FRESH GAS REQUIREMENTS OF AN ENCLOSED AFFERENT RESERVOIR BREATHING SYSTEM DURING CONTROLLED VENTILATION IN CHILDREN

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SUMMARY
An enclosed afferent reservoir breathing system (EAR) designed by Ohmeda was evaluated during anaesthesia with controlled ventilation in 104 healthy children. Carbon dioxide production and arterial carbon dioxide tension were measured in 12 children in order to determine the proportion of fresh gas (Vf) involved in gas exchange. When the ratio of minute volume ventilation to fresh gas flow (Ve:Vf) exceeded 1.5, fractional utilization of fresh gas with the EAR was 0.92. This value and values of carbon dioxide production obtained from 43 children were used to derive a simple formula relating fresh gas flow requirements to body weight. The formula, Vf = 0.6 x weight⁰⁵, was assessed in 49 children weighing 10-70 kg. The mean end-tidal partial pressure of carbon dioxide in these patients was 4.5 kPa (range 3.8-5.2 kPa). We conclude that the EAR has an efficiency of 92% in the use of fresh gas during controlled ventilation in healthy children, provided the Ve:Vf ratio is greater than 1.5. Under these conditions, normocapnia to mild hypocapnia was produced accurately using the formula Vf = 0.6 x weight⁰⁵.

KEY WORDS
Anaesthesia, paediatric, equipment, breathing systems, EAR

In an earlier communication, we described a new version of the enclosed afferent reservoir breathing system (EAR) developed by Ohmeda, and its assessment during controlled ventilation in adults [1]. In the present study, the efficiency of the same system has been determined during controlled ventilation in children, and measurements of carbon dioxide production have been used to derive a simple formula for calculating fresh gas flow rates.

APPARATUS
The Ohmeda version of the EAR is shown in figure 1. Essentially, fresh gas flow enters a rising bellows enclosed in a transparent plastic container on the inspiratory limb of the system. The expiratory limb passes to a one-way expiratory valve at the base of the container. During spontaneous ventilation, the patient breathes from the enclosed bellows and inspiratory limb, but is prevented from breathing gas contained in the expiraory limb by closure of the one-way valve. On expiration, gas passes back into the inspiratory tube until the rising bellows is full, when the one-way valve opens, allowing gas to be vented from the system. The system thus functions as a Mapleson A with a distal expiratory valve [2].

Controlled ventilation may be instituted by means of a mechanical ventilator or a self-inflating bag. In both cases, the expiratory valve is closed tightly during lung inflation by pressure in the bellows container, opening only when the bellows refills at end-expiration. This is an important difference between the EAR and the standard Mapleson A, as the latter allows some fresh gas and deadspace gas to be vented during inflation via a partly opened expiratory valve [3].

For the paediatric study, two sizes of bellows were used. The smaller, having a capacity of 350 ml, was used for children aged up to 8 yr, while in older children we used the standard adult bellows with a capacity of 1500 ml. In addition, the standard 22-mm diameter elephant tubing of the adult system was replaced by 15-mm light plastic tubing.

SUBJECTS AND METHODS
The study was approved by the local Ethics Committee and informed consent obtained from the parents of all patients. One hundred and four paediatric patients aged 1-16 yr and ASA class I-II were studied during anaesthesia with controlled ventilation. Premedication for younger inpatients consisted of oral trimperazine 3 mg kg⁻¹, maximum 90 mg, 2 h before operation. Patients weighing more than 30 kg received diazepam 10 mg and droperidol 5 mg by mouth, 1 h before operation. Day-case patients received no premedication. In all patients, anaesthesia was induced with thiopentone 6-8 mg kg⁻¹ followed by atracurium 0.5 mg kg⁻¹ and fentanyl 1-2 μg kg⁻¹. The trachea was intubated with an uncuffed tracheal tube of appropriate size and sealed with a throat pack. Anaesthesia was main-
tained with approximately 66% nitrous oxide and 0.5–1% isoflurane in oxygen. Ventilation was controlled using an Ohmeda 7800 ventilator with the I:E ratio set at 1:2. A heated water mattress and a warm air blower were used to maintain rectal temperatures greater than 36.5 °C.

