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1. Concentrator oxygen and low-flow anaesthesia

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Concentrator oxygen is contaminated with argon, because the pores of the molecular sieve exclude both argon and oxygen, and the atmospheric argon fraction is 0.94%. When oxygen is concentrated from air, argon is concentrated also and appears as 5% of the product gas. When concentrator oxygen is used in low-flow anaesthesia, argon will accumulate. Argon is inert [1], but it dilutes oxygen and anaesthetic gas in the breathing system. Three approaches have examined the extent of argon accumulation, when concentrator oxygen is the main component of fresh gas.

Theoretical

Simulations predict the rate of argon accumulation under varying conditions of fresh gas flow and oxygen consumption. Using standard assumptions [2], an equation for the rate of argon accumulation can be derived, eqn 1.

$$\frac{dF_{sys}}{dt} = \frac{\dot{V}_{FGF} \times F_{fg}}{V} - \frac{F_{sys} \times (\dot{V}_{FGF} - \dot{V}O_2)}{V}$$

where:

F_{sys} is the argon fraction in the breathing system
F_{fg} is the argon fraction in the fresh gas
V is the system gas volume
$\dot{V}_{FGF}$ is the fresh gas flow rate
$\dot{V}O_2$ is the rate of oxygen consumption

If the breathing system is closed, argon will accumulate inexorably. With concentrator oxygen as the sole fresh gas, a system volume of 8000 mL, and an oxygen consuption of 250 mL min^{-1}, the rise of argon fraction is about 0.16% min^{-1}. When the fresh gas flow rate is twice the oxygen consumption, a steady state will be reached in which the argon fraction in the system is double that in the fresh gas. Some predictions are shown in Fig. 1.

Laboratory experiments

These predictions were confirmed using argon 9.5%, in oxygen, as the fresh gas supply to a circle system with a conscious subject attached by a mouthpiece. Fresh gas flows ranging from 310–2000 mL min^{-1} were used [3]. Even in the closed system, and using a gas source with almost twice the argon content of concentrator oxygen, it was over an hour before the oxygen concentration fell below 50%.

Clinical studies

Five patients have been anaesthetized with low flows of halothane in concentrator oxygen. After a period at high flows, the fresh gas flow was reduced to 500 mL min^{-1}, about twice the likely oxygen consumption of the anaesthetized patient. In the following 45 min the oxygen concentration in vented gas fell by about 5%; this fall is consistent with a doubling of the argon fraction in the system [3].

Conclusions

(i) In the closed circle system, argon will accumulate inexorably, but at a rate that is unlikely to double the initial concentration in less than half an hour.

(ii) If low flows are used, argon concentration in the breathing system should not exceed twice the concentration in the fresh gas supply if the fresh gas flow is twice the total gas consumption.

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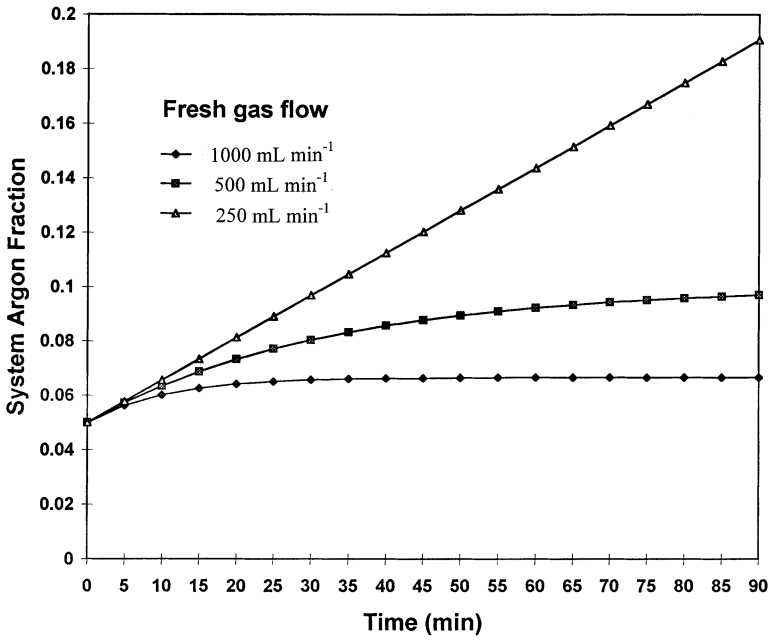

Fig. 1 (abstract 1). Predicted argon fraction in the breathing system at a range of fresh gas flows, assuming that the circle system and lungs have a total volume of 8000 mL, the argon fraction of fresh gas is 0.05 and the oxygen consumption 250 mL min^{-1}. When fresh gas flow is 250 mL min^{-1}, the breathing system is closed and argon accumulation is linear; at a higher fresh gas flow the argon fraction approaches a plateau.

