A VERSATILE CLOSED CIRCUIT

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SUMMARY

A versatile closed circuit with new features is described. It may be used in a totally closed manner, without continuous gas inflow. As gas is absorbed from the circuit, it is replaced through a demand valve. Facilities for continuous gas input and use of a ventilator are included, and one control converts it to a non-rebreathing circuit. The circuit has excellent mechanical characteristics in all modes, and has been used extensively in routine clinical practice.

The use of closed circuit anaesthesia is frequently suggested as a method of reducing atmospheric pollution by anaesthetic gases. In practice, however, truly closed circuits are very rarely used. Normally a flow of fresh gas is fed into a circle system with carbon dioxide absorption. This gas flow invariably exceeds patient requirements and the excess gas is spilled from the circuit.

A totally closed circuit was described by Bushman and others (1977) in which the fresh gas requirement was obtained by use of a demand valve activated by sub-atmospheric pressure in a circle system after gas absorption from the circuit. One circuit configuration which utilized this principle used a self-inflating Oxford bellows in order that manual ventilation, as well as spontaneous ventilation could be undertaken. However, the mechanical characteristics of this circuit proved unsatisfactory. The work required for spontaneous ventilation when the circuit was used by conscious volunteers was too great to be tolerated for more than a few minutes.

Consequently a new circuit was designed, the characteristics of which are described here. Fresh gas flow is obtained by delivering mixtures of nitrous oxide and oxygen on demand during spontaneous ventilation or intermittent positive pressure ventilation (IPPV). If desired, a continuous low flow of oxygen may be added in a similar way to fresh gas supply in conventional closed circuits.

THE CIRCUIT

The circuit is of normal configuration (fig. 1). Continuous gas supply into the circuit passes through a low-flow oxygen meter (8). Nitrous oxide with or without oxygen may only enter the circuit as a result of the opening of demand valve (7) in response to sub-atmospheric pressure in the circuit.

The circuit has comprehensive leak-proofing to allow totally closed use, but may be switched to a non-rebreathing system by use of a single valve (3, fig. 2) mounted near the bellows. All the valves, and the soda-lime canister are mounted near the bellows for compactness, and to allow light-weight patient connections (fig. 2).

A blow off valve is provided to ensure that the pressure in the circuit can not increase to greater than 40 cm H₂O (1, fig. 1).

Bellows design

The key to achieving maximum efficiency is the design of the bellows (fig. 2). There are two opposing springs, one controlling the expansion of the bellows and the other its contraction.

The bellows bag itself is made of a light silicon rubber (Bennett Ventilator part No. 1650). It has a metal base-plate, the centre of which is connected to the two springs. The internal one (1, fig. 2) is a constant force spring (Tensator type No. BA 274), with a force calculated to be slightly greater than the weight of the bellows and base-plate. This minimizes the work involved in moving the bellows. On
the outside of the bag is a spring obeying Hooke's Law (8, fig. 2). This is arranged to balance the slight lifting force on the bellows at a resting position giving the bag a volume of 700 ml. Displacement of the bag upwards from the resting position results in a restoring force which increases with increasing displacement.

Thus, during IPPV, as gas is extracted from the circuit the return of the bag to resting position will generate a sub-atmospheric pressure sufficient to open the demand valve, restoring circuit volume.

During spontaneous ventilation, as gas is absorbed from the circuit, the patient will be unable to obtain a normal inspired tidal volume from the bellows without the bellows entering an area of decreasing compliance, thereby generating a sub-atmospheric pressure sufficient to open the demand valve and restore circuit volume.

Eight stainless steel tubing rings are used in the bellows to maintain its shape during ventilation. The bellows is placed in a Penlon Ventilator casing. A Bird Mark 8 Ventilator is connected to the outlet of the casing to allow for automatic ventilation. The connection has a T-piece in it, closed by a cap for IPPV, open during spontaneous ventilation.

**Demand flow inlet**

The demand flow is controlled by a modified Entonox valve, which delivers to the circuit nitrous oxide or oxygen or any preset mixture as soon as the pressure on the circuit side of the valve decreases to less than $-1.4 \text{ cm H}_2\text{O}$. The gas supply to the valve is controlled by the main Rotameters and the valve functions well if these are set to allow flows of at least 10 litre min$^{-1}$. 

![Diagram](image-url)
For monitoring purposes, the demand flow passes through a dry gas pneumotachograph head before entering the circuit at the top of the bellows.

Low flow oxygen inlet system
This allows oxygen to be delivered to the circuit, at a constant flow rate. The rate of flow is set using a low-range (1 litre min⁻¹) Rotameter of high accuracy (GEC Marconi Process Control type No. 1100-VAA-300).

