9</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Body surface area (m²)</td>
<td>0.48 ± 0.04</td>
<td>0.62 ± 0.04</td>
<td>0.29 ± 0.03</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Sex (M/F)</td>
<td>16/9</td>
<td>9/6</td>
<td>7/3</td>
<td>0.61</td>
</tr>
<tr>
<td>Total CPB duration (min)</td>
<td>120 ± 7</td>
<td>131 ± 10.3</td>
<td>105 ± 9.0</td>
<td>0.0092</td>
</tr>
<tr>
<td>CPB rewarming duration (min)</td>
<td>48 ± 4</td>
<td>52 ± 4</td>
<td>41 ± 7</td>
<td>0.15</td>
</tr>
<tr>
<td>Lowest temperatures (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Venous blood</td>
<td>19.5 ± 0.6</td>
<td>19.2 ± 0.4</td>
<td>20.0 ± 1.2</td>
<td>0.47</td>
</tr>
<tr>
<td>Nasopharyngeal</td>
<td>20.5 ± 0.5</td>
<td>20.4 ± 0.4</td>
<td>20.6 ± 1.2</td>
<td>0.86</td>
</tr>
<tr>
<td>Rectal</td>
<td>25.7 ± 0.4</td>
<td>26.0 ± 0.4</td>
<td>24.1 ± 0.8</td>
<td>0.004</td>
</tr>
<tr>
<td>[Hemoglobin]† (g/dl)</td>
<td>8.0 ± 0.2</td>
<td>7.7 ± 0.3</td>
<td>8.4 ± 0.3</td>
<td>0.11</td>
</tr>
<tr>
<td>Base excess† (mEq/l)</td>
<td>-2.5 ± 0.5</td>
<td>-3.3 ± 0.4</td>
<td>-1.4 ± 1.1</td>
<td>0.075</td>
</tr>
<tr>
<td>NaHCO₃ dose† (mmol/kg)</td>
<td>0.94 ± 0.2</td>
<td>0.92 ± 0.2</td>
<td>0.98 ± 0.4</td>
<td>0.90</td>
</tr>
<tr>
<td>Cardiac diagnosis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tetralogy of Fallot</td>
<td>9</td>
<td>8</td>
<td>1</td>
<td>0.034</td>
</tr>
<tr>
<td>A-V Canal</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>0.53</td>
</tr>
<tr>
<td>VSD</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>0.35</td>
</tr>
<tr>
<td>Transposition great vessels</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0.80</td>
</tr>
<tr>
<td>ASD</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0.65</td>
</tr>
<tr>
<td>Other</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>0.53</td>
</tr>
</tbody>
</table>

Values are mean ± standard error. TCA = total circulatory arrest. § "TCA group" vs. "No-TCA group." † During cardiopulmonary bypass. The HCO₃ dose administered during CPB excludes the bicarbonate given as part of the pump priming solution. Nine of 25 patie1nts received no HCO₃ during CPB (range 0–4.3 mmol/kg body weight). ‡ Range 2 days–14.5 months. § Range 16 months–9 yr 2 months.

= 24), and vecuronium (n = 1). When used, N₂O was discontinued at least 10 min prior to CPB. During CPB, the only anesthetic or adjuvant drugs used were fentanyl, scopolamine, and pancuronium; no patient received volatile agents or N₂O during CPB. The temperature of the operating room was approximately 19–18°C during the pre-CPB and CPB periods. In an attempt to improve the uniformity of cooling and rewarming, all patients received phenolamine 0.75 mg·kg⁻¹ as follows: 0.5 mg·kg⁻¹ with initiation of CPB, and 0.25 mg·kg⁻¹ with the beginning of rewarming.

PERFUSION MANAGEMENT

The CPB priming solution contained whole blood 500 ml and heparin 3000 u in all patients. Additionally, the priming volume of crystalloid (lactated Ringer’s or plasmalyte), NaHCO₃ dose, and bubble oxygenator model were based upon the patient’s weight as follows: 1) patients <10 kg: crystalloid 250 ml, NaHCO₃ 20 mmol, with BIO-2 oxygenator (American Bentley, Irvine, CA); 2) patients 10–15 kg: crystalloid 500 ml, NaHCO₃ 25 mmol, with BEN-5 oxygenator (American Bentley); and 3) patients 15–29 kg: crystalloid 750 ml, NaHCO₃ 25 mmol, also with BEN-5 oxygenator. After initiation of CPB using a Sarns non-pulsatile non-occlusive roller-head bypass pump, the patient was cooled to an average minimum venous blood temperature (Tᵥ) of 19.5 ± 0.6°C, using the integral heat exchanger of the oxygenator.