2 Holmes C McK, Spears GFS. Very-nearly-closed-circuit anaesthesia – a computer analysis. *Anaesthesia* 1977; **32**: 846–857.

3 Parker CJR, Snowdon SL. Predicted and measured oxygen concentrations in the circle system using low fresh gas flows with oxygen supplied by an oxygen concentrator. *Br J Anaesth* 1988; **61**: 397–402.

2. Cost effectiveness of semi-closed and circle systems

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With increasing awareness of the high costs and pollution effects of inhalation anaesthetic gases, recycling has with the advent of reliable monitors become attractive. Reducing fresh gas glows (FGF) from 7–8 litres L min^{-1} to less than half this flow would effect considerable savings. Cotter *et al*. observed that an average FGF of 2.8 L min^{-1} was used by anaesthetists in a representative British hospital [1]. However, the assumption that recycling is the *only* effective low-flow technique needs to be re-examined. With the introduction of significantly more efficient multi-purpose semi-closed systems such as the Humphrey ADE system [2], a similar reduction in FGF down to an average of 3–4 litre min^{-1} can be achieved without recycling. This technique is simpler, and avoids the increased complexity and potential hazards when using carbon dioxide adsorption.

While many factors are involved in an analysis of the cost-effectiveness of these alternative techniques, three factors reduce the cost-effectiveness of re-cycling. First, a popular misconception is that savings achieved by recycling are directly proportional to the reduction in FGF. However, prior to achieving an equilibrium in body tissues, it is necessary to use a *higher* vaporizer setting when using a circle system compared with a semi-closed system in order to maintain similar inspired vapour tensions, the latter always being diluted by recycled gas. As actual vapour usage is not significantly reduced in this uptake phase when compared with efficient semi-closed systems, lowering the

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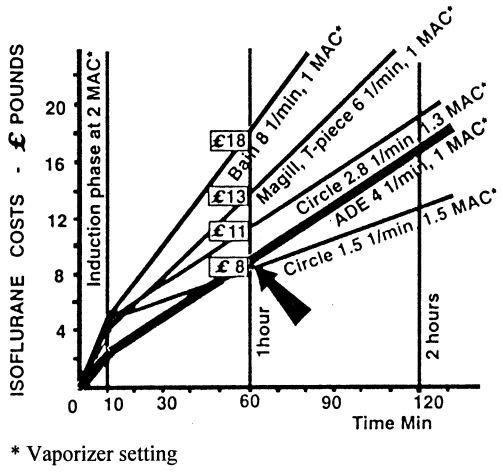

Fig. 2 (abstract 2) Cost of anaesthesia semi-closed and circle systems.

FGF does not proportionately lower costs especially as the vapour itself is significantly more expensive than the gas saved. The second disadvantage of recycling is that the inspired gas composition is not known. For safe use at low FGFs, monitors are mandatory. However, the latter are expensive and require regular servicing. In contrast, the inspired gas composition with semi-closed systems can generally be assumed to be that as set by the anaesthetist, making monitors optional (though nevertheless useful). Finally, during the induction phase when high vaporizer settings are used, low FGFs into a circle system are abandoned in favour of high flows to speed up induction, Cotter reporting an average FGF of 7 L min^{-1} [1]. However, even at these high FGFs the circle system is significantly less efficient than any semiclosed system, again because some recycled gases are always present and cause dilution of fresh gas [3]. Considering these factors, the varying efficiency of different breathing systems is summarized in Fig. 1, in which the running costs of isoflurane are compared at *average* FGFs required for each system and with vaporizer settings calculated to give an inspired gas concentration of one MAC. While costs will vary according to the vapour used, the comparisons remain valid irrespective of the actual cost or vapour used.

