NORMOCAPNIC VENTILATION USING THE CIRCLE SYSTEM

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THE DESIRABILITY of maintaining a normal arterial carbon dioxide tension (P_{aCO_2}) during controlled ventilation is well known.¹⁻¹² The justifiable concern for adequate oxygenation during anaesthesia and controlled ventilation overshadowed consideration for maintenance of normal P_{aCO_2} levels until the work of Nunn in 1960.¹³ He reviewed the use of the Radford ventilatory normogram¹⁴ in anaesthesia and produced a blood gas predictor¹⁵ relating P_{aCO_2} and alveolar ventilation ($\dot{V}_A$) for a given body weight. Since then many studies of prediction of P_{aCO_2} have been carried out using different anaesthetic circuits.¹⁶⁻²² The last two studies used the circle system without carbon dioxide absorption. However, the selection of patients free from cardiovascular and respiratory disease, the choice of one body position and the need for graphs and normograms limit the practical applicability of these studies. In the following study the same approach was pursued further in an attempt to determine whether there was a simple and practical relationship between body weight, fresh gas flow ($\dot{V}_F$) and minute ventilation ($\dot{V}_E$) that would maintain within normal limits the P_{aCO_2} of patients anaesthetized and artificially ventilated, unselected in terms of cardiovascular or respiratory disease or body position (*vide infra*).

THEORETICAL ANALYSIS

$$P_{A_{CO_2}} \propto \frac{1}{\dot{V}_A}$$

Where $P_{A_{CO_2}}$ = Alveolar carbon dioxide tension.

It has been shown²³⁻²⁴ that during controlled ventilation in an anaesthetic system that permits rebreathing, $\dot{V}_F$ takes place of $\dot{V}_A$ provided that $\dot{V}_E > \dot{V}_F$.

Thus

$$(1) \quad P_{A_{CO_2}} \propto \frac{1}{\dot{V}_F}$$

Further it can be derived from Bohr's equation that

$$P_{A_{CO_2}} = \frac{\dot{V}_{CO_2}(P_B - P_{H_2O})}{\dot{V}_A} + P_{I_{CO_2}}$$

Where $\dot{V}_{CO_2}$ = carbon dioxide production per minute, P_B = Barometric pressure.

P_{H_2O} = Saturated water vapour pressure and $P_{I_{CO_2}}$ = Inspired carbon dioxide tension.

There is no data available on the $P_{I_{CO_2}}$ of a circle system without carbon dioxide (CO_2) absorption. The circle systems commonly used for controlled ventilation

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are the types A and C as described by Eger and Ethans.²⁵ If it is assumed that ideal conditions exist and only mixed expired gas is spilt from the system, then in a steady state CO₂ output from the system will be equal to the CO₂ output from the patient.

$$(2) \quad \dot{V}_{\text{CO}_2} = \dot{V}_F \cdot F_{\text{ECO}_2}$$

Where F_{ECO_2} = Fractional concentration of CO₂ in mixed expired gas. CO₂ output from the patient also equals

$$(3) \quad \dot{V}_{\text{CO}_2} = \dot{V}_E F_{\text{ECO}_2} - \dot{V}_E F_{\text{ICO}_2}$$

Where F_{ICO_2} = Fractional concentration of CO₂ in inspired gas.

$$\therefore \dot{V}_F F_{\text{ECO}_2} = \dot{V}_E F_{\text{ECO}_2} - \dot{V}_E F_{\text{ICO}_2}$$

Converting into partial pressures,

$$(4) \quad \begin{aligned} \dot{V}_F P_{\text{ECO}_2} &= \dot{V}_E P_{\text{ECO}_2} - \dot{V}_E P_{\text{ICO}_2} \\ \therefore P_{\text{ICO}_2} &= P_{\text{ECO}_2} \frac{\dot{V}_E - \dot{V}_F}{\dot{V}_E} \end{aligned}$$

$$\text{From (1) } P_{\text{ECO}_2} = \frac{\dot{V}_{\text{CO}_2} (P_B - P_{\text{H}_2\text{O}})}{\dot{V}_F}$$

$$(5) \quad \therefore P_{\text{ACO}_2} = \frac{\dot{V}_{\text{CO}_2} (P_B - P_{\text{H}_2\text{O}})}{\dot{V}_A} + \frac{\dot{V}_{\text{CO}_2} (P_B - P_{\text{H}_2\text{O}})}{\dot{V}_F} \cdot \frac{\dot{V}_E - \dot{V}_F}{\dot{V}_E}$$

Thus with a knowledge of $\dot{V}_{\text{CO}_2}$ ²⁶ and physiological dead space under anaesthesia¹³ it is possible to work out combinations of $\dot{V}_F$ and $\dot{V}_E$ for a given $\dot{V}_{\text{CO}_2}$ that would maintain P_{ACO_2} within normal limits. Armed with such figures and assuming that $\dot{V}_{\text{CO}_2}$ is proportional to body weight,¹⁴ a pilot study was formulated.

METHOD

The study was carried out in two parts.

