ENCLOSED AFFERENT RESERVOIR BREATHING SYSTEMS
Description and Clinical Evaluation

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An afferent reservoir system can be defined as one which has a reservoir bag or reservoir facility on the inspiratory supply tube or afferent tube between the fresh gas supply and the patient. Examples of simple afferent reservoir systems are Mapleson A type systems: namely, Magill, Lack and Preferential Flow (PF) systems. Their unique advantage of efficiency in the use of fresh gas applies only to spontaneous ventilation. Conversely, efferent reservoir systems have reservoir capacity on the expiratory limb. These include all the "T systems", for example, Mapleson D to F. Their advantage of efficiency in the use of fresh gas only applies to controlled ventilation.

In order to secure the advantages of both the afferent and efferent reservoir systems, many combination systems are being introduced [1-7]. The advantages of the combination systems are now obtained with a single system, namely the enclosed afferent reservoir (EAR) system.

One of the main features of an ideal breathing system should inevitably be one which selectively eliminates alveolar gas in both spontaneous and controlled ventilation. Previously, the only system for which such a claim could be made was the "Circle H" system investigated by Eger and Ethans [8]. Unfortunately, the commercially available Circle H arrangement suffers from a number of serious disadvantages which Eger himself has pointed out: (1) it is somewhat bulky and slightly heavier than the simple Y-piece; (2) The valves are more difficult to see than dome valves; (3) The valves may "stick" on first use after a period of non-use. Opening these valves at this time may require considerable pressure; (4) Resistance to flow may be slightly greater than the resistance in dome valves; (5) Flushing with oxygen does not clear the inspiratory limb since inflow gases flow backwards.

Eger also claimed that, for Circle B, D and G arrangements, the same selective shunting out of alveolar gas could take place if the overflow valve was replaced with a Steen valve which closes with rapid increases in system pressure.

The newly introduced EAR systems, of which two types are described in this paper, also appear to have the property of selective alveolar gas elimination. These may be described as the "Enclosed Mapleson A" (EMA) and the "Enclosed Preferential Flow" (EPF) systems. The conventional Mapleson A system and its modifications have been shown to require a minimum

SUMMARY

A new group of breathing systems, namely the Enclosed Afferent Reservoir (EAR) systems, is described. They allow for the selective elimination of alveolar gas in association with both spontaneous and controlled ventilation. A comparison with the Bain system in controlled ventilation demonstrates greater efficiency in eliminating carbon dioxide. A fresh gas flow ($\bar{V}_f$) of 70 ml kg$^{-1}$ min$^{-1}$ using an EAR system gave mild hypocarbia which equated to a $\bar{V}_f$ of 100 ml kg$^{-1}$ min$^{-1}$ using the Bain system. Smaller minute volumes of ventilation are required for optimal performance than with the Bain system. The minimum recommended minute volume of ventilation ($V_t$) should equal $\bar{V}_f$ plus anatomical deadspace ventilation ($\dot{V}_{dead}$). The pattern of ventilation appears to have little influence upon the efficiency of carbon dioxide elimination when using an EAR system, whereas the Bain system does appear to be affected.
fresh gas flow almost equal to the alveolar minute volume of ventilation during spontaneous ventilation [9-13]. During controlled ventilation the flow dynamics change completely as gas is eliminated from the system during the inspiratory phase instead of during the expiratory phase as in spontaneous ventilation. The EAR systems differ from Mapleson A type systems in that the expiratory valve is enclosed by connecting the exhaust outlet to a bottle which also encloses the afferent reservoir bag. The result is that pressurizing the bottle during the inspiratory phase of controlled ventilation squeezes gas from the afferent reservoir bag into the lungs and at the same time holds the expiratory valve closed so that expired gas is eliminated through the valve only during the expiratory phase. The same efficient shunting of gas fractions found during spontaneous breathing in Mapleson A type systems should, theoretically, now occur during controlled ventilation as well. Selective elimination of alveolar gas should, therefore, occur regardless of the mode of ventilation. This being the case, the EAR systems should be more efficient during controlled ventilation than the Bain system, since efferent reservoir systems cannot selectively eliminate alveolar gas [14]. Furthermore, the ability to maintain $P_{CO_2}$ by adjusting fresh gas flow should be improved and it should be possible to maintain $P_{CO_2}$ stable over a larger range of minute volumes. This may have clinical significance in those situations in which the large minute volumes of ventilation required for normocapnia in the Bain system may have an adverse effect on the cardiovascular system.