An analysis of costs for the first hour of anaesthesia suggests that the circle absorber system is *more expensive* to run than the Humphrey ADE system, even at low FGFs of 1.5 L min^{-1} (see arrow Fig. 1). The benefits of absorption only become significant with long operations and then only if the additional capital costs of the equipment itself and extra monitors can be recovered from the savings achieved. Should anaesthetists wish to use sevoflurane, the Humphrey ADE system provides a solution to any concern over incompatibility with soda lime when used at low FGFs.

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3. The carbon monoxide story

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In several patients undergoing inhalation anaesthesia unexpectedly high levels of carbon monoxide haemoglobin (COHb) – up to 20–30% – have been found. Slow carbon monoxide (CO) generation in carbon dioxide absorbents, unused for a long period of time and previously contaminated with inhalation anaesthetics, was assumed to be the cause of these accidental CO intoxications [1]. As low-flow anaesthesia is associated with trace gas accumulation, Moon recommended that fresh gas flows lower than 5 L min^{-1} should not be used, that the breathing system should be flushed with a high flow of oxygen prior to its use, and that the absorbent should be changed frequently. However, because of the increasing availability of modern rebreathing systems and comprehensive anaesthetic gas monitoring, low-flow anaesthetic techniques are performed increasingly often in clinical practice. Furthermore, owing to economic and ecological considerations, the carbon dioxide absorbent should be used until fully exhausted provided that continuous carbon dioxide concentration monitoring is provided.

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At the authors' hospital minimal flow anaesthesia using a fresh gas flow of 0.5 L min^{-1} is routine. The absorber canisters are filled with pelleted soda lime and used for several days, the content of the canisters being routinely changed only once a week. In a trial of 1258 patients arterial or venous blood samples for oximetric analysis were taken 30 min after fresh gas reduction from 4.4 to 0.5 L min^{-1} during routine performance of minimal flow anaesthesia. The mean COHb concentration was 1.22% (SD $\pm$ 0.98), ranging from 0 to 7.6%, the 5th percentile being 0.2%, the 95th percentile 3.2% [2]. Although the carbon dioxide absorbent was used for up to 7 days, not a single case of an excessively high COHb level was observed. As expected, there was a highly significant difference between smokers (2.09 $\pm$ 1.3%) and non-smokers (0.86 $\pm$ 0.5%). However, if the whole group of patients was differentiated according to the volatile anaesthetic used (isoflurane vs. enflurane), to the size of the absorber canister (1 l vs. 1.5 l Jumbo canisters), or to the utilisation time of the carbon dioxide absorbent (ranging from 1 to 7 days), no statistical difference in the corresponding COHb levels could be found. On the contrary, in a control group of 75 patients a highly significant (Student's *t*-test: $P<0.0001$) decrease in the venous COHb concentration was observed when comparing the samples taken just before anaesthetic induction (2.15% $\pm$ 0.75) with the samples taken 45 min after induction, i.e. 30 min after flow reduction (1.37 $\pm$ 0.73). The same applies to minimal flow anaesthesia using desflurane: $n=57$, 2.23% $\pm$ 1.07 vs. 1.6% $\pm$ 1.05, $P<0.0001$. Even during long lasting inhalation anaesthesia, performed with extremely low fresh gas flow, a mean increase in COHb concentration of 0.4% in 6 h remains negligibly low.

Recently, Eger and co-workers [3] revealed that CO is generated in considerable amounts in absolute dry carbon dioxide absorbents exposed to desflurane, enflurane or isoflurane (descending order of CO liberated). However, only partial wetting of the absorbent markedly reduces the CO generation. Thus, all situations in which the absorbent is liable to dry out should be carefully avoided. By frequent performance of low flow anaesthetic techniques the humidity of the carbon dioxide absorbent is readily preserved. This is not only as a result of the better humidification of the anaesthetic gases, but also to an increased water generation resulting from an increased loading of the absorbent with carbon dioxide. According to the results of our investigations, low flow anaesthesia does not increase the risk of accidental dangerous carbon monoxide accumulation. On the contrary, regular performance of low flow anaesthetic techniques is an effective measure for the prevention of accidental carbon monoxide intoxication by the preservation of the absorbent's water content.