In the first part of the study, the fractional utilization of fresh gas was determined in 12 patients at various ratios of minute ventilation to fresh gas flow (VE:VF) [4]. This term refers to the proportion of fresh gas involved in gas exchange, and is derived as follows:

\[
F_{ACO_2} = \frac{V_{CO_2}}{V_A}
\]  

Equation (1) is a form of the familiar alveolar gas equation, which states that the fraction of alveolar carbon dioxide (FACO₂) is equal to carbon dioxide production (VCO₂) divided by the alveolar ventilation (VA). But in a semi-closed breathing system, the effective alveolar ventilation is that part of the fresh gas flow which takes part in gas exchange. Thus we can write;

\[
V_A = F_U \cdot V_F
\]

where F_U is the fractional utilization of fresh gas and V_F is the fresh gas flow. Substituting for V_A in equation (1) and rearranging we have:

\[
F_U = \frac{V_{CO_2}}{V_F \times F_{ACO_2}}
\]

Minute volume of ventilation (VE) was measured using the rotary transducer supplied with the Ohmeda 7800 ventilator and placed between the patient and the breathing system [1]. The accuracies of the flow transducer and the anaesthetic machine flowmeters were checked using a pneumotachograph and a dry gas meter, respectively. With the tidal volume maintained at 12 ml kg⁻¹ min⁻¹, VE was varied between 2.4 and 8 litre min⁻¹, and V_F was varied between 1.4 and 5.5 litre min⁻¹ to produce a range of VE:VF ratios between 0.6 and 2.9. After 20 min for stabilization, VCO₂ was calculated by multiplying V_F by the mixed effluent carbon dioxide concentration. The latter was measured over a period of 1 min using a mixing box and an infra-red carbon dioxide analyser (Datex Cardiocap II). Simultaneously, radial arterial blood was taken to determine carbon dioxide concentration. From these measurements, fractional utilization was calculated and plotted against VE:VF ratio. A curve was fitted to the data using a Compaq 286 computer and the Techni-Curve statistical package (Aston Scientific Ltd), and the mean value of fractional utilization was determined when the VE:VF ratio was greater than 1.5.

In the second part of the study, carbon dioxide output was determined, as above, in 43 patients in order to calculate the V_F required to maintain an alveolar (arterial) carbon dioxide concentration of 5.3 kPa (equation (3)). The values of V_F were plotted against body weight and a curve was fitted using the Techni-Curve statistical package. Subsequently, a simple formula was derived which gave a clinically acceptable fit to the data. The formula was assessed in 49 patients by measuring end-tidal carbon dioxide partial pressures after 20 min of controlled ventilation. Optimal utilization of fresh gas was ensured by maintaining a tidal volume of 12 ml kg⁻¹ min⁻¹ and selecting a VE which was more than 1.5 times V_F. Losses caused by sampling by the capnograph were compensated by adding 150 ml min⁻¹ to the calculated fresh gas flows.

Statistical differences were determined using Student’s t test and the null hypothesis was rejected at \( P < 0.05 \).

RESULTS

The results of the first part of the study are shown in
Figure 2. Fractional utilization ($F_U$) of fresh gas plotted against minute volume: fresh gas flow ratio ($V_E:VF$). Data from 12 healthy anaesthetized children during controlled ventilation.

Figure 3. Variation of carbon dioxide output with body weight in healthy anaesthetized children.

Figure 4. Fresh gas flow rates ($V_F$) for normocarbia in healthy anaesthetized children ventilated with the EAR. The broken curve was calculated from patient data, the solid curve was derived empirically.

Figure 5. Relationship between end-tidal carbon dioxide partial pressure ($P_{e\,CO_2}$) and body weight in 50 healthy children. Fresh gas flows were determined using the formula $0.6 \times \text{body weight}^{0.28}$ and measurements were made after 20 min of controlled ventilation with a $V_E:VF$ ratio greater than 1.5.

DISCUSSION

In general, the relationship between fractional utilization and the $V_E:VF$ ratio with the EAR in children was similar to that which we described previously in adults (fig. 2) [1]. However, the mean value of fractional utilization when $V_E:VF$ exceeded 1.5 was greater than that found in the earlier study (0.92 vs 0.73) ($P < 0.01$), indicating a reduction in clinical efficiency of about 20% in the adults. It may be important that some of the adults studied previously were ASA III, and most were elderly (mean age 69 yr), with the result that their mean arterial to end-tidal carbon dioxide partial pressure difference was 1.03 kPa. This is larger than that of normal healthy adults (0.7 kPa) [5] and much larger
than that of our paediatric patients (0.23 kPa). The fraction of unperfused alveoli corresponding to these differences may be calculated using the following modification of Bohr's equation [6]:

\[
\frac{V_d^{st}}{V_T} = \frac{P_{a\text{CO}_2} - P_{e\text{CO}_2}}{P_{a\text{CO}_2}} \quad (4)
\]

where \(V_d^{st}\) = alveolar deadspace; \(V_T\) = tidal volume; \(P_{a\text{CO}_2}\) = arterial carbon dioxide partial pressure; \(P_{e\text{CO}_2}\) = end-tidal carbon dioxide partial pressure.

