Breathing systems: effect of fresh gas flow rate on enflurane consumption

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Summary
The vaporization rates of enflurane were measured in 412 anaesthetics using appropriate fresh gas flow rates in Bain (12 litre min⁻¹), Magill (6 litre min⁻¹) and circle systems (3 litre min⁻¹, 1 litre min⁻¹ and "closed"). In all patients reducing the fresh gas flow rate resulted in lower enflurane consumption. The percent savings were 18–86% depending on the initial fresh gas flow rate and the size of the change in fresh gas flow. The reduction in enflurane use was more marked in inpatients (long cases) than in day-case patients (short cases). (Br. J. Anaesth. 1994; 73: 775–778)

Key words
Anaesthetics volatile, enflurane. Equipment, breathing systems.

The requirement to minimize unnecessary expenditure, wastage and environmental pollution has led to renewed interest in the use of low fresh gas flow rates for delivery of volatile anaesthetics. In circle absorption systems, the use of fresh gas flow rates less than 6 litre min⁻¹ is known to lower the total amount of volatile agent vaporized during anaesthesia [1, 2]. For enflurane, as much as 77% of the delivered agent is estimated to be lost through the scavenging system [3]. A particularly marked reduction in vaporization occurs with even lower flow rates of approximately 0.5 litre min⁻¹ but with significant loss of control of system concentrations [4, 5]. Quantification of the savings produced by low-flow regimens have proved difficult to estimate because of the variability in duration and depth of anaesthesia, the wide range of surgical specialties studied and especially the lack of specificity of fresh gas flow rates used [6]. In order to facilitate prospective budgeting, there is a need to determine the reduction in volatile agent consumption which results directly from the lowering of fresh gas flows.

To quantify the comparative volatile agent savings of low-flow anaesthesia, the present study was designed to compare the rates of vaporization of enflurane using a comprehensive range of fresh gas flow rates used in current clinical practice.

Patients and methods
Volatile agent vaporization was measured during anaesthesia in 412 patients undergoing gynaecological surgery. All operating lists consisted of entirely day-case patients or entirely inpatients and not a combination of the two. On any single day, all day-case patients were allocated to one treatment group, selected at random (closed envelope method) from the four groups: Bain system with a fresh gas flow rate of 12 litre min⁻¹, Magill with 6 litre min⁻¹, circle with 3 litre min⁻¹ and circle with 1 litre min⁻¹. Similarly, all inpatients were allocated to one group selected at random from the same four groups or an additional modified "closed" system group. All anaesthetics were induced with propofol 2–3 mg kg⁻¹ followed by spontaneous breathing with enflurane and nitrous oxide in oxygen, titrated continuously to maintain anaesthesia at a depth of minimal surgical anaesthesia. In addition, inpatients undergoing laparotomy also received extradural anaesthesia to permit spontaneous respiration throughout. The nine groups, the breathing systems and fresh gas flow rates are shown in table 1. In the groups where the fresh gas flow rate was scheduled to be 1 litre min⁻¹ or less, during the initial 5 min the flow rate was 3 litre min⁻¹. Thereafter the fresh gas flow rate was reduced to the rate shown in table 1. The closed group was therefore closed after 5 min of anaesthesia and not from the start. The closed fresh gas flow rate was determined by the patient gas uptake requirement and was not used for day-case patients. The circle system used was a standard BOC Mk4 system with the spill valve positioned immediately beyond the expiratory valve and separated from the fresh gas inflow by the absorber. Monitoring of breathing system volatile agent and gases was performed throughout (Datex Cardiocap II and Datex Ultima). With the circle system, all sampled gases were returned to the breathing system. All patients were anaesthetized in the operating theatre in order to use a single vaporizer, without interruption throughout the anaesthetic.

At the start of each list the vaporizer (Ohmeda Mk3, 7%) was prepared by filling fully with enflurane and then emptying completely to ensure that the wicks were fully saturated. The volume of enflurane used during the list was measured by careful filling and drainage of the vaporizer at the beginning and end of each list, and the volumes noted using a graduated measuring cylinder. During emptying, the vaporizer was tipped 15° anterolaterally to ensure that all remaining enflurane was measured. The mean volume used per patient was

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calculated for each list. The duration of anaesthesia was timed from the moment the vaporizer was turned on until the system was disconnected from the patient at the end of surgery. The average rate of usage for each list was obtained by dividing the total usage by the total anaesthetic time. For each treatment group, mean (SD) values between lists were calculated from these averages for time and for rate of usage.

**Results**

The accuracy of the technique of filling and draining the vaporizer to measure the total volume of enflurane used was tested over a drainage range of 10–85 ml and found to have an accuracy of ±2.1 ml (SD).

Mean duration of anaesthesia was 53.2 (SD 12.7) min for the inpatients (long) and 11.6 (4.6) min for the day-case patients (short). Table 1 shows the average rate of enflurane consumption per minute and the range of total consumption per list for each group. Enflurane consumption was 24–315 ml per list. The comparative consumption of volatile agent is presented as the percent reduction in enflurane usage by the total anaesthetic time. For each group required a brief increase in flow rate to 1 litre min⁻¹ to achieve adequate depth of anaesthesia before returning to the closed state.