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4. The Coxeter-Mushin circle absorber: An idea before its time

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This circle absorber was designed by Coxeter and Mushin in 1941 [1] for use by the Emergency Medical Service. The Circle system though introduced in America in 1930 [2] was still relatively new to British anaesthetic practice, and this absorber incorporates a number of improved design features.

The apparatus is shown in Fig. 3. It differs from current circle design in that it has a bellows (a) instead of a reservoir bag, mounted on a crank which moves with SV and also allows IPPV with movement of the handle (b) a vaporizer for either (c) as an integral part of the circle, i.e. it is a vaporizer in the circle (VIC), an absorber (d), which is a Waters cannister designed within the circle for to and fro absorption and has a control to vary the amount of CO_2 absorbed. As well as an expiratory valve (e) there is an inspiratory valve (f) which, when opened, allows air to be taken into the circle when the bellows are opened.

It is interesting that a vaporizer in the circle was used in 1941, given the reluctance of present day

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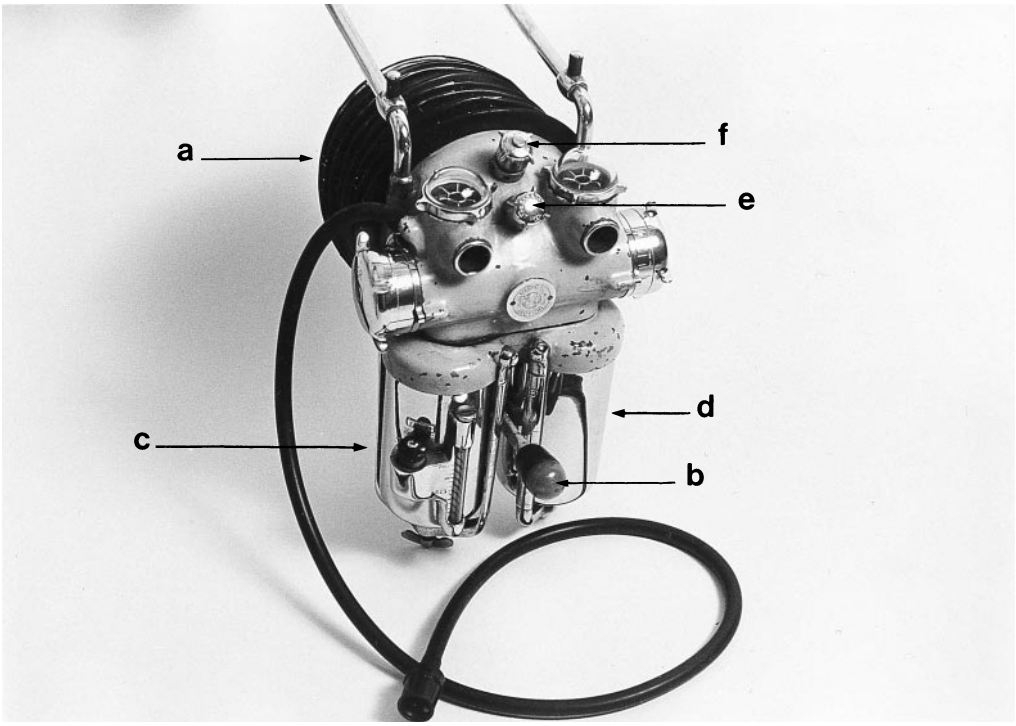

Fig. 3 (abstract 4)

anaesthetists to use a vaporizer in the circle. This probably reflects the fact that the level of ether anaesthesia is assessed by the clinical state of the patient irrespective of the origin of the ether vapour, either VIC or VOC and a knowledge of the inspired ether concentration is not therefore necessary to provide satisfactory anaesthesia. In contrast, halothane introduced in 1955 and subsequently the other potent volatile agents, were potentially dangerous if administered without a knowledge of the inspired vapour concentration. Until recently, this was not possible if the vaporizer was used in the circle.

However, the introduction of accurate and reliable vapour monitors now enables the vapour concentration within a circle to be measured on a breath-by-breath basis, so making the VIC practical once again. The design features of the Coxeter–Mushin absorber also allow an air/oxygen mixture to be generated within the circle so that an air/O_2/volatile anaesthetic can be given without any other apparatus other than a source of oxygen.

