A MICROPROCESSOR-CONTROLLED GAS MIXING DEVICE

E. PALAYIWA, C. E. W. HAHN, B. R. SUGG, D. LINDSAY-SCOTT AND P. J. TYRRELL

This paper describes a microprocessor-controlled gas mixing system, which is capable of supplying accurate gas mixture over a wide range of flow rates. The apparatus supplies a binary oxygen/nitrous oxide gas mixture and has been designed specifically for use in an anaesthetic machine. However, the principle may be extended to provide mixtures of several different gases for general hospital or laboratory use. For many years conventional anaesthetic machines have utilized rotameters to provide the desired gas mixture and total flow rate of gas. The apparatus described represents a radical change from conventional practice. It also differs in design from the more recent techniques of providing gas mixtures from binary-coded orifice devices (Lundsgaard, Einer Jensen and Juhl, 1977; Cooper et al., 1978), and from the techniques described by Robbins and colleagues (1982), by the use of sonic flow conditions. Other systems for producing gas mixtures have been described by Clark and Wallace (1977), Heim and Albarda (1979), Jacky (1980) and Wallace and colleagues (1978). The system described in this paper has been designed to be used with a new microprocessor-controlled vaporizer, and with a microprocessor-controlled gas-analysis refractometer, both of which will be described in subsequent papers.

SUMMARY

This paper describes the use of solenoid valves for the production of binary gas mixtures. The system is controlled by a microprocessor and is capable of delivering accurate flows and concentrations of gases over the ranges commonly used in anaesthesia. Since the flow produced by the valves is pulsatile, a system for mixing the gases and smoothing the pulses is described. A back pressure regulator is fitted downstream of each of two mixing/damping chambers and a method of using this as a flow transducer is described. The advantages of this system over conventional rotameters are discussed.

MATERIALS AND METHODS

Apparatus

A schematic diagram of the gas mixing apparatus is shown in figure 1. A Z80-based microprocessor electronic control board activates two electromagnetic solenoid valves (Festo type MFH-2-M5), which are connected to oxygen and nitrous oxide gas supplies at pressures approximately 300 kPa (42 psi) greater than atmospheric. After leaving its respective solenoid valve each gas is fed through a choke. The gases then pass through two gas-mixing surge damper chambers, each of which produces a constant back pressure at its outlet.

Solenoid valve–choke combination

When the solenoid valves are activated and are “open”, supply gas flows through these, and the two chokes—which are housed in an aluminium block to maintain both at the same temperature. Since the upstream gas pressure is set, by the use of additional pressure regulators, at approximately 400 kPa absolute, and the downstream pressure is approximately 120 kPa absolute, the flow through the chokes will be sonic and will, therefore, be unaffected by small downstream fluctuations in pressure (Wallace et al., 1978). (The condition for sonic flow is that upstream absolute pressure must be at least twice that of the downstream pressure,
If either solenoid valve is pulsed "open" for short, equal periods, the same gas volume will be delivered. The total flow may, therefore, be varied by altering the pulse frequency. Since the gas flow through each choke is sonic, pressure fluctuations downstream caused by the opening and closing of one valve should not affect the pulse volume delivered by the other. Furthermore, since the two chokes are maintained at the same temperature, the ratio of pulse volumes for the two gases delivered by the valves remains constant.

The actual gas volume delivered in each pulse depends on the physical properties of the gas in question. For ideal gases, with a perfect orifice and with equal pulse "open" times, the ratio of the pulse volumes of the two gases \( R_{12} \) is given by

\[
R_{12} = \left( \frac{M_2}{M_1} \right)^{1/2}
\]

where \( M_1 \) and \( M_2 \) are the respective molar masses of the two gases.

However, in practice, orifices may not be perfect, and the viscosity of the gas may affect the pulse volume delivered by the solenoid valve–choke combination. It was, therefore, necessary to calibrate each solenoid valve–choke combination for the particular gas with which it was to be used.