This investigation compared the EAR systems (namely the EMA and EPF) with the Bain system during controlled ventilation. The effect of different minute volumes of ventilation upon $P_{a_{CO_2}}$ using the EPF and the Bain system was also studied. Finally, a comparison of the EMA and EPF systems was made.

Another investigation which evaluated minimum fresh gas flow requirements for spontaneous ventilation using a lung model has shown that the flow requirements of an EMA and an EPF system are similar to the Magill and PF Systems [15].

**DESCRIPTION OF APPARATUS**

*The “enclosed Mapleson A system”*

The system consists of a Mapleson A system enclosed within a non-distensible structure (fig. 1, upper diagram). The non-distensible structure may be considered in two parts. The first may consist of a bottle which encloses the reservoir bag A and the second a co-axially or parallel arranged tube which incorporates a one-way valve. A more practical arrangement (fig. 1, lower diagram) simply extends the expiratory tube to site the one-way expiratory valve in the bottle so that gas is vented into the latter. Other ports opening into the bottle include a means for positive pressure ventilation and a variable orifice.

In operation during spontaneous ventilation, gas is vented from the system in a manner which is identical to the conventional Mapleson A system. In this mode of ventilation the variable orifice would be wide open. In controlled ventilation the variable orifice is partially closed to allow for a controlled leak from the bottle, while the reservoir bag B is squeezed intermittently. The movement of the various gas fractions during IPPV is no different from that during spontaneous ventilation. This is because the expiratory valve is held closed during the inspiratory phase by the inflating pressure within the bottle. This contrasts with the conventional Mapleson A system during IPPV when gas is vented through the valve during the inspiratory phase.
The enclosed "Preferential Flow System"

The EPF system may be considered in two parts: the fresh gas section and the exhaust gas section.

Fresh gas section. This section (fig. 2, upper diagram) consists of an arrangement similar to the Mapleson A system, except that the expiratory valve is replaced by a preferential flow T-piece which has a functional objective similar to that of the Heidbrink valve [3, 13].

Exhaust gas section. This consists of a means by which the above section may be enclosed, as it were, "in a box" (fig. 2, lower diagram). This takes the form of a non-distensible corrugated tube co-axially arranged and a bottle enclosing the reservoir bag A as described above for the enclosed Mapleson A system.

In operation the only adjustment required is that of the variable orifice. This is opened maximally during spontaneous ventilation and partially closed during manual controlled ventilation. It is shut completely for mechanical controlled ventilation, when the ventilator is plugged into the bottle via the tube connecting the reservoir bag B. Excess gas is then disposed of through the ventilator spill valve.

The Variable Orifice (fig. 3)

This has been designed so as to have a sliding action, as opposed to the conventional screw mechanism of adjustment. This allows for quicker adjustment. The gradual taper on the plunger results in a gradual variation in the annular cross-sectional area of the orifice for a relatively large vertical movement of the head of the plunger. The position of the latter gives a clearly visible indication of orifice patency.

PATIENTS, MATERIALS AND METHODS

Permission for the study was obtained from the Ethical Advisory Committee. Consent was obtained from the patients for radial artery cannulation.

Patients selected were non-smokers, free of obvious pulmonary or cardiovascular disease and were classified as ASA grading I or II.

All patients not premedicated with an opioid were given one during the surgical procedure. Where indicated, a benzodiazepine was prescribed the night before surgery.

Evaluation of the systems during controlled ventilation was conducted on 27 patients. Most of the surgery was abdominal for an initial evaluation of 12 patients with several patients in the Trendelenberg position. For the study in the next 15 patients, using different tidal volumes, the need for very stable anaesthetic conditions was deemed necessary and surgery was restricted to orthopaedic and gynaecological procedures which combined general anaesthesia with an appropriate regional technique—such as brachial plexus block or caudal extradural block.

Anaesthesia was induced with a "sleep" dose of...
thiopentone and intubation of the trachea was facilitated by topical anaesthesia, and the administration of an appropriate dose of alcuronium or suxamethonium.

A volume-preset ventilator with a bellows in the bottle arrangement was used. This comprised a constant flow generator (Bird Mark II) coupled to a Ventviva bellows in a bottle with an inspiratory time set for 1 s. The tidal volumes used were 10 ml kg⁻¹ at a rate of 13 b.p.m. for the study on 12 patients using the three different systems: Bain, EMA and EPF. The I:E ratio was, therefore, approximately 1:3.5–1:4. The order in which the systems were used was randomized. For the next 15 patients the ventilatory rate was 13 b.p.m. and the tidal volumes used were 10 ml kg⁻¹ followed by 7 ml kg⁻¹ on each of the EPF and Bain systems. A calibrated Wright spirometer was used to measure expired tidal volumes. The systems were used in alternating order. Patients were kept adequately anaesthetized with nitrous oxide and halothane in oxygen. Appropriate doses of an opioid, and of alcuronium, were given as required.