The oxygen passes through a flow-limiting valve (13, fig. 1) preset to a maximum flow rate of 400 ml min⁻¹, and enters the closed-circuit at the top of the bellows.

Soda-lime canister
This is a Penlon canister (Type No. 52522), placed in the expiratory limb of the circuit. One of its connections is directly to the patient and the other to the top of the bellows through a flap valve (Ambu Hesse type).
Non-rebreathing facility
A non-rebreathing facility is included so that changes in circuit gas can be made rapidly. A control valve (3, fig. 2) operates so that all expired gas is vented to atmosphere or exhaust system. Fresh gas is drawn into the circuit through the demand valve during late inspiration, and as the bellows returns to rest during expiration. During non-rebreathing with IPPV the expiratory port is closed during inspiration by a Bird Pneumatic valve (No. 338).

Operation
The overall operation of the circuit can best be described by considering one breathing cycle
During IPPV, expired gases are returned to the bellows through the soda-lime absorber. The bellows expand to a constant resting position so that a shortage of volume produced by the absorption of circuit gases results in sub-atmospheric pressure which opens the demand valve. Gas flows in through the demand valve to restore resting circuit volume.
During spontaneous ventilation demand occurs at end inspiration as the bellows enters a less compliant region (see above). If a constant flow of gas is supplied through the Rotameter, the volume of gas demanded to replace the absorbed gases is reduced.

METHOD
Experiments
Simulated spontaneous ventilation. For these studies a mechanical pump was placed at the patient connection of the closed circuit to simulate spontaneous ventilation. This pump generated a sinusoidal flow, and for these experiments breathing rates of 12 and 14 per minute were simulated, with tidal volumes of 450 and 800 ml. The pump was connected to an extraction pump via a Rotameter. In this way, it was possible to extract different gas flows from the system in order to simulate uptake by the body. Extraction rates of zero, 200 and 800 ml min⁻¹ were used. This could be used to illustrate the functioning of the demand action in the circuit.

Spontaneous ventilation by volunteers. Five volunteers (four male) all fit and between 20 and 30 yr and 54–75 kg were studied. They breathed into the totally closed circuit, using a mouth-piece and noseclip. The circuit was filled with air and oxygen was supplied on demand. The volunteers breathed into the circuit for at least 15 min, and their subjective comments were recorded at the end of the experiment.

IPPV. A model lung (Manley lung ventilation performance analyser) was attached at the patient connection, and was set to have a compliance of 50 ml cm H₂O⁻¹ with zero airway resistance. The performance of the circuit using IPPV was examined, as both a totally closed circuit and a non-rebreathing circuit.

Observations
The general method assessing the work of breathing in a closed circuit will be discussed by Greer (in preparation).

The pressure (P₁) at the patient connection was measured with a physiological pressure transducer (Gould, Model P50) at position 10 (fig. 1). The pressure on the circuit side of the demand valve (P₂) was monitored by a similar transducer at position 11 (fig. 1).

The flow signal at the mouth (V₁) was obtained using a heated Fleisch No. 2 pneumotachograph placed in the patient connection (12, fig. 1) in conjunction with a micromanometer. The demand flow reading (V₂) was collected from a dry pneumotachograph head in the demand inflow (6, fig. 1) connected to an appropriate micromanometer. Continuous records of pressures and flows were obtained from an eight-channel chart recorder (Grass Polygraph) and data were gathered for subsequent processing on an Analogue Tape Recorder (Tandberg Model 1600 S3).

The pressure and flow transducers were calibrated against a water manometer and certified Rotameters, respectively, before each set of experiments were carried out, and the calibrated signals read on to magnetic tape at the beginning of the experimental session. During tests selected sections of pressure and flow data were recorded for the various experiments. These sections were selected after time had been allowed to reach stability of circuit behaviour.

Data analysis
This information was transferred directly into a Nova computer (Data General) and the data processed using programs developed in this department. The routines used synchronize the different sets of data to allow study of each breath independently. The programs derive volumes by integrating flow–time curves. This numerical information was then plotted as a variety of graphs including flow–pressure loops, volume–pressure loops and volume–differential pressure loops. This method of
analysis allows the allocation of various elements of the total work involved to specific components of the circuit and connections to the circuit.

RESULTS

Closed circuit, spontaneous ventilation

For assessing the mechanisms of the circuit, the most important readings obtained are those from the patient connection. Figure 3 illustrates the changes in pressure, flow and volume with the time at this point, obtained in one volunteer using a closed circuit. Figure 4 illustrates the pressure–volume loop for one breathing cycle derived from these. By calculating areas $A_1$, $A_2$, $A_3$ and $A_4$, the work done in the various parts of the cycle can be found. The sum of the whole equals the total work involved: $A_1 + A_2$ is the work in inspiration, $A_3 + A_4$, the work in expiration. The work done by the patient is $A_2 + A_4$ and that by the bellows $A_1 + A_3$.