### Table 1

<table>
<thead>
<tr>
<th>Group</th>
<th>Breathing system</th>
<th>FGFR (litre min⁻¹)</th>
<th>No. of patients</th>
<th>No. of lists</th>
<th>Enflurane consumption (ml min⁻¹)</th>
<th>Enflurane consumption (ml list⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inpatients</td>
<td>Circle</td>
<td>&quot;Closed&quot;</td>
<td>25</td>
<td>6</td>
<td>0.18 (0.02) [24–62]</td>
<td></td>
</tr>
<tr>
<td>Inpatients</td>
<td>Circle</td>
<td>1</td>
<td>30</td>
<td>6</td>
<td>0.22 (0.06) [30–67]</td>
<td></td>
</tr>
<tr>
<td>Inpatients</td>
<td>Circle</td>
<td>3</td>
<td>31</td>
<td>6</td>
<td>0.49 (0.06) [86–174]</td>
<td></td>
</tr>
<tr>
<td>Inpatients</td>
<td>Magill</td>
<td>6</td>
<td>28</td>
<td>6</td>
<td>0.73 (0.05) [202–264]</td>
<td></td>
</tr>
<tr>
<td>Inpatients</td>
<td>Bain</td>
<td>12</td>
<td>32</td>
<td>6</td>
<td>1.31 (0.08) [226–296]</td>
<td></td>
</tr>
<tr>
<td>Outpatients</td>
<td>Circle</td>
<td>1</td>
<td>65</td>
<td>6</td>
<td>0.49 (0.11) [46–79]</td>
<td></td>
</tr>
<tr>
<td>Outpatients</td>
<td>Circle</td>
<td>3</td>
<td>70</td>
<td>6</td>
<td>0.74 (0.09) [64–81]</td>
<td></td>
</tr>
<tr>
<td>Outpatients</td>
<td>Magill</td>
<td>6</td>
<td>63</td>
<td>6</td>
<td>1.08 (0.14) [189–235]</td>
<td></td>
</tr>
<tr>
<td>Outpatients</td>
<td>Bain</td>
<td>12</td>
<td>68</td>
<td>6</td>
<td>1.76 (0.18) [257–315]</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>412</td>
<td>54</td>
<td></td>
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</tr>
</tbody>
</table>

Discussion

In this study a simple volumetric measurement technique has been used to determine the likely savings in enflurane costs when a high fresh gas flow technique is replaced by lower flows. Being a clinical study, it encompassed all the subtle variations in anaesthetic management not easily incorporated in formulae and computer models. The relationship between fresh gas flow and enflurane utilization was thus influenced by the different gas flow regimens necessary for the delivery of the correct inspired concentration of anaesthetic agent and by the different breathing systems appropriate to each flow rate. For any breathing system, all enflurane delivered to the system other than that taken up by the patient to produce anaesthesia or absorbed into the tubes of the breathing system or the soda lime, is spilt into the scavenging system. All else being equal, this wastage of enflurane would be proportional to the fresh gas flow rate. In this study, at fresh gas flow rates of 3 litre min⁻¹ and over, the flow rate was constant throughout the anaesthetic. However, in the 1-litre min⁻¹ and closed groups, there was a necessary initial 5 min of 3 litre min⁻¹ flow to prime the breathing system, reach adequate overpressure enflurane concentrations and partially denitrogenate the patient. These requirements resulted in an increase in enflurane usage over this initial period. However, the apparent linear relationship between fresh gas flows and enflurane usage seen in figure 1 does not show a positive deviation at the lower flow rates. One possible explanation for this is the efficient positioning of the spill valve on the expiratory limb of the circle system. During the early part of the overpressuring phase, rapid uptake of enflurane occurs. The expired alveolar concentrations are low and wastage through the spill valve is consequently minimized. In addition, the ability to turn off the vaporizer before the end of surgery and allow the
Enflurane consumption at different fresh gas flow rates

![Graph](image)

**Figure 1** Modified linear relationship between fresh gas flow rate (FGFR) and enflurane delivery (mean (3σ)) in day-case patients (▲) and inpatients (●).

Circuit enflurane concentrations to "coast" gradually downwards, when using flow rates less than 3 litre min⁻¹, results in a period of anaesthesia with ultimate economy during which there is no vaporization of enflurane whatsoever. The initial high flow and later coating phases have opposing effects on the average enflurane usage. The resultant effect depends on the magnitude of each factor and, with the techniques used, is virtually balanced giving the linear relationships in figure 1. It is likely that this balance is unique to these fresh gas regimens. If a longer period of initial high flow rate had been used, perhaps 10 min, the wastage of enflurane would have been greatly increased without clinical benefit. The duration of the coasting phase would not have changed and a positive deviation from linearity might be expected, especially in the short day-case groups.