A period of at least 30 min was allowed for stabilization before arterial samples were taken. Throughout the entire experiment a \( \dot{V}_F \) of 70 ml kg⁻¹ min⁻¹ was used. A period of 20 min was allowed for stabilization after each adjustment had been made. All arterial blood samples were sent immediately to the laboratory once collected. Capnography was used in all patients to prevent undue increases in expired carbon dioxide during the lower minute volumes of ventilation.

An independent evaluation of the EPF and Bain systems was conducted in a different hospital on 17 patients. The design of the study and the methods were in all respects the same as for the investigation on the 27 patients except for the following differences. Ventilation was set on a Bird Mark 8 pressure-cycled ventilator with an anaesthetic circuit–ventilator volume of 2.5 litre [16], and a frequency of 10–12 b.p.m., with a tidal volume of 12–15 ml kg⁻¹. The duration of the inspiratory phase varied between 1.5 and 2 s. The inspiratory flow pattern to be expected when using a pressure generator such as the Bird Mark 8 was an exponentially decreasing inspiratory flow rate and resulted in an approximate I:E ratio of 1:2. Each circuit was studied as before with \( \dot{V}_F = 70 \text{ ml kg}^{-1} \text{ min}^{-1} \). However, in 7 of the 17 patients time permitted further comparison using \( \dot{V}_F = 100 \text{ ml kg}^{-1} \text{ min}^{-1} \).

### RESULTS

Blood-gas analyses of \( P_{\text{aCO}_2} \) on 27 patients comparing the EPF with the Bain system using \( \dot{V}_F \) of 70 ml kg⁻¹ min⁻¹ and \( \dot{V}_F \) of 130 ml kg⁻¹ min⁻¹ gave values (means and standard deviations) (SD) of \( P_{\text{aCO}_2} \) of 4.77 ± 0.40 and 5.06 ± 0.37 kPa, respectively (\( P < 0.001 \)). Student’s paired \( t \) test.

A similar study by a different investigator was obtained on 17 subjects using the EPF and Bain systems and gave mean values for \( P_{\text{aCO}_2} \) of 4.54 ± 0.54 and 5.14 ± 0.49 kPa, respectively. Using the same statistical analysis a significant difference between \( P_{\text{aCO}_2} \) was again obtained (\( P < 0.001 \)). Seven of the 17 patients were also studied using a fresh gas flow \( \dot{V}_F \) of 100 ml kg⁻¹ min⁻¹. The mean \( P_{\text{aCO}_2} \) values were 4.00 ± 0.52 and 4.58 ± 0.60 kPa. The difference between the EPF and Bain systems was significant (\( P < 0.005 \)).

In 12 of the 27 patients the EPF system was also compared with the EMA system and, as expected, no difference was found between the values of \( P_{\text{aCO}_2} \) measured using these two similar systems (means and SD of \( P_{\text{aCO}_2} \) were 4.84 ± 0.41 and 4.88 ± 0.45 kPa, respectively).

On the remaining 15 patients, a comparison of the effects of using \( \dot{V}_F \) of 130 ml kg⁻¹ min⁻¹ on \( P_{\text{aCO}_2} \) using the EPF and Bain systems gave \( P_{\text{aCO}_2} \) values of 4.71 ± 0.40 and 4.95 ± 0.40 kPa for EPF and 5.01 ± 0.34 and 5.40 ± 0.44 kPa for the Bain system. The mean increases in \( P_{\text{aCO}_2} \) resulting from the reduction in minute volumes were 0.24 and 0.39 kPa for the EPF and Bain system, respectively. From analysis of covariance it was found that this increase of \( P_{\text{aCO}_2} \) caused by the decrease in minute ventilation, was significantly less when using the EPF system (\( P < 0.05 \)).

### DISCUSSION

This study shows that the EPF and EMA are more efficient than the Bain system during controlled ventilation. This is ascribed to the means by which gas fractions are shunted so as to eliminate alveolar gas selectively. In addition, this view could be supported by the finding that smaller minute volumes of ventilation had less effect upon carbon dioxide elimination in the EPF than the Bain system.

