A MICROPROCESSOR-CONTROLLED ANAESTHETIC VAPORIZER

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Conventional anaesthetic vaporizers channel the fresh gas flow along two pathways, one through the vaporizing chamber and one through a bypass. These are then recombined in a common outlet. The conventional vaporizer chamber usually contains wicks so that gas passing through the chamber passes over their surfaces, as well as that of the liquid agent itself, and so becomes saturated with anaesthetic vapour. The total vapour concentration will depend on the gas flow in each of the pathways, as well as the saturated vapour pressure of the agent in the vaporizing chamber. As vaporization proceeds, the temperature of the agent, and hence its saturated vapour pressure, will decrease and manufacturers have incorporated temperature compensators into their vaporizer design such that the fresh gas flow through the two pathways is varied as the temperature decreases. This causes more fresh gas to be delivered through the vaporizing chamber, and so maintain a constant vapour concentration at the vaporizer outlet.

In practice, these pathways are complex in a conventional vaporizer, and vaporizers can only be relied on to produce accurate vapour concentrations over a limited range of working conditions. Some vaporizers show a marked increase in output concentration when the flow rate decreases, and the output concentration of some vaporizers shows a marked dependence on the carrier gas used as the fresh gas supply (Stoelting, 1971; Diaz, 1976; Lin, 1979; Stoelting and Nawaf, 1979; Knill et al., 1980; Prins et al., 1980; Palayiwa, Sanderson and Hahn, 1983). However, in vaporizers in which the fresh gas flow rates through the bypass and vaporizing chamber are controlled separately, and where the temperature of the vaporizing chamber is measured, the output concentration of the vaporizer can be predicted accurately. This requires the anaesthetist to perform fairly complex calculations, and to adjust manually for temperature changes as the temperature of the vaporizing chamber decreases.

In recent years (Cooper et al., 1978; Anthony, 1982) a new anaesthetic delivery system has been described which has been termed the Boston Anesthesia system. In this system, mixtures of oxygen and nitrous oxide are produced by "digital valves" (Lundsgaard, Einer Jensen and Juhl, 1977; Cooper et al., 1978) and liquid anaesthetic is injected to this gas stream in metered volumes. The injection device is an automatic fuel injector,
modified for use with volatile anaesthetics. The
injector is controlled by a microprocessor, the
liquid anaesthetic being atomized into a chamber
as it emerges from the injector, and complete
vaporization achieved in a copper vaporizing coil.
Temperature compensation is not necessary
(Cooper et al., 1978.) With this design, the liquid
anaesthetic had to be supplied in a special prefilled
plastic container, which was translucent to permit
observation of the liquid level. It was envisaged
that the cannisters would be filled or refilled only
by a manufacturer or distributor, to avoid the
hazard of misuse.

We describe, in this paper, an alternative
system delivering a predicted concentration of a
volatile anaesthetic agent by means of a simple
vaporizer, which is controlled by a microprocessor.
Although this system used halothane as the
volatile agent, it could equally well be used for
other agents, such as enflurane or isoflurane.

MATERIALS AND METHODS

Apparatus

Fresh gas supply

Oxygen and nitrous oxide were supplied to the
vaporizer by an electromagnetic solenoid valve
gas-mixing apparatus, controlled by a micropro-
cessor, as described in a previous paper (Palayiwa
et al., 1986). The solenoid valves were pulsed
open for a set time, so that they passed a constant
volume of gas for each "open" period. By varying
the pulse frequency, the flow rate for each gas was
controlled, thus producing accurate nitrous oxide–
oxygen gas mixtures with known concentrations
over a wide range of constant flow rates. The gases
passed through a double mixing chamber–damping
system so that any pulsatility was smoothed. The
gas emerging from the gas mixer–pulse damper
system passed through a special constant pressure
device, described in our previous paper, which
maintained a constant pressure of 9.81 kPa
(100 cm H₂O) upstream of the vaporizer. A
schematic diagram of the gas supply system is
presented in figure 1, and highlights the major
components.