A simple anaesthetic machine could be designed using the above principles, with a modern plenum vaporizer for current volatile agents, an air flow meter, as well as an O_2 flowmeter and incorporating a ventilator into a conventional circle system. Such a circle system could be used at basal O_2 flow only, throughout the whole anaesthetic, as high FGF's would not be required to replace N_2 with N_2O nor to raise the vapour concentration in the circle from a VOC. Such a technique would also avoid the deleterious effects of N_2O.

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5. Direct injection techniques for volatile agent administration

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Anaesthetics have been injected directly into breathing systems since the pioneering days of the specialty. In the 1960s and 70s Lowe formalized the technique. He

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noted that the rate at which volatile anaesthetics had to be injected into a closed system to maintain a constant alveolar concentration was inversely proportional to the square root of the duration of anaesthesia. He developed a simple equation for the constant of proportionality which depends on the patient, volatile agent and required depth of anaesthesia. This constant, combined with the 'square root of time' principle allowed anaesthetists to estimate the concentration of volatile anaesthetic in a closed breathing system at a time when agent monitoring was not widely available.

Direct injection has been found to be a convenient delivery technique for servo-controlled systems. In 1951 Bickford described a machine which injected ether into a breathing system at a rate determined by feedback from an EEG [1]. The Northwick Park group controlled the expired isoflurane concentration and measured its uptake by patients using an automatic system [2]. We have developed a simpler system to automatically control the expired concentration of isoflurane or enflurane in oxygen [3]. A trunk of corrugated tubing connects the circle system to a Manley ventilator which provides mechanical ventilation. There is no conventional fresh gas supply, but if the Manley is driven with oxygen the trunk becomes a convenient reservoir of oxygen which automatically keeps the breathing system topped up.

More recently we have been using desflurane in our system. The only modification required is a bag of iced water placed on the syringe containing the desflurane to prevent boiling. We have found desflurane easier to control manually than isoflurane with few changes of injection rate required (Fig. 4). This allows the system to be reduced to:

(1) A gas-tight, conventional circle system.
(2) A long trunk of 22 mm corrugated tubing to separate the system from an open-system ventilator.
(3) Reliable monitors of oxygen and desflurane.
(4) A syringe pump and a gas-tight chromatography syringe with the barrel modified to fit the pump. This is kept cold with a bag of ice. A nylon manometer line is used to convey the desflurane to the breathing system where we use a metal canister to receive and vaporize it.

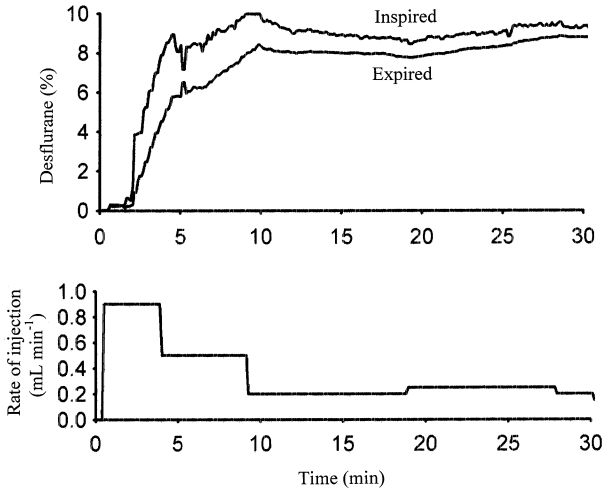

Fig. 4. Desflurane concentration in inspired gas controlled by intermittent injection into the breathing circuit.

The patient may be connected to the closed system immediately after intubation. If desflurane is injected at 0.5 mL min^{-1} an expired concentration of 8% will be achieved in 5–10 min in an average patient. Faster injection rates can be used but require correspondingly closer attention to prevent overshoot. If the system is kept closed (i.e. the analysed sample is returned to the system) the requirement reduces rapidly to 0.1–0.2 mL min^{-1} and only minor adjustments of the rate are required thereafter. As with any closed system, the oxygen concentration must be monitored carefully.

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