Precise Control of PCO_2 During Cardiopulmonary Bypass

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Introduction

Maintenance of normal arterial PCO_2 ($PaCO_2$) during cardiopulmonary bypass (CPB) is essential to both normal acid-base balance and proper blood flow distribution. Respiratory acidosis and more frequently alkalosis are commonly reported conditions concurrent with CPB.[1,2] Furthermore, decreased $PaCO_2$ causes a shift in the oxyhemoglobin dissociation curve to the left resulting in less oxygen being available to the tissues at a given PO_2.[3] Couple these events with the fact that decreased $PaCO_2$ decreases cerebral perfusion[4,5] and the importance of maintaining normal values becomes readily apparent.

$PaCO_2$ is primarily a function of CO_2 production, minute ventilation, and inspired CO_2 concentration ($FiCO_2$). In the past, due to the relative oxygenating inefficiency of our gas exchange devices, we have been forced to hyperventilate in order to oxygenate. The only means left to prevent respiratory alkalosis was to add CO_2 to the ventilating gas, thus reducing the CO_2 driving gradient. With the advent of efficient membrane oxygenators (MO) and their independent control of the two respiratory blood gases, precise regulation of $PaCO_2$ has become possible by manipulating the ventilatory flow rate (QG). This study was designed to demonstrate the effectiveness of this method for $PaCO_2$ control during CPB.

Methods and Materials I

A mathematical method was developed (Equation 1) to estimate the optimal ventilation (EOV) required for normothermic perfusion.

Equation 1: Estimation of Optimal Normothermic Minute Volume

$$\text{EOV (ml/min)} = \frac{\text{BSA (m}^2\text{)} \times 80 \text{ (ml/m}^2\text{/min)}}{.053}$$

This method was utilized during 50 consecutive CPB procedures utilizing either a SciMed* or Travenol** Membrane Oxygenator. Blood samples were drawn from a well flushed arterial sampling port during normothermic perfusion. The samples were subjected to blood gas analysis (BGA) by an Instrumentation Laboratory (IL) Micro 13 blood gas analyzer,*** operating at 37°C. Ninety-five percent confidence limits were constructed for the measured $PaCO_2$'s.

Methods and Materials II

A simple proportionality formula (Equation 2) was developed for correcting abnormal $PaCO_2$ during stable periods of CPB. This method was utilized during 100 consecutive CPB procedures using either MO device. Once stable CPB was attained, a blood sample was taken from a well flushed arterial sampling port of the MO, and analyzed by the IL Micro 13 blood gas analyzer operating at 37°C. The raw data were temperature corrected,[6] if necessary, to the patient's blood temperature measured by an arterial temperature

* Sci-Med Life Systems, Inc., Minneapolis, MN 55441
** Travenol Laboratories, Inc., Deerfield, IL 60015
*** Instrumentation Laboratory Inc., Model 326.10, Lexington, MA 02173

probe.**** Once the temperature corrected $PaCO_2$ (measured $PaCO_2$) was determined, the new QG required to normalize the $PaCO_2$ was derived from Equation 2.

Equation 2: Simple Proportionality Formula Used For Estimating Optimal Minute Volume

$$\text{New Minute volume (ml/min)} = \text{Old minute volume (ml/min)} \times \frac{\text{Measured } PaCO_2}{\text{Desired } PaCO_2} \text{ (mm Hg)}$$

After the newly adjusted QG was maintained for at least five minutes, a second arterial blood sample was analyzed. Ninety-five percent confidence limits were constructed for the measured $PaCO_2$'s.

Methods and Materials III

$PaCO_2$ control was attempted using an in-line infra-red CO_2 concentration analyzer***** (Figure 1). The sampling probe from the analyzer was strategically placed so that the CO_2 concentration in the exhaust gas from either a membrane****** or bubble******* oxygenator was continuously monitored. The QG was altered until the desired expired CO_2 concentration ($FeCO_2$) was attained. Results were displayed in percent concentration and exhaust gas PCO_2 ($PexCO_2$) were determined with Equation 3.

Equation 3: Formula used for Calculation of $PexCO_2$

$$PexCO_2 \text{ (mm Hg)} = \frac{\text{Percent Concentration}}{CO_2 \text{ in Exhaust Gas}} \times P_{\text{Barometric}} \text{ (mm Hg)}$$

These data were compared to measured $PaCO_2$ determined by an IL Micro 13 blood gas analyzer. One hundred and twenty samples were drawn from an arterial sampling port located next to an in-line temperature probe. Samples were analyzed during all stages of CPB and temperature corrected accordingly. Correlation between the measured $PaCO_2$ with expired CO_2 concentration as well as $PexCO_2$ was determined. Statistical comparisons were made using the student's t-test. Results were expressed as mean ±1 SD.