The gas supply for the actual vaporizer was
taken off beneath the second constant pressure
valve. The float of the valve was placed in a
continuously tapering tube so that, if the upstream
pressure were to decrease, gas would still bypass
the vaporizer and, therefore, prevent the delivery
of saturated vapour. The vaporizer gas supply
passed through a solenoid valve, which was pulsed
at a frequency controlled by the microprocessor,
and this gas then bubbled through the liquid
agent in the vaporizer. The gas/vapour emerging
from the vaporizer then entered a steel mixing
chamber. The fresh gas, which bypassed the
vaporizer, entered on the opposite side of the
Microprocessor-controlled anaesthetic vaporizer

Mixing chamber, both entry ports being arranged tangentially opposite each other, so that gases and vapour travelled in toroidal paths, to ensure good mixing. The mixing chamber was similar in operation to those used in the gas mixing system, except that the upper wall of the chamber was fixed and contains the gas outlet.

Early vaporizer design

Initially, a simple halothane bottle (as supplied by the manufacturer) was used as the vaporizer, and the fresh gas was simply bubbled through the liquid agent. A special screw cap held the tubes for entry and exit of the gases, and a thermistor was immersed in the liquid in a thin stainless steel tube. Temperature was fed into the microprocessor as a “feedback” control.

The microprocessor contained a program which was written so that the required oxygen concentration, total gas flow rate, and halothane concentration could be entered via a keyboard. The program then calculated the pulsing regimen for the oxygen and nitrous oxide gas mixing valves and used the vapour pressure—temperature relationship of the halothane (Hill, 1976), together with the knowledge of the total gas flow rate into the liquid agent, to calculate the pulsing rate necessary to give a required vapour concentration. These calculations are contained in the Appendix, and assume that the vapour emerging from the vaporizing chamber is fully saturated. The temperature was read every 2 s and the vaporizer valve frequency was adjusted to accommodate any change in temperature as the vaporization process took place.

This simple vaporizer design was finally discarded, for reasons given in the discussion section, and a final vaporizer design was developed.

Final vaporizer design

The final vaporizer design is shown in figure 2. In concept, this design is very similar to that of a conventional carburretor. It is machined out of a cylindrical copper rod. The liquid anaesthetic enters a float chamber, where the float activates a needle valve, which controls the input of liquid anaesthetic agent to the vaporizer. The total volume of liquid anaesthetic in the vaporizer is set to approximate 10 ml, and the needle input valve is connected to either a halothane bottle, or a metal halothane reservoir tank, via a flexible tube. The float chamber connects directly with a small vaporizing chamber, which also contains a sintered gas inlet port, positioned so that the fresh gas bubbles through the liquid anaesthetic contained in the vaporizing chamber.

In the event of the chamber overfilling, a second safety valve comes into action and liquid halothane flows out through a spill tube. Spillage can be returned by gravity to the metal reservoir tank, although this is not possible if the halothane bottle is used as the reservoir. A thermistor is mounted in the copper block to monitor the temperature of the vaporizer, and this information is fed directly to the microprocessor. Anaesthetic vapour leaves the vaporizer block assembly through a port in its upper surface, and is fed into the mixing chamber illustrated in figure 1.

Experimental Procedure

Measurements of vapour concentration were undertaken with a respiratory mass spectrometer (Centronic MGA 200), with halothane being measured on mass number 117. The mass spectrometer was calibrated against a small portable refractometer (Riken Gas Indicator), as described by Palayiwa, Sanderson and Hahn (1983).

The volume of a pulse of gas from the solenoid valve was measured first of all in the absence of the vaporizer, by pulsing gas into a wet spirometer (P. K. Morgan Ltd) and measuring the total
volume. The open time of the solenoid valve was set at 100 ms. The actual pulse volume delivered by the solenoid valve when connected to the vaporizer was deduced empirically by inserting the pulse volume, in the absence of the vaporizer, to the computer program and then comparing the vapor concentration delivered by the vaporizer with the value "set" by the microcomputer. The difference between the "actual" and "set" vapour concentrations was used to determine the pulse volume delivered by the solenoid valve.