The bypass pump was adjusted to deliver blood to the ascending aorta at a flow rate that depended on the venous blood temperature as follows (pump flow units are 1·min⁻¹·m⁻²): Tᵥ ≥ 37°C, flow = 2.5; Tᵥ 25–37°C, flow = 2.0; Tᵥ 20–25°C, flow = 1.5; and Tᵥ < 20°C, flow = 0.5. The heart was arrested with cold cardioplegic solution (Plegisol, Abbott, Chicago, IL; [K⁺] = 16 mmol/l). Following a period of active rewarming, total CPB was converted to partial CPB (with ejection of blood by the left ventricle) when Tᵥ averaged 35.9 ± 0.3°C. The CPB rewarming duration was measured from onset of full rewarming until onset of partial CPB.

TOTAL CIRCULATORY ARREST

In 10 of the 25 patients (TCA group), it was elected preoperatively to use hypothermic total circulatory arrest (duration 34 ± 4 min) after a period of active cooling using CPB. These TCA group patients also received surface cooling, with ice surrounding the head and a cooling blanket under the body. Surface cooling began before surgical draping and continued until commencement of rewarming. TCA group patients also received methylprednisolone 30 mg·kg⁻¹ in the priming solution, and thiopental 9 mg/kg 3–5 min prior to onset of total circulatory arrest.

MEASUREMENT TECHNIQUE

Measurements of CO₂ elimination were made using a non-invasive technique. Measurements were obtained
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Table 2. Carbon Dioxide Q₁₀ Data

<table>
<thead>
<tr>
<th>Temperature Range (°C)</th>
<th>Q₁₀</th>
<th>95% Confidence Interval* for Q₁₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;25</td>
<td>5.4</td>
<td>3.2–9.1</td>
</tr>
<tr>
<td>25–30</td>
<td>6.5</td>
<td>1.8–23</td>
</tr>
<tr>
<td>&gt;30</td>
<td>1.2</td>
<td>0.82–1.7</td>
</tr>
<tr>
<td>All data</td>
<td>2.7</td>
<td>2.5–3.0</td>
</tr>
</tbody>
</table>

Q₁₀ data are calculated from the slope of the simple linear regression of Tₑ on log VCO₂ over the specified range of temperature values, using data pooled from no-TCA and TCA groups (23 patients, multiple determinations per patient). When Q₁₀ values were computed by fitting separate simple linear regression functions to each patient’s data, the mean Q₁₀ was 3.0 ± 0.23. This method yielded a 95% confidence interval of 2.5–3.5.

* The asymmetric confidence intervals with upper limits result from the exponential transform of confidence limits estimated for data on the logarithmic scale.

Results

Younger and smaller patients tended to undergo total circulatory arrest (TCA); age, weight, and the use

DATA ANALYSIS AND STATISTICAL TESTS

VCO₂ (in ml · min⁻¹ · kg⁻¹) was calculated as \(F_\text{CO}_2 \times \text{gas flow rate} \div \text{body weight}\). For the gas transfer rate calculations, we assumed equality between the effluent and inflow gas flow rates. All VCO₂ values are expressed at ATPD. Linear models were fit to the log transform of VCO₂ to ensure homoscedasticity. Q₁₀ (the variation in metabolic activity produced by a 10°C change) was determined from the linear regression slope of the log VCO₂ versus Tₑ relationship, transformed to a linear scale. Q₁₀ values were also computed individually by fitting separate simple linear regression functions to each patient’s data; the mean of the individual slopes was then calculated.

Patient descriptive variables (table 1) in the TCA and no-TCA groups were compared with the two-tailed t test, X² test (sex), or Fisher’s exact test (cardiac diagnoses). The effects of age, weight, total bypass time, total warming time, and use of TCA on the relationship of log VCO₂ with Tₑ were assessed by analysis of covariance, adjusted for within- and among-subject variation. To avoid interpretational inaccuracies, single factors were chosen to represent clusters of correlated variables. After important mediating variables were identified, coefficients for the best-fitting polynomial regression model relating log VCO₂ with Tₑ were estimated. Tₑ for each regression model is expressed as a deviation from the group mean value in order to reduce the correlation between the linear and quadratic terms (table 2). Attempts to represent curve of the data as an exponential function rising to an asymptote by non-linear regression were unsuccessful. Observations were then pooled across relevant subject categories to establish prediction intervals from the data. The effect of different temperature monitoring sites was examined using analysis of variance and linear modeling. Values are presented as mean ± standard error.
of TCA were significantly associated with one another (table 1). Therefore, the presence or absence of TCA was used to represent age and weight also in further analyses. Total CPB duration and CPB rewarming duration were correlated with each other ($r = 0.67$, table 1); we chose the former to represent the two variables. Use of TCA is the only variable identified that affects the relationship of $\dot{V}CO_2$ with venous blood temperature ($T_v$).