These characteristics were investigated for 100% oxygen and 100% nitrous oxide by pulsing the valves "open" for periods of 100 ms, at frequencies which varied between 0 and 8 Hz. The total gas volume delivered by the solenoid valve–choke, at a given frequency, was measured over a period of 1 min, using a 6-litre wet-gas spirometer (P. K. Morgan Ltd) and from this the flow rate was calculated. Volume could be measured to an accuracy of 20 ml. The pulse "open" time of 100 ms was chosen because it was long enough for the valve opening transients (about 10 ms) to be considered unimportant and short enough to supply a pulse volume (approximately 30 ml) which would give good resolution in total gas flow and in the concentration of gases in the mixture.

Software

During the initial valve-testing procedures, the valves were controlled by a Nascom (Z80-based) microcomputer. In practice, the total gas flow and the mixture concentrations were decided \emph{a priori}, and a BASIC program calculated the corresponding flow of each gas which was required to produce the specified values. Knowing the flow characteristics for each valve–choke–gas combination, the pulsing period for each valve was calculated and was stored in memory, ready to be
used by the program (in Z80 Assembler code) which was used to drive the valves. Since the Nascom microcomputer did not have a counter/timer unit, a 10-ms delay routine was incorporated into the assembler language program, and was used as a timer.

For generating binary-gas mixtures, as described in this paper, bits 0 and 1 of the data output from the computer were used to drive the solenoid valves, the valves being switched "open" when the corresponding bit was high. The use of 10 ms as the basic unit of time in the program obviously limited the resolution available, since the pulsing periodic time (the inverse of the pulsing frequency) had to be chosen to the nearest 10 ms. For accuracy greater than that required in these studies, the "open" time could have been reduced.

**Mixing chamber surge dampers**

Since the solenoid valves obviously produced very pulsatile gas flows, a gas-mixing chamber was incorporated to the system to ensure the constancy of the gas concentrations delivered. Furthermore, since a practical system must deliver a constant flow rate, the gas flows from the valves were "smoothed" with a two-stage surge damper.

![Diagram](image)

**Fig. 2.** A schematic diagram showing a single gas-mixing chamber and flow surge damper in vertical and horizontal cross section.

A schematic diagram depicting horizontal and vertical cross-sections of a single gas-mixing surge damper chamber is shown in figure 2. The mixing chamber is cylindrical in shape, with a volume of approximately 250 ml, and the gases enter tangentially in opposite directions. This means that each gas tends to produce an opposing toroidal flow, which increases the efficiency of gas mixing. In order to absorb the fluctuations in incoming gas pressure, the top wall of the chamber consists of a rolling diaphragm which is secured across the chamber, and which is attached to a spring-loaded piston. This device acts as the mechanical analogue of an electrical capacitor, and smooths out the pulses in pressure generated by the solenoid valves. A second stage damper (fig. 1) helps eliminate the pressure fluctuations even further.

**Back pressure regulator**

The outlet pressure from each mixing chamber/surge damper was maintained at a constant value of 100 cm H₂O (9.81 kPa), by means of a variable orifice valve. A cross-section of one of these valves is shown in figure 3, and their positions in the system are shown in figure 1.

The valve works, in essence, like the float of a conventional rotameter, with a tapered column housing a tapered bobbin, attached to a weight. Gas entering causes the bobbin to rise to an equilibrium position where the gravitational force exerted on the weight equals the force exerted by the incoming gas pressure. The mass and geometry of the valve system are such that a
constant pressure of 100 cm H₂O (9.81 kPa) is maintained at the outlet of each mixing chamber.

**Flow transducer**

Since the vertical position of the bobbin of the variable orifice valve is related to gas flow (as in conventional rotameters), a displacement transducer is connected to the top of the valve, and generates an electric signal in relation to total gas flow. The transducer comprises a ferrous rod moving within an assembly of three coils, making a linear variable differential transformer (LVDT). This LVDT is connected to phase- and amplitude-sensitive circuitry to produce a d.c. voltage proportional to flow.