For both the early and final designs of vaporizer, different total fresh gas flow rates and different oxygen–nitrous oxide mixtures were passed through the vaporizer, and the final halothane concentration was measured at the exit to the mixing chamber. Flow rates were varied between 2 and 16 litre min\(^{-1}\), and the oxygen concentration was varied between 20% and 100%, the balance being nitrous oxide.

RESULTS AND DISCUSSION

Solenoid Valve Pulse Regimen

It was found that, for total gas flows in excess of 2 litre min\(^{-1}\) (flow conditions where the constant pressure valve works well, and maintains 100 cm H\(_2\)O forward pressure), the pulse volume delivered by the solenoid valve was constant and equal to 7.2 ml. For flow rates less than 2 litre min\(^{-1}\), the open time for the valve was reduced to 50 ms in order to decrease fluctuations in the vapour concentration at the output of the vaporizer. Under these conditions, the pulse volume was found empirically to be given by the equation \(V_p = 2.75 + 1.01 \frac{O_2}{100}\) where \(V_p\) is the pulse volume (ml), and \(O_2\) is the oxygen concentration in % v/v. This formula was used in the microprocessor software to calculate the predicted halothane composition delivered by the vaporizer, for flow rates less than 2 litre min\(^{-1}\).

Early vaporizer design

The initial results with the early vaporizer design looked promising, except that, at flow rates less than 5 litre min\(^{-1}\), the vapour concentration delivered by the vaporizer appeared to be totally unpredictable. Further investigations made it clear that a change in carrier gas concentration produced a transient change in the output of the vaporizer. In some cases, this was very large, such that the vaporizer output concentration decreased to half of its original value when the carrier gas was suddenly changed from 100% oxygen to 21% oxygen in nitrous oxide. At low flow rates, this transient change was prolonged, lasting up to 30 min. Further investigations revealed that this phenomenon was the result of the high solubility of nitrous oxide in halothane (Gould, Lampert and Mackrell, 1982; Lampert et al., 1982; Palayiwa, Hahn and Sugg, 1985). When nitrous oxide was bubbled into the halothane in the halothane bottle, the emerging halothane concentration decreased because large quantities of nitrous oxide were simply dissolving in the liquid. The halothane concentrations returned to their set values only when nitrous oxide saturation in halothane was reached.

This effect was seen much more markedly in this type of vaporizer than in conventional vaporizers, because of the size of the bottle and because the gas was physically bubbled through halothane. In conventional vaporizers, the gas is passed over the surfaces of the wicks and this physically limits the quantity of liquid halothane available to absorb nitrous oxide.

One possible solution was to bubble oxygen alone through the vaporizing chamber and, thus, avoid the nitrous oxide absorption effect. However, this would have entailed a redesign of the system, and it would have meant that, under certain circumstances, the bypass would contain a hypoxic mixture. This would be dangerous if there were any failure of the vaporizer valve, such that this hypoxic mixture was the only gas delivered to the patient. Also, since our method of gas analysis (to be published in a following article) required that the oxygen–nitrous oxide mixture passed through the vaporizer, it meant that the vaporizer had to be redesigned, with a small volume of halothane only available for nitrous oxide absorption.

Final vaporizer design

The final design has already been described, and is illustrated in figure 2. The volume of the vaporizing chamber was drastically reduced, to 10 ml, so that the transient effect would be small and shortlived. This reduction in halothane volume was found to decrease the duration of the transient effect to 1 or 2 min at the lowest flow rate used (1 litre min\(^{-1}\)) and to a few seconds at flow rates greater than 10 litre min\(^{-1}\).

Also, using a large block of copper for the construction of the vaporizer increased its heat capacity considerably and, therefore, reduced the
rapidity of cooling—which occurred in the early design. However, cooling of the liquid agent was still a problem since, if the vaporizer is to be used for enflurane, it should be able to deliver 7% enflurane at a total fresh gas flow of 16 litre min⁻¹. This requirement introduces its own problems, since it is not advisable to reduce the period of the vapor valve to less than twice its open-time, because opening and closing transients for the valve become important. In effect, this restriction means that the maximum gas flow available for flow through the vaporizer is a little over 2 litre min⁻¹, since the volume of a 100-ms pulse is 7.2 ml.

