EFFICIENCY OF AN ENCLOSED AFFERENT RESERVOIR BREATHING SYSTEM DURING CONTROLLED VENTILATION

P. M. DROPPERT, G. MEAKIN, P. C. W. BEATTY, A. J. MORTIMER AND T. E. J. HEALY

SUMMARY

We describe an enclosed afferent reservoir (EAR) breathing system developed by Ohmeda and designed to operate efficiently in spontaneous and controlled ventilation. The efficiency of the system was evaluated by calculating the fractional utilization of fresh gas in 10 ASA I–III patients during anaesthesia with controlled ventilation. Maximum efficiency occurred when the minute ventilation to fresh gas flow ratio was greater than 1.5. Under these conditions, fractional utilization was relatively constant with a value of 0.73 (95% confidence interval 0.69–0.78). The minimum fresh gas flow for use during controlled ventilation was determined in another eight ASA I–III patients when the minute volume to fresh gas ratio was greater than 1.5. In view of an increased arterial to end-tidal carbon dioxide partial pressure difference in patients in the first part of the study (1.03 kPa), normocapnia was defined as an end-tidal carbon dioxide partial pressure of 4.3 kPa. Normocapnia was achieved with a mean fresh gas flow of 66 ml kg\(^{-1}\) min\(^{-1}\), while 70 ml kg\(^{-1}\) min\(^{-1}\) produced mild hypocapnia.

KEY WORDS

Equipment: Breathing systems, EAR system.

In recent years, there has been great interest in the development of an “ideal” breathing system capable of being used efficiently during both spontaneous and controlled ventilation. One proposed system is the enclosed afferent reservoir system (EAR) [1–4]. This paper describes a new version of the EAR developed by Ohmeda and the clinical studies to determine its efficiency during controlled ventilation.

APPARATUS

The EAR (fig. 1) is essentially a modification of the Magill or Mapleson A system [5]. Fresh gas flow enters a rising bellows enclosed in a transparent plastic container on the inspiratory limb of the system. The expiratory limb passes back 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 expiratory limb by the closure of the one-way valve. On expiration, gas passes back into the inspiratory tube until the rising bellows is full, at which time the one-way valve opens, allowing gas to be vented from the system; thus the system functions as a Mapleson A with a distal expiratory valve.

Controlled ventilation may be effected by means of a mechanical ventilator or a self-inflating bag. In both instances 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 [6].

In the development of the present prototype, great care was taken to ensure correct functioning...
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Fig. 1. Diagram of the enclosed afferent reservoir breathing system.

of the expiratory valve. During bench tests, the operation of the valve was observed directly via the gas scavenging aperture (fig. 1). The opening pressure of the valve was set at 1.9 cm H₂O—greater than the pressure required to inflate the bellows. The valve was tested also before clinical use by occluding the patient Y-piece and allowing the bellows to fill with oxygen at a flow rate of 200 ml min⁻¹. The ability of the bellows to fill completely under these conditions and stay full even after the valve opens, indicates that the valve is operating correctly and that the breathing system is leak-free.

The ventilator used in the present study was the Ohmeda 7800. This is a volume-preset, time-cycled ventilator fitted with internal and external alarm sensors. The internal sensor consists of a pressure transducer while the external sensor, which is situated between the patient and the breathing system, comprises a rotary flow transducer.

SUBJECTS AND METHODS

The study was approved by the Ethics Committee of South Manchester Health Authority. We studied 18 patients (mean age 69 yr (range 56–85 yr), ASA class I–III) during anaesthesia with controlled ventilation. Anaesthesia was induced with propofol 1–2 mg kg⁻¹ followed by vecuronium 0.1 mg kg⁻¹ and fentanyl 1–2 μg kg⁻¹. The trachea was intubated with a cuffed tracheal tube and anaesthesia was maintained with 66% nitrous oxide and 1–2% isoflurane in oxygen. Ventilation was controlled by means of an Ohmeda 7800 ventilator with an I:E ratio of 1:2.

In the first part of the study, the fractional utilization of fresh gas was determined in 10 patients at various ratios of minute ventilation to fresh gas flow (\(\dot{V}_E: \dot{V}_F\)). The term fractional utilization denotes the proportion of fresh gas which takes part in gas exchange; it can be derived from the alveolar gas equation as follows:

\[
F_{A CO_2} = \frac{\dot{V}_{CO_2}}{\dot{V}_A}
\]

(1)

where \(F_{A CO_2}\) = fractional concentration of alveolar carbon dioxide; \(\dot{V}_{CO_2}\) = carbon dioxide production; \(\dot{V}_A\) = alveolar ventilation.

