CLOSED-CIRCUIT HALOTHANE AND ENFLURANE USING AN
IN-CIRCLE GOLDMAN VAPORIZER

M. J. JORDAN AND J. A. BUSHMAN

SUMMARY

A closed-circle absorber system incorporating an in-circle Goldman vaporizer was used to administer halothane or enflurane in oxygen to adult patients. The attained inspired and end-tidal concentrations of volatile agent after a period of stabilization at each vaporizer setting were measured by mass spectrometry. During spontaneous respiration under halothane the ranges of inspired concentrations at settings 1, 1⅓ and 2 were respectively 0.5-0.9%, 1.4-2.4% and 3.3-4.5%. Corresponding inspired enflurane concentrations at the same settings were 0.8-1.4%, 1.9-2.8% and 3.7-5.0%. IPPV to 5% end-tidal carbon dioxide, although increasing the inspired concentrations slightly, produced considerable increases in end-tidal concentrations. Minimal pre-oxygenation was used to assess the problem of nitrogen accumulation within the circuit. The maximum nitrogen concentration was 56%.

The recent revival of interest in totally closed system anaesthetic techniques has produced a number of reviews of the associated advantages and disadvantages (Bushman et al., 1977; Adams, 1979). Recent work (Rayburn and Watson, 1980) suggests that, in patients who are artificially ventilated, the Bain system may provide better humidification of inspired gas, but circle-absorber systems used with basal fresh gas flows are unsurpassed in economy of gases and volatile agents, as well as freedom from pollution.

Non-rebreathing systems enable the inspired concentration to be held constant without difficulty. The alveolar concentration will increase towards the inspired concentration asymptotically with time at a rate that depends on the alveolar ventilation.

In circle-absorber systems, the relationship between ventilation and the inspired and alveolar concentrations developed is profoundly affected by the position of the vaporizer (Mapleson, 1960). If this is in the fresh gas supply line (VOC configuration) then the rate of supply of volatile agent to the circle is fixed and an increase in the patient’s minute volume results in a decrease in inspired concentration. At basal flows of fresh oxygen, this effect negates the increase in alveolar concentration that would otherwise result from an increase in ventilation. As a result, the alveolar concentration is independent of ventilation over a wide range (Mushin and Galloon, 1960).

The vaporizer-in-circle (VIC) configuration, on the other hand, will deliver an increased inspired volatile concentration if the minute volume increases. This effect produces a sharp increase in alveolar concentration and deepening of anaesthesia as a result. Such a system can truly be described as self-regulating provided the patient continues to breathe spontaneously. By the same token, VIC systems are almost universally regarded as dangerous if the ventilation is controlled (Churchill-Davidson, 1978).

The fact that, short of measurement, there is no way of knowing the precise volatile concentration within the system at any given time, is probably the largest single obstacle to the more widespread acceptance of VIC circuits into clinical practice. A large number of factors affect the volatile concentrations attained (table I) and while some of the quantities involved will be known, or at least constant and easily measurable, many, particularly

<table>
<thead>
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<th>TABLE I. Factors affecting the attained concentrations in closed-circuit systems with in-circuit vaporizer</th>
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<tr>
<td>Physical/equipment factors</td>
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<tr>
<td>Blood–gas sol. coeff. of agent</td>
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<tr>
<td>Volatility of agent</td>
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<tr>
<td>Vaporizer setting</td>
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<tr>
<td>Temperature</td>
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<td>Agitation of vaporizer</td>
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<td>Uptake by rubber, soda-lime</td>
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those dependent on the physiology of the patient, will be changing with time, measurable only with difficulty, or may have to be assumed.

The physics of closed circuits has been subjected to mathematical analysis by a number of workers. Mapleson (1960) showed that the inhaled concentration of a volatile agent in any circle system is given by:

$$F_i = \frac{V_{in\text{an}}}{V_{out} \left(1 - \frac{\theta}{V}\right) + \theta}$$

where $F_i$ is the fractional inhaled concentration, $V_{in\text{an}}$ is the rate of supply of anaesthetic vapour to the circle, $V_{out}$ is the rate at which oxygen is leaving the circle, $V$ is the patient's minute volume and $\theta$ is the rate of uptake of the volatile agent per unit inspired concentration.