Figure 1 shows the curve of $\dot{V}CO_2$ plotted as a function of $T_v$ for the 198 $VCO_2$ observations in all 25 patients. $\dot{V}CO_2$ tends to increase with temperature. The $Q_{10}$ for $CO_2$ averages $2.7 \pm 1.0$ when a straight line is fit to the data from all patients over the entire $T_v$ range, and averages $3.0 \pm 23$ when straight lines are fit individually by patient and then meaned (table 2). No patient exhibited signs suggestive of malignant hyperthermia during the perioperative period.

Figure 1 also demonstrates that curvature exists in the relationship between log $VCO_2$ and $T_v$; this curvature presents as a significant ($P < 0.0001$) lack of fit of the data by a straight line, and is adequately represented as a second order polynomial. The 95% prediction intervals for $\dot{V}CO_2$ are depicted in figure 1. Because of the curvature, it may not be appropriate to represent the $Q_{10}$ for our patients by a single value. When the data are divided into three temperature segments, the calculated $Q_{10}$ values differ for each segment (table 2).

The substantial overlap of the 95% prediction envelopes for the log $VCO_2$ versus $T_v$ data in the no-TCA and TCA groups are depicted in figure 2. For purposes of predicting the value of $VCO_2$ that could be expected for a given $T_v$ value, separate polynomial regression models were developed for the pooled data, and for each TCA condition. The estimated $VCO_2$ values and 95% prediction intervals for these conditions are presented in table 3, to facilitate clinical use of the data since log scales may be difficult to read. The polynomial coefficients for the associated statistical models are shown in table 4. The only statistically significant difference between the TCA and no-TCA group curves was a small increase in the y-intercept term ($P = 0.008$, table 4) in the TCA group.

Plotting log $VCO_2$ versus venous blood temperature produced the smallest scatter, in comparison with the other temperature monitoring sites. Thus, use of $T_v$ as a predictor variable explained the largest amount of variability in log $VCO_2$ ($r^2 = 0.77$), as compared with nasopharyngeal temperature ($r^2 = 0.69$) or rectal temperature ($r^2 = 0.09$).

**Discussion**

We demonstrated that the rate of $CO_2$ elimination is readily measured in the gas phase during clinical CPB using a multiplexed mass spectrometer. Using our patient data, this technique may be valuable as a clinical tool for routine patient management. $VCO_2$ showed a clear dependence upon venous blood temperature, with the latter explaining 74% of the variability in $CO_2$ elimination. The difference in $CO_2$ elimination between the TCA and no-TCA groups manifested as a small but statistically significant increase in y-intercept in the TCA group. This increase in $VCO_2$ for a given temperature during rewarming could indicate improved global aerobic metabolic function when TCA is utilized, but further research is needed before the clinical implications of these observations can be determined.

Abbott et al. measured $VCO_2$ during CPB in four patients using a gas-phase technique incapable of gen-
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erating VCO₂ data until after CPB was completed. By modifying and simplifying their technique, we were able to obtain results in real-time, and to demonstrate the applicability of VCO₂ monitoring to patient care and clinical research. In addition to defining the relationship between VCO₂ and temperature, our research extends the observations of Abbott et al. to study patients during conditions more representative of those in common use today in the United States. For example, our patients' oxygenators were ventilated with gas containing no CO₂, whereas the patients of Abbott et al. received CO₂ in concentrations of 5–15%.

In another study, VCO₂ was measured in the blood phase in dogs undergoing partial CPB with normothermia by Kawashima et al.⁷

The rise in VCO₂ that we observed with increasing temperature may have several potential causes. Metabolic CO₂ generation increases with temperature (the Arrhenius effect), shivering may occur, and the rightward shift in the oxyhemoglobin dissociation curve may increase the availability of oxygen in peripheral tissues. As regional blood flow is improved, mobilization of CO₂ stores may occur from hypoperfused body tissues. Additionally, gas solubility in fluids and tissue stores is reduced as temperature rises (increasing the partial pressure), and carbonic anhydrase activity may increase. Changes in oxygenator efficiency may also occur as gas flow, blood flow, and inlet blood P<sub>CO₂</sub> vary. These factors all tend to increase CO₂ efflux across the oxygenator.⁵