In a breathing system, \(\dot{V}_A\) is that fraction of the fresh gas flow which takes part in gas exchange. Thus:

\[
\dot{V}_A = FU \cdot \dot{V}_F
\]

(2)

where \(\dot{V}_F\) = fresh gas flow; \(FU\) = fractional utilization of fresh gas.

Substituting in (1) and rearranging we have:

\[
FU = \frac{\dot{V}_{CO_2}}{\dot{V}_F \times F_{A CO_2}}
\]

(3)

Initial settings of \(\dot{V}_E\) and \(\dot{V}_F\) were guided by
TABLE I. Minute volumes (VE) and fresh gas flow rates (VF) used in first part of study

<table>
<thead>
<tr>
<th>VE (ml kg⁻¹ min⁻¹)</th>
<th>VF (ml kg⁻¹ min⁻¹)</th>
<th>VE:VF</th>
</tr>
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<tbody>
<tr>
<td>100</td>
<td>40</td>
<td>2.5</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
<td>2.0</td>
</tr>
<tr>
<td>70</td>
<td>47</td>
<td>1.5</td>
</tr>
<tr>
<td>70</td>
<td>70</td>
<td>1.0</td>
</tr>
<tr>
<td>70</td>
<td>88</td>
<td>0.8</td>
</tr>
<tr>
<td>70</td>
<td>100</td>
<td>0.7</td>
</tr>
<tr>
<td>70</td>
<td>117</td>
<td>0.6</td>
</tr>
<tr>
<td>70</td>
<td>140</td>
<td>0.5</td>
</tr>
<tr>
<td>60</td>
<td>150</td>
<td>0.4</td>
</tr>
</tbody>
</table>

laboratory test results. Subsequently, the tidal volume was maintained at 12 ml kg⁻¹ and ventilatory frequency and VF were adjusted to produce VE:VF ratios of 0.4–2.5 (table I).

At least 20 min was allowed for equilibration at each fresh gas flow. The effluent gas volume and the mixed effluent carbon dioxide concentration were measured over a period of 2–5 min using a mixing box, dry gas meter and a mass spectrometer (Ohmeda MGM 6000). From these measurements, VCO₂ was calculated. Simultaneously, samples of radial arterial blood were taken for measurement of PaCO₂. Fu was plotted against VE:VF and a best fit curve with 95% confidence limits was generated using a Compaq 286 computer and the Techni-Curve statistical package (Aston Scientific Ltd). The confidence limits indicate the range within which we are 95% confident that the population curve lies [7].

In the second part of the study, the minimum fresh gas flow required to ensure normocapnia during controlled ventilation was determined in eight patients. In order to optimize utilization of fresh gas, VE:VF was maintained greater than 1.5. Tidal volume was set at 12 ml min⁻¹. Fresh gas flow was reduced progressively from 100 to 20 ml kg⁻¹ min⁻¹, and end-tidal partial pressure of carbon dioxide (PE'CO₂) was measured using the mass spectrometer after an equilibration period of 20 min at each new flow rate. PE'CO₂ was plotted against VF and a best fit curve with 95% confidence limits was derived using the Techni-Curve regression analysis program.

RESULTS

The mean weight of patients in the first part of the study was 68 kg and their mean carbon dioxide output was 167.5 ml min⁻¹. The mean difference in arterial to end-tidal partial pressures of carbon dioxide (PaCO₂ – PE'CO₂) in these patients was 1.03 kPa.

From figure 2 it may be seen that fractional utilization of fresh gas increased until VE:VF reached 1.5. The mean value of 14 measurements performed when VE:VF exceeded 1.5 was 0.73 (95% confidence interval 0.69–0.78).

Fig. 2. Fractional utilization of fresh gas plotted against minute volume: fresh gas flow ratio. Data from 10 anaesthetized ASA I–III patients during controlled ventilation. Broken lines represent 95% confidence limits as calculated by the Techni-Curve statistics program.
In the second part of the study, $P_{E'}CO_2$ was related inversely to $\dot{V}F$ (fig. 3); a mean fresh gas flow of 66 ml kg$^{-1}$ min$^{-1}$ resulted in $P_{E'}CO_2$ 4.3 kPa, which should correspond to normocapnia in this group of patients. A fresh gas flow rate of 70 ml kg$^{-1}$ min$^{-1}$ produced mild hypocapnia.