(1) A pilot study with values derived from Equation 5 above attempting to correlate P_{ACO_2} to body weight and ventilation.

(2) The main study to determine the clinical applicability of observations from the pilot study.

(1) The standard circle system was used with the carbon dioxide absorber out of the circuit. The inspiratory and expiratory limbs were about 500 ml each and the Y connector about 20 ml.

The systems studied belonged to the A (inflow between inspiratory valve and patient) and C (inflow between inspiratory and expiratory valves) types of circle systems as described by Eger and Ethans.²⁵ The reservoir bag was replaced by a ventilator connected to the system by a tube of about 500 ml. The ventilators used were the Bennett BA 4 Anaesthesia Ventilator and the Ohio 300 Anaesthesia Ventilator.

There was no selection of patients and anaesthesia was not standardized. Some patients had no premedication while others had anileridine 25 mg or meperidine

50 mg and promethazine 25 mg intramuscularly one hour before operation. Anaesthesia was induced with thiopentone or a mixture of nitrous oxide, oxygen and halothane and maintained with nitrous oxide, oxygen and muscle relaxant (either d-tubocurarine or pancuronium) supplemented with neurolept analgesia, narcotic (either fentanyl or meperidine) or halothane.

The following combinations of fresh gas flow and minute ventilation were then chosen.

- 1) Eight patients each had a total gas flow of 70 ml/kg/min for a minute ventilation of 120 ml/kg (rate 10–12/min).
- 2) Fourteen patients each had a total fresh gas flow of 60 ml/kg/min for a minute ventilation of 120 ml/kg (rate 10–12/min). In ten of these patients the minute ventilation was increased to 150 ml/kg keeping the rate the same.
- 3) Twelve patients each had a total fresh gas flow of 50 ml/kg/min and were ventilated at 120 ml/kg and then at 150 ml/kg at a rate of 10–12/min.

Arterial blood was then drawn from the radial artery or the dorsalis pedis artery (if the arms were by their sides) and the first sample was taken at least 45 minutes after induction. Subsequent samples were taken at least 30 minutes after any change was made, to ensure proper equilibration. These samples were analysed by one technician using an IL 113 pH/gas analyzer (Instrumentation Laboratory Inc., Boston, Mass.). This machine was calibrated daily and the results were checked at random, using ABLI acid base laboratory (Radiometer, Copenhagen).

(2) In the main study 70 patients were studied. Their classification according to age and sex, ASA status, obesity, body position during operation, type of anaesthetic administered and the type of anaesthetic circuit used, are shown in Figures 1 to 6 respectively. The only patients excluded were those having open chest operations and those with fever.

For each patient a total fresh gas flow of 50 ml/kg/min was set as closely as possible with a minimum of 3 l/min. The ventilation was set at about 120 ml/kg using a rate of 10–12/min. The minute ventilation was approximate but was not set below 120 ml/kg, often being slightly higher. The blood gas analysis was done as before.

The oesophageal temperature was measured in ten patients, selected at random.

RESULTS

In the pilot study (Figure 7) the mean P_{aCO_2} of the patients who were in the $\dot{V}_F$ 70 ml/kg/min group was 28.0 mm Hg with a range between 26.0 and 31.0 mm Hg. The mean P_{aCO_2} of the patients in the $\dot{V}_F$ 60 ml/kg/min group was 32.9 mm Hg with a range between 29.0 and 39.0 mm Hg at a $\dot{V}_E$ of 120 ml/kg. The decrease in P_{aCO_2} on increasing the $\dot{V}_E$ to 150 ml/kg was a mean of 3.83 mm Hg with a range between 2.5 and 6.5 mm Hg. In the group with a $\dot{V}_F$ of 50 ml/kg/min the mean P_{aCO_2} was 38.8 mm Hg with a range between 36.0 and 42.0 mm Hg at a $\dot{V}_E$ of 120 ml/kg. On increasing the $\dot{V}_E$ to 150 ml/kg the P_{aCO_2} decreased by a mean of only 0.96 mm Hg with a range between zero and 3.5 mm Hg. The validity of Formula (1) is clearly seen in this range of $\dot{V}_F$.

FIGURE 1. Age and sex distribution.

FIGURE 2. Distribution of ASA physical status.

FIGURE 3. Distribution of obese patients.

FIGURE 4. Distribution of body position during surgery.

In the main study the values for observed P_{aCO_2} of the total patient population is presented in the form of a histogram (Figure 8). The maximum frequency of distribution is between 35.0 and 40.0 mm Hg with a range of 33.0 to 45.0 mm Hg. When the sample is subdivided into sex, age, ASA status, obesity, body position, type of anaesthetic used and type of circuit used the differences in the mean values for P_{aCO_2} are not clinically significant (Figure 9).

The fall in temperature in the ten patients selected at random was a mean of 35.7° C with a standard deviation of 0.6° C.

FIGURE 5. Type of anaesthetic administered.

FIGURE 6. Type of circle system used.