Assuming a maximum flow of 2 litre min⁻¹ through the vaporizer, and 14 litre min⁻¹ through the bypass, and a saturated vapour pressure of 25% of an atmosphere, then 2.5 litre of gas emerged from the vaporizer and this contained 25% vapour. The total vapour concentration is therefore given by $2.5 \times 25/16.5$, which is approximately 4% v.v. This would be the maximum concentration available, and would be sufficient when halothane is the agent used. However, in an enflurane vaporizer this concentration could only be increased by introducing a heating device to the vaporizer construction. The simplest way to achieve this would be by mounting a thermostatically-controlled heater in the copper block, and maintaining the temperature of the vaporizer at a preset level. Further investigations are necessary to determine whether this method would work well.

**Vaporizer Performance**

Figure 3 shows an illustration of the variation in halothane concentration with time, for different total fresh gas flow rates. Some pulsatility is evident, because of the nature of the pulsed gas flow through the vaporizer. However, the pulsing is rapid and the fluctuations will be averaged out in the inspiratory period. The average delivered concentration was equal to the value predicted by the microprocessor algorithm software. At high flow rates, the frequency of the pulsing of the vapour valve was high, and the fluctuations illustrated in figure 3 could only be detected by instruments with a fast response time such as a mass spectrometer, or an "Emma" Vapour Analyser.

Table I illustrates the performance of the vaporizer for a 50% nitrous oxide in oxygen gas mixture at flow rates of 2, 5, 10 and 16 litre min⁻¹.

<table>
<thead>
<tr>
<th>Set vapour concentration</th>
<th>Flow rate (litre min⁻¹)</th>
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<tbody>
<tr>
<td></td>
<td>2</td>
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<tr>
<td>1.0</td>
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<td>3.0</td>
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<td>4.0</td>
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It is clear that the vaporizer was performing very well at all flow rates, and that the predicted and measured values were in agreement to within 0.1% v/v.

Figure 4 illustrates the performance when the total fresh gas flow rate is set at 10 litre min⁻¹ and the oxygen in nitrous oxide concentrations are varied between 20, 50 and 100%. Again, the measured against predicted halothane concentrations did not vary by more than 0.2% v/v.

Whilst we have retained the conventional volumetric percentage expression of vapour concentration, this type of vaporizer provides a
controlled flow of saturated vapour at a known temperature and could, therefore, readily be adapted to calibration in mass flow terms; for example, for use with totally closed breathing systems.

CONCLUSIONS

The general conclusion is that it is possible to design a new type of vaporizer constructed on the copper kettle principle, which is controlled by a microprocessor, and yet can deliver predictable and accurate vapour concentrations in the clinical range. The principle of using the vapour pressure-temperature relationship for a particular anaesthetic agent as the feedback control for the vaporizer has been shown to be practical at both high and low fresh gas flow rates. This design should provide an alternative method for manufacturers to produce anaesthetic vaporizers, without resorting to complicated engineering specifications, and complicated automatic temperature correction devices.

APPENDIX

CALCULATION OF VAPOUR VALVE PULSE RATE

Let the total fresh gas flow be \( F \), and the required vapour concentration (% v/v) be \( C \). The volume flow rate of vapour added to the fresh gas flow, \( V \), is given by:

\[
C = \frac{(V \times 100)}{(F + V)}
\]

Hence,

\[
V = F \times C \div (100 - C)
\]

If the saturated vapour pressure of the agent (% v/v) is given by \( S \), then for a flow rate, \( X \), into the vaporizer, the volume of agent added will be given by:

\[
\frac{V}{(X + V)} = \frac{S}{100}
\]

Hence

\[
X = V \times \frac{(100 - S)}{S}
\]

Therefore, by substitution:

\[
X = \frac{F \times C \times (100 - S)}{(S \times (100 - C))}
\]

Since the pulse size is 7.2 ml, the frequency with which the vapour valve must pulse is \( X \times 1000 \div 7.2 \times 60 \) Hz.

REFERENCES