**DISCUSSION**

Fractional utilization of fresh gas defines the efficiency of a semi-closed breathing system in terms of the proportion of fresh gas which takes part in gas exchange. Arterial carbon dioxide measurements are necessary for its measurement, as these approximate closely to the mean concentration of carbon dioxide in perfused alveoli [8]. Although the term "fractional utilization" is attributed to Conway [9], the concept was used earlier by Snowdon and colleagues [10] to describe the efficiency of two circle systems without an absorber during controlled ventilation. As a measure of efficiency, it has the advantage over end-tidal or arterial measurements of carbon dioxide in that it is independent of carbon dioxide production. It should, therefore, provide a useful basis for comparing the efficiency of different types of semi-closed breathing systems.

Because fractional utilization depends on the gas exchange properties of the lungs, it is reasonable to ask if the inclusion of some ASA III patients in the present study may have affected our results. $(P_{a}CO_2 - P_{E'}CO_2)$ in patients in the first part of the study, 1.03 kPa, is slightly greater than that reported previously in healthy anaesthetized adults (0.7 kPa) [8]. The fraction of unperfused alveoli corresponding to these differences may be calculated using the following formula [11]:

$$\frac{(P_{a}CO_2 - P_{E'}CO_2)}{P_{a}CO_2}$$

(4)

From the above, $(P_{a}CO_2 - P_{E'}CO_2)$ in our patients corresponds to an alveolar deadspace of 19%, while that of healthy patients corresponds to 13%. These values suggest that the increased $(P_{a}CO_2 - P_{E'}CO_2)$ in our patients should not have reduced the efficiency of the breathing system by more than 6%.

Our finding that the maximum utilization of fresh gas with the EAR during controlled ventilation was 70–80% may be surprising in view of the claim by Miller and Miller that it should be easy to achieve 100% utilization of fresh gas with this type of system [4]. However, these authors seem to have assumed that the same efficient shunting of gas fractions found during spontaneous ventilation in Mapleson A type systems occurs in the EAR during controlled ventilation. In view of the greater minute volumes and ventilatory flow rates used during controlled
ventilation, this seems unlikely. If arterial carbon dioxide data from their studies of the EAR are used to calculate mean fractional utilization, assuming that the mean carbon dioxide output of their patients was the same as ours (15% less than basal [11]), values in the range 0.70–0.75 are obtained at $V_e:V_F$ ratios greater than 1.6. These values are similar to the mean value of 0.73 obtained in the present study.

The fractional utilization curve shown in figure 2 is similar to that obtained by Rose and Froese using a Bain system [12], and that obtained by Snowdon and colleagues using one of two circle systems without an absorber with a tidal volume of 750 ml [10]. This suggests that, although there are well-documented advantages of the EAR during spontaneous ventilation [13, 14], there may be little difference in clinical efficiency between the above systems during controlled ventilation. This agrees with the work of Criswell and colleagues, who found only a small difference in $P_{E \text{CO}_2}$ values in patients during ventilation with an EAR system and the Bain (0.35 kPa), and concluded that they were of similar clinical efficiency [15].

When interpreting the data from figure 3, it is important to note that these are end-tidal measurements of carbon dioxide. In the first part of this study, mean $P_{a \text{CO}_2}$ differed from the $P_{E \text{CO}_2}$ by 1 kPa, so that normocapnia (mean $P_{a \text{CO}_2}$ 5.3 kPa) corresponded to a mean $P_{E \text{CO}_2}$ of 4.3 kPa. From figure 3, the mean $V_F$ required to maintain this value of $P_{E \text{CO}_2}$ was 66 ml kg⁻¹ min⁻¹, while a $V_F$ of 70 ml kg⁻¹ min⁻¹ produced mild hypocapnia. Allowing for differences in methodology, these results are in agreement with those of Keeri-Szanto [1], Miller and Miller [4] and Chriswell and colleagues [15], but not with those of Bruce and Soni [16] whose prototype EAR required a mean $V_F$ of 100 ml kg⁻¹ min⁻¹ to maintain a mean $P_{E \text{CO}_2}$ of 5.0 kPa. The latter suggest that the inefficiency of their system was caused by the expiratory valve opening prematurely, allowing fresh gas to displace deadspace gas stored in the inspiratory tube.

In summary, an EAR breathing system has been described which is designed for use during spontaneous and controlled ventilation. During controlled ventilation the system had a maximum efficiency in the use of fresh gas of 70–80%, which is similar to that obtained with a Bain system and some circle systems without an absorber. In practice, provided $V_e:V_F$ is greater than 1.5, a fresh gas flow of 70 ml kg⁻¹ min⁻¹ should be sufficient to maintain mild hypocapnia in adults.

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**REFERENCES**