A Q₁₀ of 2.5–3.0 is consistent with most biological systems. Using a steady-state immersion/perfusion hypothermic method, Kent and Peirce showed in the dog that the Q₁₀ for O₂ was 2.8, and similar values have been shown for humans and in vitro tissues.⁸ The curvature apparent in our data may be an artifact, since the relationship between log VCO₂ and T, analyzed separately for each patient demonstrated no significant deviation from a straight line fit, although slopes and intercepts differed (table 2). Further research is needed to help identify the causes of this inter-patient variability in VCO₂, as indicated by the wide 95% confidence intervals obtained for the data grouped by temperature range (table 3). Etiologies for the observed variability may include: differences in sympathetic and vascular tone affecting the regional distribution of blood flow, the use of different metabolic substrates altering the respiratory quotient, dissimilar rates of cooling and re-warming, unequal degrees of hemodilution, and variations in the degree of neuromuscular blockade and sup-

<table>
<thead>
<tr>
<th>Table 3: Predicted Values of VCO₂ at Various Venous Temperature Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venous Temperature (°C)</td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td>All patients</td>
</tr>
<tr>
<td>15</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>25</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>35</td>
</tr>
<tr>
<td>38</td>
</tr>
<tr>
<td>No-TCA group</td>
</tr>
<tr>
<td>15</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>25</td>
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<tr>
<td>30</td>
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<tr>
<td>35</td>
</tr>
<tr>
<td>38</td>
</tr>
<tr>
<td>TCA group</td>
</tr>
<tr>
<td>15</td>
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<tr>
<td>20</td>
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<td>25</td>
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<td>30</td>
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<td>35</td>
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<tr>
<td>38</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4: Polynomial Regression Coefficients*: VCO₂ Versus Venous Temperature: Effect of Total Circulatory Arrest (TCA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>All patients</td>
</tr>
<tr>
<td>No-TCA group</td>
</tr>
<tr>
<td>TCA group</td>
</tr>
<tr>
<td>P value‡</td>
</tr>
</tbody>
</table>

All values are mean ± standard error.

* The polynomial coefficients (terms) relate to the equation:

\[ \log_{10} \text{VCO}_2 = a_0 + a_1 (T - T_m) + a_2 (T - T_m)^2 \]

where T<sub>m</sub> is the venous blood temperature, and T<sub>m</sub> is the mean value of T<sub>v</sub> derived from all observations within each group, as follows:

1) All patients T<sub>m</sub> = 27.8°C; No-TCA group T<sub>m</sub> = 27.4°C; and TCA group T<sub>m</sub> = 26.4°C.

† P values testing hypothesis that coefficient is equal to zero.

‡ P values comparing coefficient of "No-TCA group" versus "TCA group."
pression of shivering. These variables were not controlled prospectively in this study.

The gas-phase method for \( \text{\textit{VCO}} \) determination presents several advantages over the blood phase oxygen uptake (\( \text{\textit{VO}} \)) technique, which has been applied to CPB previously.\(^a\) Direct determinations of blood \( \text{\textit{O}} \) and \( \text{\textit{CO}} \) content by chemical reaction are accurate techniques for \( \text{\textit{VO}} \) and \( \text{\textit{VCO}} \) measurement,\(^b\) but are cumbersome and time-consuming, and require discrete samples. For these reasons, real-time monitoring is difficult so blood oxygen content often is estimated from \( \text{PO} \) measurements through the use of "standard" oxygen-hemoglobin dissociation curves. However, the marked hypothermia, alkalosis, and changes in 2,3-diphosphoglycerate usually present during CPB may introduce inaccuracy in such estimates.\(^c\)\(^d\) By measuring changes in gas concentration across the pump oxygenator, gas-phase methods such as ours circumvent many of the problems associated with blood-phase \( \text{\textit{VCO}} \) and \( \text{\textit{VO}} \) measurements. Effluent \( \text{CO} \) analysis is a standard technique for evaluating membrane lung gas exchange.\(^e\)

**LIMITATIONS**

Limitations of our technique involve the non-steady-state nature of clinical CPB, in that temperature gradients always exist among the different body regions. Because of these gradients, the representation of a patient's temperature using a single value is merely an approximation. We chose the venous blood temperature as our standard value because it explained the largest proportion of variability log \( \text{\textit{VCO}} \), and also for theoretical reasons, since \( T_s \) should represent the average temperature of those tissues that contribute \( \text{CO} \) to the blood.

We have noticed that one bubble oxygenator, the Harvey® H-1700 (Bard, Billerica, MA) cannot be utilized for gas-phase \( \text{\textit{VCO}} \) measurements because its design incorporates the obligatory entrainment of room air in variable quantities. Membrane oxygenators present little problem in this regard.