A number of modifications of this expression have appeared in later publications, and Jennings and Styles (1968) derived a form describing specifically the conditions in VIC circuits:

$$F_i = F_v \frac{V}{(V_{in\text{o}} - 200) \left(1 - \frac{\theta}{V}\right) + \theta}$$

where $F_v$ is the "vaporizer concentration", in this context the amount by which the volatile concentration increases as the gas passes through the in-circle vaporizer, and $V_{in\text{o}}$ is the fresh gas flow. The patient's oxygen uptake is assumed to be 200 ml min$^{-1}$, so it can be seen that when the supply is matched to the uptake (when the circle is closed) the expression will simplify considerably, although even then its practical application will require an assumption to be made about both $\theta$ and $F_v$. With the type of uncalibrated vaporizer usually used in closed circuits, an accurate value for $F_v$ will necessitate direct measurement.

Fortunately, the behaviour of closed circuits in practice is more predictable than the theory might suggest and many anaesthetists use halothane in VIC systems with no means of measuring the inspired concentration directly, merely by knowing the approximate concentration developed and adjusting the vaporizer to the patient's response.

The fact that enflurane has physical properties broadly similar to those of halothane (table II) has lead to the supposition that it might be suitable for use in existing apparatus. Despite this there has been little published work on closed-circuit anaesthesia with this agent. Jones and others (1979) have described its use in the Marrett head, but currently available equipment has not been examined in a truly closed-circuit configuration.

The object of this work was to evaluate the practicality of using enflurane in a closed VIC system using the Goldman vaporizer (Goldman, 1962) by comparing the attained inspired and end-tidal concentrations with those achieved using halothane in the same apparatus. The effect on these concentrations of carefully controlled IPPV to 5% end-tidal carbon dioxide was examined and some assessment made of the problem of nitrogen accumulation.

### METHODS

The apparatus involved incorporated a Goldman vaporizer (Medishield) in the inspiratory limb of a circle based on a 1.8-kg soda-lime canister (Boyle Mk III BOC) and two 1-m lengths of breathing hose. A miniature pneumotachograph head (Accutach, McGaw Respiratory Therapy) was situated between the patient Y-piece and the endotracheal tube, with a side-arm for the sampling probe of a Medishield MS 2 mass spectrometer and multiplexer. The integrated pneumotachograph output and the mass spectrometer signals for nitrogen, carbon dioxide and the volatile agent were fed to four chart recorder channels. The instantaneous oxygen concentration was displayed on the front panel of the mass spectrometer but was not recorded. A scheme of this arrangement is shown in figure 1.

The circuit was adapted for IPPV by the replacement of the breathing bag with the patient valve of a Pneupac Model 2 ventilator-resuscitator. This pneumatic logic device, described elsewhere (Adams and Henville, 1977) is driven by a separate 400-kPa oxygen supply, and is used both to ventilate the circle and act as the source of fresh oxygen, the machine flowmeter shown at the top of figure 1 being turned off during

<table>
<thead>
<tr>
<th>Vapour pressure 20 °C (mm Hg)</th>
<th>Halothane</th>
<th>Enflurane</th>
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<tbody>
<tr>
<td>Concentration of Sat. Vap. (%)</td>
<td>32</td>
<td>23</td>
</tr>
<tr>
<td>MAC (%)</td>
<td>0.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Blood-gas solubility coeff.</td>
<td>2.4</td>
<td>1.9</td>
</tr>
<tr>
<td>Oil-gas solubility coeff.</td>
<td>224</td>
<td>98</td>
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*Table II. Comparison of the physical properties of halothane and enflurane*
IPPV. As the patient continues to take up oxygen, this will be replaced from the ventilator limb. As a result, instead of a symmetrical oscillation of gas within the ventilator limb, a stepwise net movement of gas towards the circle occurs. Provided the volume of the ventilator limb, in this case 1000 ml, is greater than the tidal volume then, even at the end of expiration, the volatile-laden contents of the circle never reach the patient valve exhaust port. Effectively, the circuit remains closed, venting only pure oxygen.

Patients were drawn from a heterogeneous pool of individuals ranging in age from 26 to 65 yr and in weight from 55 to 108 kg. Informed consent was obtained and they were randomly allocated to two groups of 10, to receive either halothane or enflurane via the system described. Measurements were made in the period before urological surgery.

Diazepam 10 mg was given by mouth 2 h before induction of anaesthesia. In the anaesthetic room an i.v. infusion of Hartmann's solution was started, e.g. electrodes applied and the arterial pressure measured then and subsequently every 1 min by automated oscillometry (Dinamap 845 Applied Medical Research).