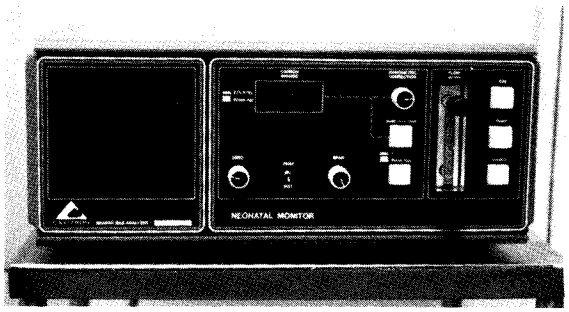

FIGURE 1. Cavitron Neonatal CO_2 Concentration Analyzer

Results I

Sixty-three blood samples were analyzed after estimation of the optimal ventilatory flow rate during normothermic perfusion. With the use of Equation 1, the measured $PaCO_2$ averaged 38 ± 3.1 mm Hg (mean

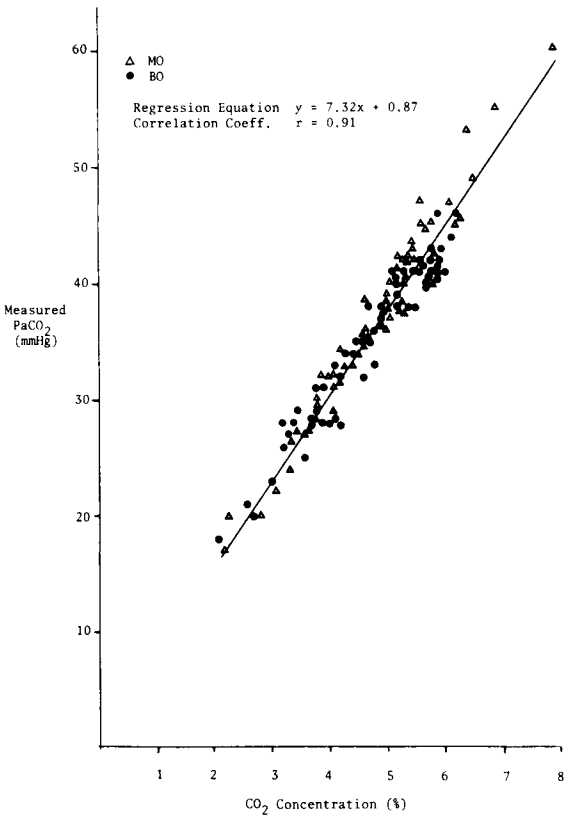

FIGURE 2. Comparison of Measured $PaCO_2$ with CO_2 Concentration in Exhaust Gas from Blood Oxygenator

**** Sarns, Inc., Ann Arbor, MI 48103

***** Cavitron Neonatal Monitor, Model No. PM-20N, Anaheim, CA 92802

****** Sci-Med Life Systems Inc., Minneapolis, MN 55441

Travenol Laboratories Inc., Deerfield, IL 60015

******* Shiley Scientific Inc., Irvine, CA 92714 S-070 and S-100

William Harvey, Division of C.R. Bard Inc., Santa Ana, CA 92705 H-400 and H-1000

TABLE I

COMPARISON OF MEASURED $PaCO_2$ WITH CO_2 CONCENTRATION IN EXHAUST GAS FROM BLOOD OXYGENATORS

DEVICE	TEMPERATURE RANGE (°C)	NO. OF SAMPLES	PERCENT CONCENTRATION CO_2 IN EXHAUST GAS	CALCULATED $PexCO_2$ (MM HG)	MEASURED $PaCO_2$ (MM HG)	PERCENT DIVERGENCE FROM MEASURED $PaCO_2$
MO	16 - 38	60	4.8±1.1	36.5±9.3	37.1±8.6	4.0±3.3
BO	15 - 38	60	4.7±1.0	34.4±7.2	35.1±6.9	4.8±4.2

±1 SD). Ninety-five percent of the measured $PaCO_2$ fell within the range of 32–44 mm Hg.

Results II

One hundred and seventy-two consecutive blood samples were analyzed after changing QG based upon Equation 2 during periods of stable CPB. With the use of Equation 2, the measured $PaCO_2$ averaged 39 ± 2.7 mm Hg (mean ±1 SD). Samples were analyzed during any stable period of CPB with a temperature range of 17°C–38°C. Ninety-five percent of the measured $PaCO_2$ fell within the range of 34–44 mm Hg.

Results III

Table I summarizes the data for the 120 consecutive blood samples analyzed with either a MO or BO. Figure 2 vividly demonstrates the very high correlation which existed between the measured $PaCO_2$ and the CO_2 concentration in the exhaust gas from either device ($r = 0.97$, $p < .001$).

The difference between measured $PaCO_2$ and $PexCO_2$ was expressed as percent divergence. The $PexCO_2$ deviated from the measured $PaCO_2$ by an average of 4.0 ± 3.3% (MO) and 4.8 ± 4.2% (BO).

Discussion

In the past, QG control has predominantly been by empirical estimation and no consistently good technique has been reported. This becomes obvious when examining operational instructions for the various gas exchange devices. Hyperventilating gas to blood flow rates are recommended and frequently it is suggested that CO_2 should be added to the ventilating gas. Using pure oxygen, the gas flow in blood oxygenators can be adapted to match the metabolic production of CO_2.

