Carbon Dioxide in Expiratory Water Condensate Are Equivalent to Mixed Expired Carbon Dioxide and Oxygen*

William R. von Pohle, M.D., F.C.C.P.; James D. Anholm, M.D., F.C.C.P.; and James McMillan, M.D.

This study was to determine whether the $P_{CONCO_2}$ and $P_{CONO_2}$ which collect in the expiratory trap of a ventilator circuit are equivalent to $PCO_2$ and $PEO_2$. Fifty studies were performed in 34 mechanically ventilated male patients. Five milliliters of condensate fluid were collected and $PCO_2$ and $PO_2$ were measured. Exhaled gases were collected simultaneously with condensate fluid for 5 min in a meteorologic balloon and $FECO_2$ and $FEO_2$ were measured; $PCO_2$ and $PO_2$ were then calculated. The mean $PCO_2$ was not significantly different from $P_{CONCO_2}$, nor was the $P_{CONO_2}$ significantly different from the condensate $PCO_2$. There was a high correlation between mixed expired $FECO_2$ and $P_{CONCO_2}$ as well as $FEO_2$ and $P_{CONO_2}$.

These data indicate expiratory $P_{CONCO_2}$ and $P_{CONO_2}$ provide a valid reflection of $FECO_2$ and $FEO_2$. The $P_{CONCO_2}$ and $P_{CONO_2}$ measured in a clinical blood gas analyzer are accurate and may be used in calculation of $VD/VT$ and in metabolic assessments. (Chest 1992; 101:1601-04)

Measurements of expired gases, obtained by a simple, repeatable, and readily available method, can add valuable information for patient management. The measured values of $PCO_2$ and $PO_2$ are used for calculation of $VD/VT$ and in metabolic calculations, particularly assessment of nutritional status.

The $VD$ frequently is expressed as a fraction of $VT$ and calculated from $PaCO_2$ and $PECO_2$. Calculation of physiologic $VD$, traditionally has required measurement of $PECO_2$ in exhaled gases and an arterial blood gas value for determination of $PaCO_2$, which is assumed to be equivalent to $Paco_2$. This procedure usually requires use of a breathing valve gas collection device (Douglas bag), and a $CO_2$ analyzer for the measurement of $FECO_2$, which is then converted to $PECO_2$ by use of a measured $Pa$. The Bohr equation is then used to calculate $VD$:

$$VD/VT=(Paco_2-Peco_2)/(Paco_2-Prco_2)$$

(Eq 1)

Since inspired $CO_2$ is usually negligible, this term can be dropped. The equation can be modified further by substituting arterial for alveolar $CO_2$ since they are considered equivalent.

Metabolic measurements on patients supported by mechanical ventilators allow assessment of energy expenditures and nutritional requirements. The $FIO_2$ must be stable. As the $FIO_2$ increases, the magnitude of instability increases; however, the use of wall blowers and more sophisticated ventilator circuitry has lessened this problem. The calculations of $VCO_2$ and $VO_2$ are based on different assumptions and affected to a varying degree by errors in volume or gas fraction measurement.

$$R=(VCO_2/VO_2)=[(FEPO_2(1-FIO_2)]-Prco_2]/[(FeO_2-Prco_2)-(Paco_2×FIO_2)]$$

(Eq 2)

Again, since inspired $CO_2$ usually is negligible, this term can be dropped. The $Prco_2$ can be substituted for by multiplying the barometric pressure by the $FIO_2$ ($PrCO_2=Pa×FIO_2$).

Traditionally, these metabolic measurements utilize equipment not always readily available and which may be technically difficult to use and calibrate. A simple method of determining these values would make them more widely available and would encourage their use for possible improvement of patient care. We sought to determine whether $P_{CONCO_2}$ and $P_{CONO_2}$ were a valid reflection of $PECO_2$ and $PEO_2$.

**METHODS**

Patients were eligible for study if they were at least 18 years of age, required mechanical ventilation and were in the Medical or Surgical Intensive Care Units at the Jerry L. Pettis Memorial Veterans Administration Medical Center in Loma Linda, Cal. We performed 50 studies in 34 male patients (mean age, 65.6 ± 8.9 years [mean ± standard deviation]) who had been mechanically ventilated for 19.4 ± 43.5 days. All patients were in the supine position when studied and had a size 7.5 or greater endotracheal
Table 1—Values of $P_{CO_2}$ with and without PEEP on Demand Valve (Bear 1) and Continuous Flow (Bear 5) Ventilator Circuits and Overall Mean*  

<table>
<thead>
<tr>
<th></th>
<th>No PEEP</th>
<th>PEEP</th>
<th>Bear 1</th>
<th>Bear 5</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>No.</td>
<td>30</td>
<td>20</td>
<td>27</td>
<td>23</td>
<td>50</td>
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<tr>
<td>$P_{CO_2}$ (mm Hg)</td>
<td>14.2±4.7</td>
<td>13.3±3.3</td>
<td>15.8±4.4</td>
<td>12.0±3.2</td>
<td>13.8±4.2</td>
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<tr>
<td>$P_{EO_2}$ (mm Hg)</td>
<td>13.9±4.8</td>
<td>13.0±3.4</td>
<td>15.4±4.3</td>
<td>11.5±3.3</td>
<td>13.6±4.3</td>
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*No significant differences were found between groups for any variables. Values are mean ± standard deviation.