Induction of anaesthesia was with thiopentone sodium until the loss of the lash reflex; this was followed by suxamethonium 1 mg kg⁻¹. The trachea was sprayed with 10% lignocaine and intubated. Apart from inflating the lungs with a few breaths of pure oxygen immediately before intubation, no attempt was made at preoxygenation and the circuit was kept closed from the start of the anaesthetic. The system was, however, flushed with oxygen immediately before induction, and tested rigorously for leaks. The fresh gas flow was adjusted to keep the bag adequately inflated.

Preliminary studies established that the useful range of delivered concentrations lay between settings 1 and 2 on the Goldman vaporizer for both agents. It was also found that, following an increase in vaporizer setting, a stable concentration within the circuit develops over approximately 5 min under spontaneous respiration, and rather faster during IPPV.
Thereafter the inspired concentration increases only very slowly. In the final plan, therefore, a period of 10 min was allowed for equilibration during spontaneous respiration and 5 min during IPPV.

The sequence of vaporizer settings used is shown in figure 2. Setting "1½", a point midway between settings 1 and 2, was found to be the minimum setting on which patients appeared to be anaesthetised at the beginning of an anaesthetic and was chosen as the starting point. Thereafter the plan was designed to ensure that the stable concentration was approached "from below" rather than while the concentration was decreasing. Settings 1, 1½ and 2 were evaluated during two periods of spontaneous respiration and settings 1 and 1½ during IPPV to 5% end-tidal carbon dioxide. The study ended as it began, with a period of spontaneous respiration at setting 1½, allowing comparison between the values attained under identical conditions separated by 40 min of anaesthesia. The within-patient correlation between the results obtained during these two periods was invariably to 0.2% of the volatile agent, for both inspired and end-tidal concentrations.

**RESULTS**

Figure 3 shows the inspired concentrations of halothane after the equilibration period at each vaporizer setting with spontaneous and controlled breathing. One obese individual was unable to breathe satisfactorily unassisted and data for the spontaneously breathing section of the study with halothane is based on nine patients. During...
spontaneous respiration, setting 1 provided between 0.5% and 0.9% halothane, setting 1\(\frac{1}{2}\) 1.4-2.4% and setting 2 3.3-4.5%. These values were slightly increased by IPPV.

Figure 4 shows the same data for enflurane. Setting 1 delivered 0.8-1.4% inspired enflurane during spontaneous breathing, setting 1\(\frac{1}{2}\) 1.9-2.8% and setting 2 3.7-5.0%, IPPV to normocapnia again producing a modest increase.

End-tidal concentrations for halothane are shown in figure 5, those for enflurane in figure 6. A much greater difference between spontaneous and controlled respiration can be seen, similar alveolar concentrations typically being attainable at a half-stop lower vaporizer setting.

Nitrogen concentrations within the circuit increased to a peak over the first few minutes, and maximum values of 25-56% were seen.

**Figure 5.** End-tidal halothane concentrations. Data for spontaneous respiration based on nine patients only. (For legend see figure 3.)

**Figure 6.** End-tidal enflurane concentrations. Data from 10 patients. (For legend see figure 3.)

**DISCUSSION**

Inspired concentrations of halothane developed during spontaneous respiration agreed with previous work on a very similar system (Bushman et al., 1977). The lower volatility of enflurane is more than outweighed by its lower blood-gas solubility coefficient and, as might be expected, in-circuit concentrations increased to greater values. Perhaps more surprising is the finding that IPPV to 5% end-tidal carbon dioxide produced only a comparatively small increase in inspired volatile concentrations, despite the fact that in some individuals ventilation to normocapnia involved a sizeable increase in alveolar ventilation. The true difference in conditions between spontaneous and controlled ventilation can only be seen when the end-tidal concentrations are examined, where the additive effects of an increase in inspired concentration and increased alveolar ventilation produce dramatic increases in alveolar volatile concentrations. Any element of hyperventilation would move the curves in figures 5 and 6 even further apart and steepen the characteristic of the curve for IPPV to a point where the scale on the vaporizer became dangerously cramped.

Nitrogen accumulation, as the tissue and FRC nitrogen emerged to dilute the contents of the circle, resulted in maximum nitrogen concentrations of more than 50% in some individuals. Preservation of even 10% nitrogen in the inspired mixture is of theoretical benefit to the patient and is to be encouraged in oxygen-filled circles. Unless the use of nitrous oxide is contemplated, then preoxygenation of the patient, or periods of high fresh gas flows before closing the circle would seem unnecessary precautions with a circuit of this volume, provided that it is flushed with oxygen first.

A considerable saving in liquid enflurane was possible, the hourly consumption being of the order of 10ml. A non-rebreathing system supplying similar concentrations could consume 10 times this quantity.