It has been stated correctly by Conway [14] that selective elimination of alveolar gas does not take place with the Mapleson D system. The equation applicable to the Mapleson A system (only under
the circumstances where \( \dot{V}_E \) is equal to or less than the alveolar ventilation during spontaneous ventilation)

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F_{\text{aCO}_2} = \frac{\dot{V}_{\text{CO}_2}}{\dot{V}_F}
\]

does not therefore hold for the Mapleson D arrangement. It should be noted, however, that in spontaneous ventilation with a Mapleson A system the \( \dot{V}_E \) is too low if it is less than the alveolar ventilation.

Results obtained in this study would support the view that the selective elimination of alveolar gas occurs in controlled ventilation when using the EAR systems. The above equation can only be applied to breathing systems if certain conditions of minute volume of ventilation are fulfilled. The elimination of carbon dioxide in a system only becomes independent of ventilation when all of the fresh gas entering the system enters the alveolar space. This is the ventilation at which 100% utilization of the fresh gas takes place, which is likely to occur only in a system in which alveolar gas is selectively vented. With the Bain system this is unattainable in practice, as considerable gas mixing occurs within the system [17]. Rose and Froese [18] have shown that in clinical practice only 70-75% of the fresh gas enters the alveolar space using the Bain system. It was Conway [14] who correctly suggested that only infinite minute volumes of ventilation would achieve 100% utilization of fresh gas in the Bain system. In a perfectly functioning EAR system, however, these conditions would be fulfilled when the inspired minute volume (\( \dot{V}_I \)) = \( \dot{V}_E + \dot{V}_{\text{anaT}} \). In practice \( \dot{V}_E \) was measured, and the small difference between \( \dot{V}_E \) and \( \dot{V}_I \) was ignored.

The EPF is not a perfectly functioning EAR system as it relies on mechanisms other than a valve to shunt gas in the appropriate direction. Nevertheless, the results do bear witness to improved economy during controlled ventilation when compared with the Bain system. For the EMA to be a perfectly functioning EAR system the valve needs to remain closed until the afferent reservoir bag is fully distended. If this were the case one would expect greater efficiency in utilization of fresh gas than with the EPF. This was not noticed. This could mean that either the EPF functions very efficiently or the EMA valve is not operating as it should. The fact that the \( P_{\text{aCO}_2} \) increased by 0.24 kPa when the expired minute volume (\( \dot{V}_E \)) was decreased from 130 ml kg\(^{-1}\) to 90 ml kg\(^{-1}\) min\(^{-1}\) is accounted for by the fact that, for some patients, 90 ml kg\(^{-1}\) min\(^{-1}\) was probably less than the minimum \( \dot{V}_E \) recommended, which is \( \dot{V}_E + \dot{V}_{\text{anaT}} \).

If the ratio \( \dot{V}_b/\dot{V}_t \) is 0.3, then \( \dot{V}_E = 100 \text{ ml kg}^{-1} \text{ min}^{-1}\) when \( \dot{V}_E = 70 \text{ ml kg}^{-1} \text{ min}^{-1}\). Therefore, 100% utilization of fresh gas is probably only possible when \( \dot{V}_E \) is greater than 100 ml kg\(^{-1}\) min\(^{-1}\). In addition, since the EPF is not a perfectly functioning EAR system it may require—for optimal performance—a \( \dot{V}_E \) greater than \( \dot{V}_E + \dot{V}_{\text{anaT}} \).

As the ceiling of efficiency is reached in the usual clinical range of minute ventilation in the EAR systems the regulation of \( P_{\text{aCO}_2} \) by adjusting the fresh gas supply rate should, in theory, be more precise than that observed using the Bain system. This does appear to be the case in practice, as indicated by the significantly greater increase in \( P_{\text{aCO}_2} \) in the Bain than the EPF system when using a lower \( \dot{V}_E \) for ventilation.