**OTHER GAS-PHASE MONITORING TECHNIQUES**

For theoretical reasons, routine gas-phase monitoring of \( \text{CO} \) elimination (compared with oxygen uptake) is preferred for routine clinical use when using existing clinical operating room mass spectrometers that do not undergo special calibration techniques. Since oxygen uptake measurement involves accurately detecting small differences between large concentrations of gas (e.g., 99–97.5%), small errors in measurement (typically crowded into the high end of a 0–100% scale) are magnified when computing \( \text{\textit{VCO}} \). Determination of \( \text{\textit{VCO}} \), however, is made from a more precise measurement of the effluent \( \text{CO} \) concentration alone, since \( \text{CO} \) is usually absent from inlet gas and the mass spectrometer signals obtained typically represent the middle range of a 0–10% full-scale instrument.

The monitoring of \( \text{CO} \) tension alone in the oxygenator effluent gas (\( P_{\text{\textit{CO}}}, \text{\textit{CO}} \)) has been recommended;\(^f\) however, this partial pressure will be a function of variables relating to the oxygenator (blood flow, gas flow, and oxygenator efficiency), as well as venous blood \( \text{PCO} \). The use of infrared capnography to measure \( P_{\text{\textit{CO}}} \) may be confounded by unrecognized sample dilution with room air. In contrast, our mass spectrometric technique permits identification of nitrogen, \( \text{N}_2 \), and other gases, the presence of which would indicate contamination within the gas stream. \( \text{\textit{VCO}} \) is more reflective of patient metabolic function; when \( \text{\textit{VCO}} \) is combined with the \( P_{\text{\textit{CO}}} \) value, perfusion-related problems can be identified with greater specificity. For example, elevated \( P_{\text{\textit{CO}}} \) together with normal \( \text{\textit{VCO}} \) would indicate inadequate gas inflow to the oxygenator.

**POTENTIAL CLINICAL IMPLICATIONS**

There are several reasons why a \( \text{\textit{VCO}} \) measurement may lie outside of the prediction interval defined above. \( \text{\textit{VCO}} \) values above normal for a given \( T \), may indicate hyperactive metabolism (e.g., hyperthyroidism) or subclinical shivering due to inadequate muscle relaxation. This monitor may be valuable for detecting early malignant hyperthermia crisis during rewarming on CPB, when temperature normally rises quickly. In one patient who was potentially malignant hyperthermia susceptible and required surgery with CPB,\(^g\) we retrospectively compared \( \text{\textit{VCO}} \) data collected during CPB with the results of the present study; all data points fell within the 95% prediction interval. That patient showed no clear signs of malignant hyperthermia before or during CPB.

\( \text{\textit{VCO}} \) values below normal for a given \( T \), may indicate: 1) impaired or non-uniform nutritive regional blood flow, causing a reduction of the total mass of perfused body tissue, and which may benefit from vasodilator therapy; 2) impaired \( \text{O} \) delivery, such as excessive hemodilution, hypoxemia, or inadequate blood flow rate; 3) oxygenator malfunction or improper operation (e.g., inadequate roller-pump occlusion); 4) reduced metabolic \( \text{CO} \) production by the patient (e.g., hypothyroidism); and 5) technical monitoring problems, particularly room air contamination of the oxygenator effluent gas.

It should be recognized that the data presented here

**LARACH ET AL.**

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are specific for the precise conditions under which we performed CPB. While the data were obtained during routine operations and apparently normal perfusions, small base deficits were present during CPB, and optimization VCO₂ at any Tₑ was not necessarily achieved. The influences of various factors upon VCO₂, such as the pump flow rate, the rates of cooling and rewarming, patients' disease states, and the use of drugs such as vasodilators, vasoconstrictors, anesthetics, and muscle relaxants, deserve further research.

Real-time determination of CO₂ elimination may be a useful continuous monitor of metabolic, circulatory, and oxygenator function during CPB. Detection of a VCO₂ below the 'normal' range defined herein may provide evidence of tissue non-perfusion, despite lack of abnormalities in arterial blood pH and lactate, or in mixed venous oxygenation. We believe this technique is applicable to membrane as well as bubble oxygenation, and to adults in addition to pediatric patients. By using microcomputer technology, we have recently achieved full automation of this monitoring technique, thereby simplifying its clinical application. Further investigation is needed to determine whether interventions designed to increase VCO₂ during CPB, in real time, can be helpful in optimizing the bypass state. The "normal" ranges of VCO₂ defined for this patient population can help to guide patient management during CPB, with the goal of improving the safety of total CPB during cardiac surgery, and of partial CPB during extracorporeal membrane oxygenation (ECMO).

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References