DISCUSSION

Any attempt at prediction of P_{aCO_2} is made difficult by the variability of the many factors that govern CO_2 production. However, it seems that normocapnia can be achieved in the system described in many variable situations by using a fresh gas flow as low as 50 ml/kg body weight/min with mild or moderate mechanical hyperventilation at a $\dot{V}_E$ of 120 or 150 ml/kg body weight and a rate of 10–12/min. If moderate hypocapnia is desired, a $\dot{V}_F$ of 60 ml/kg body weight/min with a $\dot{V}_E$ of 120 ml/kg body weight, rate 10–12/min, should be used.

FIGURE 7. Pilot study. The mean P_{aCO_2} in the $\dot{V}_F$ 50, 60 & 70 ml/kg/min groups is shown ($\bullet$). (Range I). The smaller lines (Φ) in the $\dot{V}_F$ 50 & 60 ml/kg/min groups show the drop in P_{aCO_2} on increasing $\dot{V}_E$ to 150 ml/kg.

FIGURE 8. Histogram showing the distribution of P_{aCO_2} in the total patient sample.

With changes in ventilation, the two components on the right hand side of Equation 5 change in opposite directions so that the net change in P_{aCO_2} is small. The smaller drop in mean P_{aCO_2} on increasing the $\dot{V}_E$ from 120 to 150 ml/kg body weight in the $\dot{V}_F$ 50 ml/kg/min group as compared to the $\dot{V}_F$ 60 ml/kg/min group is probably due to the greater accuracy of Equation 4 as the ratio $\dot{V}_E/\dot{V}_F$ becomes larger and less fresh gas bypasses the patient.

FIGURE 9. The mean P_{aCO_2} (●) and the range (I) in the various patient groups (see text). M = males, F = females. Body position, S = supine, L = lithotomy, T = trendelenberg, O = others. Anaesthetic, N.L.A. = Neurolept anaesthesia, N = narcotic, H = halothane. Circuit = circle systems A & C.

The advantages of such a system are (a) greater accuracy in achieving normocapnia than with the use of the Radford normogram; (b) flexibility with ventilation, allowing larger minute volumes for adequate ventilation in patients with respiratory disease, yet maintaining the P_{aCO_2} constant; (c) changes in lung compliance that may occur during anaesthesia and surgery do not affect the efficiency of the system even when non "volume-cycled" ventilators are used; (d) lack of need to set accurately respiratory volumes using respirometers which have doubtful accuracy; and (e) use of small fresh gas flows are advantageous in terms of economy and reducing operating room atmospheric pollution.

Finally, the steps for achieving normocapnia are (a) turning the CO_2 absorber to the "off" position; (b) set total fresh gas flow at 50 ml/kg/min with a minimum of 3 l/min; and (c) set minute ventilation approximately between 120 to 150 ml/kg at a rate of 10 to 12/min. Example for a 70 kg man: fresh gas flow 3.5 l/min, tidal volume between 840 and 1050 ml and a rate of 10/minute.

SUMMARY

A formula is derived for maintaining normocapnia during controlled ventilation using a circle system without carbon dioxide absorption. In a series of 70 patients, unselected in terms of age, sex, obesity, ASA status, body position during operation, type of anaesthetic administered or type of circle system used, it was found that a total fresh gas flow of 50 ml/kg body weight/min and a minute ventilation of 120 to 150 ml/kg body weight at a rate of 10 to 12/min achieved normocapnia. For moderate hypocapnia a total fresh gas flow of 60 ml/kg body weight/min and a minute ventilation of 120 ml/kg at a rate of 10-12/min is suggested.

RÉSUMÉ

L'objet de cette étude était la recherche d'une formule, basée sur le poids corporel, l'apport de gaz frais/minute et le volume de la ventilation/minute, formule

qui permettrait le maintien en normocapnie de malades anesthésiés et ventilés artificiellement, en utilisant les circuits standards mais en excluant le filtre à chaux du circuit.

Une étude préalable a indiqué qu'un apport de 50 ml/kilo/minute en gaz frais, avec une ventilation/minute de 120 à 150 ml/kilo et une fréquence de 10 à 12/minute permettait de maintenir les patients en normocapnie; si l'on portait à 60 ml/kilo/minute l'apport en gaz frais avec une ventilation/minute de 120 ml/kilo et une fréquence de 10 à 12/minute, on obtenait une hypocapnie modérée. Dans un second temps la formule:

$$\text{« Apport de gaz frais/minute} = 50 \text{ ml/kilo} - \text{Ventilation/minute} = 120\text{--}150 \text{ ml/kilo} - \text{Fréquence} = 10\text{--}12/\text{minute} \text{ »}$$

a été utilisée chez 70 patients. Aucune sélection n'a été faite aux points de vue âge, sexe, présence d'obésité, classification ASA, position sur la table d'opération, type d'anesthésie et de circuit utilisé.

La PaCO_2 moyenne s'est située à 39 mm Hg (écart de 33 à 46 mm Hg).

La corrélation des PaCO_2 avec les différents facteurs mentionnés ci-haut a donné des moyennes de 38 à 41 mm Hg.

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