tube. Vital signs were temperature, 37.7±0.9°C; pulse, 103±13 min⁻¹; respirations, 19±7 min⁻¹; and blood pressure, 126±27 mm Hg systolic and 68±13 mm Hg diastolic. All patients were ventilated with the assist control mode, with ventilator settings as follows: $FIO_2$, 0.46±0.15; $V_r$ 806±89 mL; rate, 11±3 min⁻¹; and $P_{EO_2}$, 3±4 cmH$_2$O (range, 0 to 20 cmH$_2$O); and ventilator inspiratory flow, 62±9 L/min. Bear ventilators (Bear Medical Systems Inc, Riverside, Cal) were used in all studies. The Bear 1 ventilator was used in 27 studies and the Bear 5 in 23 studies. All patients had a stable respiratory pattern and were hemodynamically stable at the time of study. At the time these studies were performed patients had the following arterial blood gases values: pH, 7.40±0.09; PaCO$_2$, 36.03±9.52 mm Hg; and PaO$_2$, 93.2±27.1 mm Hg.

Simultaneous collections of mixed expired gases were obtained from the ventilator circuit, condensation of expired gases of the expiratory limb condensate collection bottle and an arterial blood gas determination. Mixed expired gases were collected via a meteorologic balloon connected to the expiratory limb circuit as distal to the patient as possible for a period of 5 min. Immediately after collection, $P_{CO_2}$ and $P_{EO_2}$ were measured by a mass spectrometer (Perkin-Elmer 1100 Medical Gas Analyzer, Pomona, Cal) from which $P_{CO_2}$ and $P_{EO_2}$ were calculated. Expiratory limb condensate was collected from the condensate bottle with a non-hemarinized 10-ml syringe in the ventilator expiratory circuit over a 15- 30-min period. At the end of the collection period the FCO$_2$ and PO$_2$ were measured on a blood gas analyzer (Corning 178 pH/Blood Gas Analyzer, Medfield, Mass). The arterial blood gas collected was analyzed on the same blood gas machine prior to analysis of the condensate sample.

The study was approved by the Research and Development Committee and the Human Subjects Subcommittee at the Jerry L. Pettis Memorial Veterans Administration Medical Center. The Human Studies Subcommittee determined that informed consent was not required for the study. A paired t test was used to compare the expired gas collection measured via the meteorologic balloon and the expiratory limb condensate. Linear regression between $P_{CO_2}$ and $P_{EO_2}$ and between $P_{CO_2}$ and $P_{EO_2}$ were performed.

RESULTS

Table 1 shows the values for the $P_{CO_2}$ in the condensate and mixed expired gases. All values are shown as means ± standard deviation. The mean $P_{CO_2}$ of 13.8±4.2 mm Hg was not different from the $P_{EO_2}$ value of 13.6±4.3 mm Hg (p = NS). There was a high degree of correlation between these values ($r = 0.93; p < 0.01$). Table 1 further shows comparison of these two methods in subgroups with and without PEEP. Also shown are values for the different valve systems in the two ventilators used in the study. These were a demand valve in the Bear 1 and a continuous flow system in the Bear 5. In none of these comparisons was any significant difference demonstrable. Figure 1 illustrates the line of regression [P$P_{CO_2}$(0.99)] $P_{EO_2}$+0.19 for the comparison of $P_{CO_2}$ and $P_{EO_2}$.

Table 2 shows the values for the PO$_2$ in the condensate and mixed expired gases. Again all values are shown as mean ± standard deviation. The mean PO$_2$ of 315.1±99.1 mm Hg was not significantly different from the PEO$_2$ of 319.2±105.9 (p = NS). These also were highly correlated (r = 0.98; p < 0.01). Table 2 also shows comparison of these two methods under conditions with and without PEEP. Again shown are values for the valve systems in the two ventilators used in the study. Figure 2 illustrates the line of regression (P$P_{CO_2}$=[1.05] PEO$_2$+11.73) for the comparison of $P_{CO_2}$ and PEO$_2$.

No significant differences were found within any of the subgroups in comparison of the mixed expired gases from the condensate values for either CO$_2$ or O$_2$.

DISCUSSION

Wasted ventilation or physiologic VD is an important determinant of abnormal blood gases and reflects the adequacy of ventilation. The VD determinations include the amount of physiologic and anatomic VD. Because anatomic VD is relatively constant, increases in VD must result from increases in alveolar VD. Normally, alveolar VD is not present to any significant degree. In the presence of ventilation-perfusion abnormalities, physiologic VD is increased. This is largely because of ventilation to lung areas with abnormally high ventilation-perfusion ratios. In fact, it may be one of the indices of the degree of mismatching of ven-

Table 2—Values of $P_{CO_2}$ with and without PEEP on Demand Valve (Bear 1) and Continuous Flow (Bear 5) Ventilator Circuits and Overall Mean*  

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<td>50</td>
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<tr>
<td>$P_{CO_2}$ (mm Hg)</td>
<td>277.1±61.2</td>
<td>372.3±117.4</td>
<td>345.3±121.5</td>
<td>294.4±74.4</td>
<td>315.1±99.1</td>
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<tr>
<td>$P_{EO_2}$ (mm Hg)</td>
<td>281.4±66.0</td>
<td>375.9±128.9</td>
<td>340.5±121.1</td>
<td>294.2±80.2</td>
<td>319.2±105.9</td>
</tr>
</tbody>
</table>

*No significant differences were found between groups for any variables. Values are mean ± standard deviation.