The independent evaluation comparing the EPF and Bain systems showed a more marked difference in \( P_{\text{aCO}_2} \). This may be accounted for by the fact that the pattern of ventilation using a Bird Mark 8 ventilator does not favour the Bain system, tending to prolong the inspiratory phase and, consequently, shorten the total expiratory time. The total expiratory time includes the phase which Stenquist and Sonander [19] refer to as the time fraction for active expiration (\( F_{\text{Et}} \)) (although it is passive) and the pause phase. It is the pause phase which is shortened, since a change in the pattern of ventilation cannot usually alter the passive \( F_{\text{Et}} \) component of expiration. The pattern of ventilation with the Bain system appears to play a significant role in determining the degree of mixing of fresh gas with expired gas. This is consistent with what Stenquist and Sonander [19] have shown using a lung model—that the larger the time fraction for active expiration (\( F_{\text{Et}} \)), the greater the degree of rebreathing for a given \( \dot{V}_E/\dot{V}_I \) value. Consequently, for a given rate of ventilation, the shorter the inspiratory phase, the longer the post-expiratory pause phase becomes, assuming that \( F_{\text{Et}} \), which is passive, remains constant. A proportionately smaller ratio \( F_{\text{Et}}/\text{total expiratory time} \) is obtained and the efficiency of the Bain system is greater. The time-cycled constant-flow generator combined with a bellows in a bottle arrangement achieved a pattern of ventilation with an I:E ratio of about 1:3.5. This would allow for a longer pause phase than the study using a Bird Mark 8 with an I:E ratio of 1:2.
It seems likely, therefore, that, in a system where alveolar gas is selectively eliminated, it is easy to achieve 100% utilization of fresh gas using minute volumes in the clinical range. In addition, the efficiency is not dependent upon the pattern of ventilation. However, the pattern of ventilation does appear to influence the efficiency of T-systems [19,20].

Additional evidence supporting this claim for the EAR systems is illustrated in figure 4. A comparison of the inspiratory carbon dioxide pattern obtained from sampling in the tracheal tube during IPPV in a typical patient, using the two systems, is shown. The square-wave pattern can be seen using the EPF system, indicating the better fresh gas utilization and separation of gas fractions. In contrast to this is an inspiratory hump of increased carbon dioxide tension, indicating the reinhalation of a mixture of alveolar gas with fresh gas when using the Bain system (fig. 4). Notice also that, when the tidal volume is increased from 800 ml to 1000 ml using the EPF, the inspiratory carbon dioxide value increases, but the record still stays flat and the square-wave pattern is retained. This would be consistent with the theory that simple addition of deadspace ventilation equal to the increase in minute volume of ventilation is what is occurring when $V_E > V_f + V_{B\text{am}}$. Nevertheless, although the circumstantial evidence supporting this is strong, an experiment using a lung model would be necessary to prove this.

For spontaneous ventilation the EAR systems are not expected to perform in a manner significantly different from their simple afferent reservoir counterparts—Magill, Lack and PFS. This has been confirmed experimentally using a lung model [15].

An additional advantage discovered, as it were, by accident includes the possibility of built-in scavenging when the system is used for spontaneous ventilation. Suction may be applied directly to the expiratory port of the variable orifice with the reservoir bag B detached from the length of corrugated hosing. A continual flow of gas through the latter toward the suction tube provides for effective scavenging of the expired gases which are deposited into the bottle which behaves as a large reservoir. This is useful when no permanent scavenging system is available on the Boyle’s machine.

Possible disadvantages include (as with the circle system) the inaccessible valve of the EMA system. It is for this reason that the EPF system is also presented here, since it is valveless. Both systems should, theoretically, produce even lower values of $P_{aCO_2}$ if they functioned perfectly. Valve function needs to be guaranteed and this is even more important if the suggested means of scavenging is to be utilized. It may be argued, however, that any slight negative pressure created by the scavenging suction, would be transmitted to both afferent and efferent limbs of the system and should, therefore, have no influence on the flow dynamics of the system.

Another possible disadvantage of such a system
is that it could be considered bulky. However, if one realizes that the afferent reservoir bag-in-the-bottle arrangement takes the place of the ventilator bag, or bag-in-the-bottle, then the system is no more bulky than a combination A-D system.

In conclusion, a new group of breathing systems has been introduced, called the enclosed afferent reservoir systems. They are breathing systems in which the selective elimination of alveolar gas possibly takes place in association with both spontaneous and controlled ventilation. This results in a better control over $P_{aCO_2}$ and a greater efficiency in the use of fresh gas. Furthermore, the pattern of ventilation when using EAR systems appears to have little or no influence upon the efficiency of carbon dioxide elimination. The Bain system, however, does appear to be influenced by the ventilatory pattern. Accidental errors, which can occur when using combination breathing systems as a result of inappropriate use of Mapleson A or D mode, are obviated.

One small, but not insignificant benefit is the possibility for built-in scavenging to which the design lends itself. In addition, any unmodified ventilator with a power source other than the anaesthetic gases can be used with the system without any need for a bellows or bag-in-the-bottle arrangement, or a ventilator deadspace tube.

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