Continuing concern about atmospheric pollution and the increasing attention directed to systems that preserve heat and humidity in inspired gas has renewed interest in closed circuits. Their safe use requires meticulous attention.
REFERENCES

HALOTHANE ET ENFLURANE EN CIRCUIT FERMÉ AYANT UN VAPORISATEUR GOLDMAN INCLUS DANS LE CIRCUIT

RESUME
Un système absorbant en circuit fermé, comprenant un vaporisateur Goldman incorporé dans le circuit, a été utilisé pour administrer de l’halothane et de l’enflurane dans de l’oxygène à des patients adultes. Les concentrations d’agent volatil atteintes, inspirées et de fin d’expiration ont été mesurées par spectrométrie de masse, après une période de stabilisation à chaque réglage du vaporisateur. Pendant la respiration spontanée sous halothane les plages des concentrations inspirées aux réglages 1, 1,5 et 2 étaient respectivement de 0,5-0,9%, 1,4-2,4% et 3,3-4,5%. Les concentrations correspondantes d’enflurane inspirées aux mêmes réglages ont été de 0,8-1,4%, 1,9-2,8% et 3,7-5,0%. L’IPPV (ventilation au moyen de respirateurs à pression positive intermittente) à 5% de gaz carbonique en fin d’expiration, bien qu’augmentant légèrement les concentrations inspirées, a produit des augmentations considérables dans les concentrations de fin d’expiration. On s’est servi d’un minimum de pré-oxygénation pour estimer le problème de l’accumulation d’azote dans le circuit. La concentration d’azote maximale a été de 56%.

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HALOTHANE UND ENFLURAN IM GESCHLOSSENNEN KREISLAUF UNTER ANWENDUNG EINES IM KREIS ANGESCHLOSSENNEN GOLDMAN-VERDAMPFERS

ZUSAMMENFASSUNG
Ein Umlauf-Absorptionsystem mit einem im Kreis geschlossenen Goldman-Verdampfer wurde verwendet, um Halothan oder Enfluran in Sauerstoff bei erwachsenen Patienten zu verabreichen. Die nach einer Stabilisierungsperiode bei jeder Einstellposition erreichten inspirierten und expirierten Konzentrationen des flüchtigen Mittels wurden mittels Massenspektrometrie gemessen. Die bei den Einstellpositionen 1, 1,5 und 2 während spontaner Atmung unter Halothan ermittelten inspirierten Konzentrationsbereiche waren 0,5-0,9%, 1,4-2,4% und 3,3-4,5%. Die entsprechenden inspirierten Enflurankonzentrationen bei den gleichen Einstellpositionen waren 0,8-1,4%, 1,9-2,8% und 3,7-5,0%. Obwohl es die inspirierten Konzentrationsbereiche etwas steigerte, führte IPPV auf 5% expirierte Kohlendioxid zu beträchtlichen Steigerungen der expirierten Konzentrationen. Eine minimale Voroxigenisation wurde verwendet, um die Probleme der Stickstoffanhäufung innerhalb des Systems auszuwerten. Die maximale Stickstoffkonzentration betrug 56%.

HALOTANO Y ENFLURANO EN CIRCUITO CERRADO, USANDO UN VAPORIZADOR GOLDMAN EN EL CIRCUITO

SUMARIO
Se usó un sistema absorbente en circuito cerrado, que incorporaba un vaporizador Goldman en el circuito, para administrar halotano o enflurano en oxigeno a pacientes adultos. Se emitió para cada establecimiento del vaporizador y mediante espectrometría de masas, las concentraciones de inspiración y de la respiración de Cheyne-Stokes terminal que se lograron, en relación a los agentes volátiles, después de un periodo de estabilización. Durante la respiración espontánea bajo halotano, las gamas de las concentraciones inspiradas en los establecimientos 1, 1,5 y 2, fueron respectivamente de 0,5-0,9%, 1,4-2,4% y de 3,3-4,5%. Las concentraciones de enflurano inspirado correspondientes a los mismos establecimientos fueron de 0,8-1,4%, 1,9-2,8% y de 3,7-5,0%. El porcentaje inspirado por volumen, hasta el 5% de dióxido de carbono, en la respiración de Cheyne-Stokes terminal, aunque incrementó ligeramente las concentraciones inspiradas, produjo incrementos considerables en las concentraciones de la respiración de Cheyne-Stokes terminal. Se usó una preoxigenización mínima para evaluar el problema de la acumulación de nitrógeno dentro del circuito. La concentración máxima de nitrógeno fue del 56%.