Table I lists the results obtained in the volunteer studies and also gives the results from a single experiment with simulated spontaneous breathing (12 cycles per min, 450 ml tidal volume, extraction rate of 200 ml min$^{-1}$). Results using faster rates and larger volumes did not vary in form.

Figure 5 illustrates volume change against the pressure differential between $P_2$ and $P_1$ (inside the bellows and at the patient connection). This curve allows calculation of work done in overcoming circuit resistance. $A_5$ gives the work involved in inspiration and $A_6$ the expiratory component. These are also included in table I.

Figure 6 illustrates the pressure changes occurring in the bellows ($P_2$) during a respiratory cycle, together with flow pattern in the demand flow inlet ($V_2$) and derived volume entering the circuit. The function of the demand valve is seen, opening at $-1.4 \text{ cm H}_2\text{O}$, reflecting some hysteresis in the

![Graphs showing pressure, flow, and volume changes over time.](image-url)
valve. In this case the delivery of gas lasts for 1.5 s and the volume delivered is 46 ml. When simulated spontaneous ventilation without gas extraction was used, no gas was demanded into the system, indicating highly effective leak-proofing.

**Non-rebreathing system**

Figure 7 illustrates a pressure–flow loop at the patient connection ($P_v, V_v$), before and after switching the circuit from closed to non-rebreathing during simulated spontaneous ventilation (12 cycles per min, 450 ml tidal volume, 200 ml min$^{-1}$ extraction). The loop obtained during non-rebreathing was similar to that obtained using a Mapleson A system (Smith, 1961).

The work involved in these conditions is very similar, whether the circuit is closed, or non-rebreathing. In the latter case, extra work involved was 137 mJ per cycle, with the bellows contributing a negligible amount. The inspiratory work (116 mJ

| Table I. Closed circuit studies with spontaneous ventilation. All units of work in mJ |
|-----------------------------------|-----|-----|-----|-----|-----|-----|-----|
| Volunteers                        | A   | B   | C   | D   | E   | Mean | Simulation |
| Breaths per minute                |     |     |     |     |     | 12   | 12          |
| Extra work per breathing cycle    | 15  | 13  | 7   | 10  | 15  | 12   | 12          |
| Work done in inspiration          | 101 | 145 | 189 | 141 | 188 | 133  | 113         |
| Work done in expiration           | 42  | 58  | 98  | 56  | 83  | 68   | 71          |
| Work done by bellows              | 59  | 87  | 91  | 85  | 105 | 85   | 42          |
| Work done by patient              | 2   | 3   | 11  | 16  | 7   | 8    | 3           |
| Total work used in breathing against circuit resistance | 99  | 142 | 178 | 125 | 181 | 145  | 110         |
| Inspiratory work used in breathing against circuit resistance | 57  | 88  | 83  | 86  | 117 | 86   | 48          |
| Expiratory work used in breathing against circuit resistance | 26  | 54  | 58  | 47  | 70  | 51   | 42          |
| Mean tidal volume (ml)            | 266 | 334 | 576 | 489 | 259 | 385  | 450         |
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FIG 6 Pressure at bellows (solid line upper diagram), flow at demand inlet (pecked line upper diagram and integrated flow (volume) at demand inlet (lower diagram) v time. From the volume trace we can see that 46 ml of oxygen are delivered per breath (therefore 322 ml min⁻¹).

per cycle) is relatively much greater than during closed circuit use, reflecting a higher (smaller volume) end-expiratory position of the bellows, with the work of inspiration occurring against an increased extension of the Hooke’s law spring.

IPPV

During IPPV the circuit behaved as expected, in line with previous experimental experience. Pressures, flows and volumes reflected the ventilator settings. Inspiratory work is of course irrelevant, but is similar to that required for spontaneous ventilation. Expiratory work was very small indeed, varying with tidal volumes used. With a tidal volume of 450 ml, total expiratory work was 35 mJ, of which 21 mJ was contributed by the bellows action.

Clinical experience

The circuit as described is mounted on a trolley with the Bird ventilator fixed to the top. The bank of precision Rotameters is mounted at the rear. Pipeline oxygen and nitrous oxide are fed to the back of the trolley with back-up cylinders and reducing valves. A control for non-rebreathing mode or closed circuit use is positioned at the front of the trolley.