**Experimental Procedure**

Gas volumes were measured with a 6-litre wet-gas spirometer, and gas flow was calculated by measuring displaced volume over a given time. Gas concentrations for oxygen and nitrous oxide were measured with a Centronic MGA 200 medical gas mass spectrometer, with oxygen and nitrous oxide measured on mass numbers 32 and 30, respectively. A subtraction box, of design similar to that described by Davis and Spence (1979), was used to correct for the interference of nitrous oxide with the oxygen signal, and the spectrometer was used in the ASC (automatic sensitivity control) mode. Room air and 100% nitrous oxide were used to calibrate the mass spectrometer.

**Flow rate v. frequency**

The variation in flow rate, delivered by the whole system with pulse frequency was determined separately for oxygen and nitrous oxide. The frequency was varied between 0 and 8 Hz so that flow rates of up to 14 litre min⁻¹ could be obtained for either gas.

**Gas concentration–flow rate characteristics**

The system depicted in figure 1 was used to investigate the ability of the total system to provide accurate mixtures of oxygen and nitrous oxide and predetermined total gas flow rates. Initially, the Nascom microcomputer was programmed so that the system would deliver 20% v/v oxygen in nitrous oxide at total flow rates of 4, 8, 12 and 16 litre min⁻¹. The actual oxygen concentration delivered by the system at each flow rate was measured with the mass spectrometer, and the procedure was repeated as the oxygen concentration.

**FIG. 4.** A plot of the flow rates obtained through a single solenoid valve-choke combination for oxygen and nitrous oxide. The abscissa shows the pulse frequency applied to the solenoid valve. The straight line through the origin was fitted by eye.

**TABLE I.** Actual concentrations of oxygen produced by the gas mixer, at the different oxygen concentrations and total gas flow rates set by the microprocessor.

<table>
<thead>
<tr>
<th>SetO₂ (%)</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>21.3</td>
<td>20.9</td>
<td>21.1</td>
<td>20.9</td>
<td>21</td>
</tr>
<tr>
<td>30</td>
<td>30.4</td>
<td>29.6</td>
<td>29.9</td>
<td>30.7</td>
<td>29.8</td>
</tr>
<tr>
<td>40</td>
<td>39.8</td>
<td>39.3</td>
<td>40.1</td>
<td>40</td>
<td>40.1</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>49</td>
<td>49.9</td>
<td>49.7</td>
<td>49.3</td>
</tr>
<tr>
<td>60</td>
<td>60</td>
<td>59.1</td>
<td>59.7</td>
<td>59.5</td>
<td>59.8</td>
</tr>
<tr>
<td>70</td>
<td>69.7</td>
<td>69.1</td>
<td>69.6</td>
<td>70.3</td>
<td>69.5</td>
</tr>
<tr>
<td>80</td>
<td>79.6</td>
<td>79.6</td>
<td>79.8</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>90</td>
<td>88.9</td>
<td>89.8</td>
<td>89.9</td>
<td>89.8</td>
<td>89.5</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
concentration was increased in 10% v/v steps up
to 100% oxygen (in this case, the nitrous oxide
delivery solenoid valve was switched hard “off”).

Second, the total gas flow rate was tested when
the system was delivering either a 21% oxygen–79% nitrous oxide mixture, or 100% oxygen, by programming the Nascom microcom-
puter to produce total gas flow rates of 4, 6, 8, 10,
12, 14 and 16 litre min^-1. The actual flow rates
delivered by the system were measured with the
wet spirometer at each predicted flow rate.

Finally, the program was set to deliver a
50:50 oxygen in nitrous oxide gas mixture, and
the mass spectrometer recorded the oxygen and
nitrous oxide concentrations as a function of time.
Total gas flow rate was varied between 2, 5, 10 and
16 litre min^-1. Concentrations of 50% were
chosen since this was where the maximum
fluctuations occurred, because the valves tended
to open and close in phase with each other.

Recordings of the stability of flow rate with time
were obtained by connecting a Fleisch pneumo-
tachograph (Gould flow transducer No. 0 con-
ected to a Validyne pressure transducer model
MP 45–14) to the output of the system, and
recording the changes in flow rate on a Watanabe
Model WR3101 hot-wire pen recorder.