CO$_2$ and O$_2$ Partial Pressure in Expiratory Water Condensate (von Pohle, Anholm, McMillan)
PEEP or the effect of various levels of pressure support ventilation can be determined. The Vd/Vt measurements provide a conceptual tool to accurately evaluate and plan treatment. The major clinical application of Vd/Vt is to provide a guideline for successful extubation.

The Vd/Vt as a reflection of gas exchange could be useful in the evaluation of extubation criteria. Expired gas monitoring has been used in the intensive care unit for monitoring the patient's course. The Vd/Vt could be useful for determining optimal ventilator settings and in defining the pathologic disturbances impeding patient progress; this could be particularly useful in weaning. Changes in pulmonary mechanics leading to impaired oxygenation and ventilation also are predictive of subsequent clinical deterioration. The trend in the ratio can be followed to assess the stability of ventilation to provide guidance in the adequacy of current ventilator support. Trends can be detected early and reversed before they result in crisis situations.

Assuming CO₂ production is constant, ventilatory criteria assess the relative proportion of Vd present. Patients whose Vd/Vt exceeds 0.6 are usually not weanable from ventilatory support. Small increases in Vd/Vt greater than 0.6 require large increases in minute ventilation in order to maintain a given PCO₂. Such increases in spontaneous minute ventilation may be difficult for many critically ill patients to achieve, ultimately resulting in hypercapnia and respiratory muscle fatigue. Factors which may vary the CO₂ production or clearance are irregularity in body temperature, fluctuations in the level of sedation, alterations in the minute ventilation and changes in the nutritional status.

Inadequate nutrition has been associated with a variety of complications, including respiratory muscle weakness, while excessive nutritional intake, especially of carbohydrates, has been associated with relatively large increases in O₂ consumption and CO₂ production. Measurement of VO₂ and VCO₂ are frequently performed to calculate energy expenditure. These calculations are used in planning nutritional requirements as well as to evaluate metabolic status. Energy expenditure is most conveniently assessed through the measurement of VO₂ and VCO₂. These measurements are easy to make in spontaneously breathing, non-intubated patients. Many critically ill patients are intubated and on mechanical ventilation. Mixed expired gas analysis is the easiest method for normal subjects but can be difficult in mechanically ventilated patients. It can be complicated by minor variations in the inspired volume and the oxygen concentration during the respiratory cycle.

We previously reported the utility of using PconCO₂ for measurement of Vd/Vt. In all patients,
using different ventilators and ventilator settings we
found a close correlation between PCONCO₂ and
PendoCO₂. We now have extended this to include the
analysis of the PEO₂. Possible sources of error in
measurement may arise due to inaccuracies of the
blood gas analyzer in the ranges measured, since they
are outside of typical physiologic values. The blood
gas analyzer we used is accurate for PCO₂ in the range
of 14 to 50 mm Hg±0.3 mm Hg and for PO₂ in the
range of 100 to 400 mm Hg±1.5 and 400 to 700 mm
Hg±8.3 mm Hg. We believe that the range of error of
<2 percent in the blood gas analyzer is clinically
insignificant. The solution also may be unstable and
subject to changes over time in the pressures of gases
in solution. A buffer such as NaHCO₃ or EDTA might
improve stability. However, all of our analyses were
performed within 5 min of collecting the sample. The
addition of buffers also would make the procedure
unnecessarily cumbersome and difficult and is unlikely
to increase the accuracy of measurements.

Figures 1 and 2 demonstrate the accuracy of the
PCONCO₂ and PendoCO₂ when used as a measurement
of mixed expired PendoCO₂ and PendoO₂. We did not
specifically repeat measures in the same subjects on
the same day. If condensate values were unreliable it
is unlikely that the regression equations shown in
Figures 1 and 2 would have had such high r values.
Thus, we cannot specifically comment as to test-retest
reliability. However, it is clear from Figures 1 and 2
that these are highly accurate measurements and in
all likelihood are extremely reliable. Therefore,
PCONCO₂ and PendoCO₂ are interchangeable with
mixed expired gas values for calculation of VCO₂ and
VO₂.

The method described here for determining
PCONCO₂ and PendoCO₂ is equal in accuracy to conven-
tional methods requiring the use of mass spectrometry
or other gas analyzers and can be performed quickly
and easily. In institutions, such as the community
hospital, it may provide a valuable resource for the
management of critically ill patients without the need
for additional personnel and costly equipment.

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