Thus the mean arterial to end-tidal carbon dioxide partial pressure difference of our paediatric patients corresponds to an alveolar deadspace of 4\%, while that of the elderly patients corresponds to 19\%. The difference between these two figures represents an increase in deadspace ventilation of 15\% in the elderly, which is sufficient to account for most of the observed reduction in clinical efficiency of the EAR.

Maximum fractional utilization with the EAR was greater also than that obtained by Rose and Froese in healthy paediatric patients undergoing ventilation with a T-piece (0.92 vs 0.72) [7]. This is consistent with the work of Miller and Miller, who showed that the arterial carbon dioxide tensions of healthy patients were significantly smaller during ventilation with an EAR system compared with a T-piece (Bain system) under the same conditions of minute volume and fresh gas flow [8]. They suggested that the difference was caused by conservation of deadspace gas by the EAR, as occurs during spontaneous ventilation with the Magill system [2]. As mentioned earlier, this is possible only because the expiratory valve of the EAR is held tightly shut during lung inflation (fig. 1). A defective valve in the EAR system tested by Bruce and Soni [9] may have resulted in their finding somewhat smaller (although significant) differences in end-tidal carbon dioxide partial pressures between patients during ventilation of the lungs with the EAR and the Bain system [10].

A major difficulty in producing a simple formula for predicting the fresh gas requirements of semi-closed breathing systems in children is that carbon dioxide output is not related linearly to weight (fig. 3) [11, 12]. In using a square root function to derive a formula for the EAR, we were influenced by the work of Nightingale and Lambert, who showed that during controlled ventilation with a T-piece in children, normocapnia was maintained with a \(V_F = 0.8 \times \text{body weight}^{0.6}\) [13]. Comparison of this formula with that derived for the EAR, \(V_F = 0.6 \times \text{body weight}^{0.6}\), suggests that, during ventilation with the T-piece, children require about 33\% more fresh gas than those in whom the EAR is used.

It is interesting to note how the fresh gas flows obtained from these formulae relate to patients' normal minute and alveolar ventilations. From figure 6, it may be seen that the T-piece formula gives a value for \(V_F\) which is close to the minute ventilation of children predicted from the nomogram of Engström and Herzog [14]. Indeed, we have found it convenient to use this formula when setting up volume preset ventilators in the intensive care unit. The EAR formula, in contrast, gives a value of \(V_F\) which approximates closely to the predicted alveolar ventilation of children (fig. 6). These findings are consistent with the theory that the greater efficiency of the EAR compared with the T-piece is the result of conserving deadspace gas.

When interpreting the end-tidal carbon dioxide values in figure 5, it should be remembered that the mean arterial to end-tidal carbon dioxide partial pressure difference of patients in the first part of the study was 0.23 kPa. Thus normocapnia for healthy children (mean arterial carbon dioxide partial pressure 5.3 kPa, range 4.7-6.0 kPa [15]) corresponds to a mean end-tidal carbon dioxide partial pressure of about 5.1 kPa (range 4.5-5.8 kPa). The data in figure 5 indicate that the majority of children studied were normocapnic when \(V_F\) was calculated from the formula, although a significant minority (44\%) were mildly hypocapnic. End-tidal carbon dioxide partial pressure was predictable within a fairly narrow range.

The reason for the mild hypocapnia in some patients is apparent from figure 4. The empirical formula gave values of \(V_F\) which were usually somewhat greater than those calculated from patient data, although the fit of the curve was considered acceptable for clinical purposes. Slight overprovision of \(V_F\) may be an advantage by providing a margin of safety for those patients whose carbon dioxide production is at the upper end of the normal range. The mild hypocapnia which occurred in some of our patients would not be considered harmful, and may contribute to the anaesthetic state [16].

The reason for the predictability of end-tidal carbon dioxide partial pressure in our patients may be appreciated from figure 2 and equation (3) above. The stability of fractional utilization when \(V_F\) is expressed as above exceeded 1.5 implies that alveolar carbon dioxide partial pressure became mainly dependent upon \(V_F\), which was controlled accurately by the anaesthetic machine flowmeters. This method of utilizing greater...
than normal minute volumes of ventilation in combination with low fresh gas flows to maintain carbon dioxide homeostasis has been used previously with the T-piece systems [7, 17, 18], a circle system without an absorber [19] and a modified Magill system [20]. It has been termed "isocapnic ventilation" [20], but it may be more appropriate to use the term isocapnic hyperventilation.

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REFERENCES