RESULTS

Figure 4 shows the flow rates delivered by the
system for 100% oxygen and 100% nitrous oxide,
plotted as a function of the pulse frequency. A
linear relationship was demonstrated in both
cases, although the slopes of the two lines were
different as a result of the different viscosities and
densities of oxygen and nitrous oxide (18.9 and
13.5 Pa s and 1.429 and 1.977 kg m^-3).

Table I demonstrates that the system will
deliver accurate concentrations of oxygen in
nitrous oxide over a wide range of flow rates.
Figure 5 demonstrates that the system will deliver
total flow rates very close to those set by the
computer algorithm. The ratio of “measured to
set” flow rates was 1.01 between 4 and 16 litre
min^-1 and deviations from the set values were only
apparent for 100% oxygen at flow rates greater
than 12 litre min^-1. Figure 6 shows how the oxygen
concentration varied with time at several total flow
rates between 2 and 16 litre min^-1. At low flow
rates (around 2 litre min^-1) there was a notice-

Fig. 5. A plot of the measured flow rates delivered by the completed system, against the flow rate set
by the computer, for 100% oxygen and for a 21% oxygen in 79% nitrous oxide mixture. The straight
line is the line of identity.
able fluctuation in the oxygen concentration with time, but this variation was small (±1%) and would be acceptable in clinical practice.

Figure 7 demonstrates that the variation in flow rate with time also appeared to be quite large at low flow rates. In general, these fluctuations took place over very short time intervals and when the total gas flow was fed into an anaesthetic bag, no pulsing could be detected by hand. The long term fluctuations seen at 2 litre min^-1 were caused by the fact that the two valve periods were very close and this meant that beats were produced.

### DISCUSSION

The system described forms part of a new anaesthetic/ventilation machine, which will be described subsequently. Figure 5 demonstrates that, when examined singly, the solenoid valve–choke system will produce predictable gas flow rates over a wide range of flows. Taken together, table I and figure 5 also demonstrate that accurate and predictable binary gas mixtures can be produced.

One advantage of controlling gas flow by computer is that it is possible to incorporate routines to the software to maintain oxygen concentration and total gas flow rate at or above their accepted minima. It is also possible to use the apparatus to produce either oxygen in air or oxygen in nitrous oxide mixtures, as would be required in an anaesthetic machine.

At present, anaesthetists have to rely on conventional rotameters for calculating oxygen concentration and total gas flow rate. Inaccuracies can be caused either by misreading a rotameter, or by a rotameter fault. The latter can be the result of several factors, including static electricity, leakage and back pressure in the system. The pulsed electromagnetic solenoid valve system eliminates these sources of inaccuracy and enables the operator to set directly the indices of interest—oxygen concentration and total flow rate.

The problem of fluctuations at low flow rates could be reduced by using shorter “open” times for the solenoid valves and, hence, a greater pulse frequency. This improvement would be at the cost of a reduced valve life, since the valve would be opening and closing more frequently. Since the valves have a life expectancy of greater than 10⁸ operating times, this might appear to be of no consequence. Rough calculations indicate that the operating mode described in this paper would...
result in a life expectancy of about 5 years for a single valve, if the system was used in an anaesthetic machine for about 5 h each day, 7 days a week.

Other applications of this system are possible. By using more than one valve in parallel, and by modifying the software, total gas flows in excess of 40 litre min⁻¹ can be generated. This has already been achieved in our laboratory. Furthermore, several valves can be combined to make tertiary or quadruple gas mixtures for laboratory calibration purposes. This system is also at work in our laboratory, at a much lower cost than conventional gas mixing pumps, and with the advantage that a wide range of gas flows can be produced.

ACKNOWLEDGEMENTS

The project, of which the work described in this paper forms a part, was supported by an M.A.P. award from the Department of Industry and is supported by the D.H.S.S. Mrs L. Sutton contributed to some of the early stages of the development work described in this paper.

REFERENCES