The mathematical formula used in Method I is based on normal oxygen consumption and CO_2 production data.[7] The generally accepted value for O_2 consumption is approximately 150 ml/m²/min while the value for CO_2 production is approximately 120 ml/m²/min, a respiratory quotient (RQ) of 0.8.[8] Oxygen consumption and CO_2 production are reduced by approximately one-third due to anesthesia, skeletal muscular paralysis, and artificial ventilation.[7] This means that the average patient undergoing open-heart surgery will have a normothermic O_2 demand of approximately 100 ml/m²/min and a CO_2 production of approximately 80 ml/m²/min.

Once the CO_2 production rate has been estimated, the ventilation rate required to achieve a desired $PaCO_2$ can be calculated. Since the $PaCO_2$ and $FeCO_2$ correlate so closely in the artificial lung, the estimated optimal ventilation rate should be that minute volume

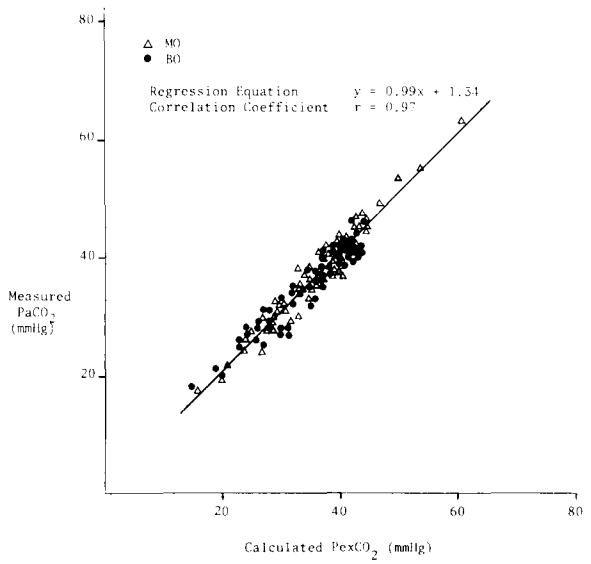

FIGURE 3. Comparison of Measured $PaCO_2$ with Calculated $PexCO_2$

in which the produced CO_2 will be diluted to achieve the desired $FeCO_2$. For example, if the barometric pressure is 760 mm Hg and the desired $PaCO_2$ is 40 mm Hg, the desired $FeCO_2$ must be 5.3% (40/760 × 100).[9] So, the desired QG is that flow that will dilute the CO_2 produced to a concentration of 5.3% or CO_2 production/5.3%.

During CPB variation in patient's CO_2 production occurs due to changes in metabolic activity. These changes are caused by the induction of hypothermia, varying levels of anesthesia, and the use of muscle relaxants. The variations in CO_2 production necessitate changes in ventilation rate if the $PaCO_2$ is to be kept within the desirable range. Changes are made using a simple proportionality formula once the CO_2 production is estimated from a measured $PaCO_2$ and ventilation rate (QG):

$$CO_2 \text{ production} = \frac{\text{measured } PaCO_2}{P_{Barometric}} \times QG$$

The formula is derived as follows:

$$\text{New QG} = \frac{CO_2 \text{ production}}{\text{Desired } FeCO_2} \text{ or } \frac{\frac{\text{Measured } PaCO_2}{P_{Barometric}} \times \text{Old QG}}{\frac{\text{Desired } PaCO_2}{P_{Barometric}}}$$

inverting the denominator and multiplying:

$$\text{New QG} = \frac{\text{Measured } PaCO_2}{P_{Barometric}} \times \frac{P_{Barometric}}{\text{Desired } PaCO_2} \times \text{Old QG}$$

cancelling the $P_{Barometric}$:

$$\text{New QG} = \frac{\text{Measured } PaCO_2}{\text{Desired } PaCO_2} \times \text{Old QG}$$

Equations 1 and 2 can be used for all oxygenators, but do not appear to be useful for bubble oxygenators due to the BO's relative oxygenating inefficiency. At gas to blood flow ratios required to achieve normal $PaCO_2$, the PaO_2 usually became less than 80 mm Hg. As increasing oxygenating efficiency is achieved in bubble oxygenators, these formulae may be applicable to these devices.

Use of the in-line exhaust gas infra-red CO_2 concentration analyzer produced excellent results in both bubbler and membrane oxygenators. The $PaCO_2$ could essentially be dialed in by fine tuning QG in MO's or the $FiCO_2$ in BO's to produce a favorable exhaust gas CO_2 concentration. Not only was the device consistent during periods of stable CPB, but dynamic changes in the patient's CO_2 production could be continuously monitored. Such rapid assessment of the patient's respiratory status can only improve the adequacy of perfusion.

Conclusions

1. Optimal ventilation can be estimated by using Equation 1 at the onset of by-pass and by modifying QG during bypass with Equation 2.

2. Expired CO_2 concentration can be monitored by an infra-red CO_2 analyzer from either a MO or BO and be used to control $PaCO_2$. This technique obviates the necessity of measuring $PaCO_2$.

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