The duration of anaesthesia has a powerful effect on the rate of enflurane usage (fig. 1). The shorter duration in the day-case patients reduced the savings seen in the inpatient by 1–5% at 3 litre min⁻¹ and 11–21% at 1 litre min⁻¹ fresh gas flows. The initial 5-min period of 3 litre min⁻¹ amounts to approximately 45% of the duration of anaesthesia in the day-case patients but only 9% of the duration in the inpatients. Thus the initial high flow period which also contains the main part of the overpressure phase of anaesthesia reduced the true 1 litre min⁻¹ flow time accordingly and reduced the relative efficiency of the flow technique in the short (day-case) patients. Even in these short day-case patients it was possible to coast for the last 1 or 2 min, greatly reducing the average enflurane delivery during the 1 litre min⁻¹ phase.

The inpatient closed group showed only an 18% saving over 1 litre min⁻¹, despite an approximate three-fold decrease in fresh gas flow rate. The initial high flow priming rate being approximately 10 times the maintenance rate has a greater influence on total enflurane usage at these minute flow rates over 1 h. This was not balanced even by the ability to coast for longer in a closed circle. The closed anaesthesia technique was not used to study day-case patients because in these short anaesthetics the initial high flow phase would have dominated the anaesthetic. And importantly, during maintenance, the closed flow rates with the vaporizer out of circuit would have seriously restricted the ability of the anaesthetist to adjust the depth of anaesthesia to suit the rapidly changing surgical requirements. This loss of agility of the system was seen even in the inpatient closed group, with four patients requiring a brief period of 1 litre min⁻¹ to maintain adequate depth of anaesthesia.

The clinical judgement of depth of anaesthesia has always been difficult to standardize. To minimize variations in the interpretation of anaesthetic depth, the same anaesthesit anaesthetized all patients. Also, the use of extradural anaesthesia with general anaesthesia in all intra-abdominal inpatients eliminated the variable effects of the surgical stimulus. It is likely that the amount of enflurane usage would have been less than for a general anaesthetic alone. However, no opioids or neuromuscular blocking agents were used and the depth of anaesthesia could be assessed more easily and kept equivalent for all cases. Thus although absolute values of the rates of enflurane vaporization are given, they are unique to the specific anaesthetic techniques used in this study and for the type of surgery involved. Other techniques may use alternative rates of vaporization although the relative differences between flow rate categories are likely to be similar.

In 1977, Herscher and Yeakel demonstrated 77% wastage of enflurane administered with flow rates of approximately 4–5 litre min⁻¹ [3]. In the present study there was a 75% difference in enflurane consumption between 6 litre min⁻¹ and basal flow requirements, perhaps reflecting the rigid high initial flow phase technique used. More recently, Cotter and colleagues [6] reported a 56% reduction in enflurane consumption when comparing 6–8 litre min⁻¹ with flows ≤ 4 litre min⁻¹. In the present study there was a 33% reduction for the more specified change from 6 to 3 litre min⁻¹. The difference between these studies is likely to be a result of the higher initial flow rate and the probability that flows well below 4 litre min⁻¹ may have been used by some anaesthetists in the study of Cotter and co-workers. Indeed, Cotter's reduction in consumption equates better with the 6–1 litre min⁻¹ fresh gas flow change in the present study which gave a 55–70% reduction in enflurane usage.

It is interesting that by changing from a Bain system at 12 litre min⁻¹ fresh gas flow rate to a Magill system at 6 litre min⁻¹, a reduction of 50% in fresh gas flow rate does not produce a corresponding 50% lower vaporization of enflurane. In these cases there is no circle system to act as a buffer between the vaporizer and the patient. However, the concentration of enflurane received by the patient was lower during the overpressure phase of inhalation anaesthesia in the Bain system groups because the vaporizer output is non-linear with fresh gas flow rate [7]. At 12 litre min⁻¹ the vaporizer, at the
maximum setting, can deliver up to 1.7% enflurane less than that shown on the vaporizer control dial, whereas, a fresh gas flow rate of 6 litre min\(^{-1}\) from a Magill system produces 0.5% less than that dialled. Thus halving the flow rate results in less than half the expected reduction in enflurane vaporization. This is most marked when comparing the percentage cost saving difference between the inpatients (long) and the day-case patients (short) if 6 litre min\(^{-1}\) was used rather than 12 litre min\(^{-1}\). The inpatients saved 44% whereas the day-case patients saved only 39% because such a high proportion of the short procedure is comprised of the overpressure phase. In day-case anaesthetics there are times during the early uptake of volatile agent when the clinical requirement of the patient exceeds the output of the vaporizer. The concentration of the agent delivered is then dictated by the maximum output of the vaporizer and not clinical needs. The non-linear output of the vaporizer reduces the ideal concentration delivered for the clinical need. However, when the flow rates of 1 litre min\(^{-1}\) or less are used, the vaporizer produces up to 2% enflurane more than dialled. This can be of considerable benefit when using low flows to offset the reduced vapour concentration inspired as a result of the dilutional effect of recycled gases.

References