The circuit is initially flushed in the non-rebreathing mode with a mixture determined by the setting of the Rotameters, which in the closed circuit mode supply the demand valve. Thus the demand valve can be supplied with a predetermined mixture of nitrous oxide and oxygen, oxygen alone, or nitrous oxide alone. In the last case a low flow of
FIG. 7. Flow—pressure loop for totally closed circuit (solid line), and semi-closed circuit (pecked line). Conditions: tidal volume 450 ml, 12 b.p.m. and 200 ml of gas extracted per min.

oxygen is fed into the circuit from the special low flow oxygen Rotameter.

Unless the nitrogen content of the functional residual capacity (FRC) is previously eliminated, within minutes after connection the closed circuit will contain an appreciable concentration of nitrogen. By temporarily selecting the non-rebreathing mode, this nitrogen can be flushed out of the system. We have found the most effective flushing regimen to be 20 breaths within the first 3 min.

Our clinical experience is similar to that of Barton and Nunn (1975) in that, after FRC washout, circuit nitrogen build-up is not a problem. However, to keep the concentration less that 5%, we would recommend flushing for 10 breaths every 30 min.

The volume of the circuit in addition to the patient's FRC is approximately 8 litre. This large volume is such that changes in concentration occur slowly, and not surprisingly we have not found any difficulty maintaining steady circuit gas concentrations.

We have used this circuit in clinical practice for nearly 2 yr. Routine unselected use during a general surgical operating list has shown that after initial familiarization it is easy to use with either spontaneous ventilation or IPPV.

More than 200 patients aged between 17 and 81 yr and mostly undergoing major surgery, have been anaesthetized using the circuit. Duration of anaesthesia in these cases ranged from 40 min to 6.5 h.

In the majority of patients (more than 70%) anaesthesia was maintained with 60–75% nitrous oxide in oxygen, with narcotic analgesic supplement, muscle paralysis and IPPV, although the circuit was switched to spontaneous ventilation mode after antagonism of the muscle relaxant. In the minority of patients, including all those in whom spontaneous ventilation was allowed throughout, the circuit was used to deliver oxygen only, with in-circuit vaporization of halothane or enfurane.

When we have used nitrous oxide and oxygen alone in the circuit, we have used one of two basic methods. After a short non-rebreathing period we set a mixture of nitrous oxide and oxygen to be delivered by the demand valve, adjusting the concentrations as required. Usually however, we have supplied a small constant flow of oxygen (the estimated oxygen uptake for the patient), and supplied only nitrous oxide on demand.

When nitrous oxide is being used in the circuit, a

FIG. 8. Halothane concentrations measured at Y-connector of patient undergoing anaesthesia on the closed circuit (IPPV). The first section of the trace (paper speed 180 cm h⁻¹) shows effect of setting the vaporizer to the 2% mark for 17 breaths. Paper speed was then reduced to 60 cm h⁻¹ concurrently with the vaporizer being reset to 0.5%. The trace remained stable, with end-expired halothane of 0.8% to the end of anaesthesia, which was approximately 1 h.
simple oxygen analyser can reassure the anaesthetist that an hypoxic mixture is not being delivered, and use of our flushing regimen, ensures that nitrous oxide concentrations are maintained.

When the circuit is being used to deliver oxygen and halothane or enflurane mixtures, we have used a low resistance draw-over vaporizer (Oxford Miniature Vaporizer) in circuit (not recommended by the makers) to produce remarkably consistent halothane concentrations, even with IPPV. Figure 8 shows that a short period of overpressure at the onset of anaesthesia helps produce these stable concentrations.

Circuit halothane concentrations can be readily monitored using an appropriate monitor. We use the EMMA (Engstrom Medical AB). Oxygen is usually admitted on demand, but a low constant flow may be supplied to reduce demand function if this is preferred.

Details of the performance of this circuit, with nitrous oxide-oxygen, and oxygen-volatile anaesthetic mixtures will be reported elsewhere. At present, when using an in-circuit Oxford Miniature Vaporizer, it is considered essential to monitor volatile anaesthetic concentrations continously.

The circuit has proved to be effective, reliable and versatile in routine clinical practice. We have only used the techniques outlined above, but other combinations are possible. There has been no instance of failure of any part of the circuit, nor has its use ever led to dangerous circumstances.

CONCLUSIONS

The circuit described has been shown to be an effective, versatile circuit, capable of being used in a totally closed or non-rebreathing manner. The analysis of its mechanical characteristics shows the system to be extremely light in action in all circumstances, a fact confirmed by opinions of the volunteers studied. This favourable impression of the function of this circuit has been reinforced by extensive clinical use. The ability to use a totally closed circuit has also facilitated clinical studies of gas uptake during anaesthesia. Subsequent experience has also confirmed that the circuit has remained substantially leak-free in normal clinical use, rendering totally closed circuit anaesthesia without continuous gas inflow a practical possibility for the future.

REFERENCES

