ANAESTHETIC APPARATUS
A Pictorial Review of the Development of the Modern Anaesthetic Machine
BY
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Though Hewitt (1893) had described an apparatus for the administration of nitrous oxide and oxygen in the closing years of the nineteenth century, the first practical “anaesthetic machines” were developed in the next decade. Such an apparatus is illustrated in figure 1.

More elaborate and reliable machines were subsequently introduced (fig. 2) until in the period immediately following the 1939-45 war the modern continuous-flow apparatus (fig. 3) had emerged.

REDUCING VALVES

The introduction of pressure-reducing valves—“pressure regulators” in the United States—greatly improved the performance of anaesthetic machines. These valves reduce the high but variable pressure within the compressed-gas cylinder to a low but constant pressure, which is maintained even when the flow of gases from the cylinder is of the order of 10 l./min or more. The principles of the design of such a valve are illustrated in figure 4 and the balance of the forces within the valve in figure 5. Figure 6 shows how these principles are incorporated into the design of a commercial reducing valve.

A good regulator which has been adjusted to the point at which the reduced pressure has a value of 1 atmosphere (= 14.7 Lb./sq.in gauge) should maintain this pressure within 10 per cent or even more closely, while the pressure in the cylinder falls from 130 to 10 atmospheres. The constancy of flow rates delivered from a regulator is more difficult to predict. In an ideal situation opening the needle valve at the far end of the low-pressure system should result in a corresponding inflow of gas from the cylinder so that the reduced pressure remains practically unaltered. For flow rates of up to 5 or more litres per minute this, in fact, happens with a good regulator, but at high flows there is a gradual decrease in the rate of flow from the cylinder as it empties while the needle valve is left in the same position. High flow rates...
at low pressures are best derived from two-stage reducing valves which operate via intermediate pressures of about 10 to 20 atmospheres (cf. Entonox valve, p. 687).

FLOWMETERS

The flowmeters on the early anaesthetic machines worked on the "water sight-feed" principle (fig. 7). Later the "dry bobbin" flowmeter was adopted widely (fig. 2). The principle on which one version works is shown in figure 8, namely that the weight of the bobbin is balanced by the frictional resistance to the flow of gases through the space between the bobbin and the walls of the tapered tube in which it rides.

Modern Rotameters are illustrated in figure 9; they work on the same principle as the dry-bobbin meter. The flutes around the upper edge of the float ensure its rotation, thus preventing it from sticking to the bore of the glass tube. The resistance to the flow of gases through the annular space between flutes and tube is mainly determined by their viscosity in the lower ranges of these Rotameters. In the higher flow ranges density of the gas tends to have a decisive influence on the resistance. Because the viscosities of helium and oxygen are practically the same, it is possible to measure in the lower ranges of an ordinary oxygen Rotameter flow rates of mixtures of these gases quite accurately.

When examining the graduations on a Rotameter used on anaesthetic machines (fig. 10a) compression of the intervals in the upper part of the tube is observed, even if this has a constant, linear taper throughout its bore. One reason for this uneven scale is that the area of the annular space does not increase linearly when the float moves up the tube; in other words, equal movements along the tube do not lead to constant increments but to steadily increasing increments in

FIG. 2

Continuous-flow machine showing main components. The valves on the reserve cylinders at the left are shut. Adam's type regulator on nitrous oxide cylinder and Endurance type on oxygen cylinder. Bank of two dry-bobbin meters with fine adjustment valves at bottom. Two simple bottle vaporizers rigidly attached to outlet from flowmeters, followed by Magill attachment with its rubber bag connected at inlet to corrugated breathing tube (c. 1935).
area. Consequently, graduations corresponding to constant increases in flow rate come closer together when moving from the bottom to the top of the tube. If the taper is not constant throughout the length of the tube it is possible to increase the range of such a flowmeter without losing discrimination for low flow rates (fig 10b). The same holds for the ball-type flowmeter illustrated in figure 11.

Compression of a gas increases its density, and during intermittent positive pressure respiration variable area meters become inaccurate, particularly near the upper part of their range. To prevent this an American manufacturer has placed a needle valve controlling gas flow between the flowmeter and the patient. The float now operates in a region where a constant pressure is maintained by the reducing valve; changes in the pressure in the equipment downstream from the flowmeter have then little effect on its accuracy.

A variable area meter using a small ball float is illustrated in figure 11. The well-known Connell meter utilized two small balls rolling in a tilted glass tube with tapered bore. The use of a pair of ball floats is aimed at reducing any tendency to oscillation in the gas stream.

![Fig. 3](https://academic.oup.com/bja/article-abstract/40/9/636/310455/409683/10455)

Main components of Boyle-type apparatus. Bank of three Rotameters with levers permitting high flows through bypass. The rods projecting into the upper ends of the glass tubes of the Rotameters prevent floats from occluding the outlets. Plunger on chloroform vaporizer is pulled up so that gases pass high above liquid surface. Plunger in adjoining ether bottle pushed down, forcing gases through liquid ether and producing maximum concentration. The bag mount on the Magill attachment is fitted with a stopcock; in "off" position rebreathing is impossible.
Single-stage pressure-reducing valve (simplified scheme). Compressed gas cylinder $H$ (pressure $= P$) supplies gas to low pressure compartment $L$ (reduced pressure $= R$). Flow regulator $T$ partly open. Regulating spring $S$ has been compressed by the screw on the top to adjust the reduced pressure. The large flexible diaphragm $I$ is pushed upwards by the force of the reduced pressure and would pull $B$ tightly against the high-pressure outlet when $T$ is shut.

Section through a commercial pressure-reducing valve. The plunger ($h$) facing the high-pressure orifice is pressed against it by a light spring ($s$); if the main regulating spring ($S$) is fully relaxed, no high-pressure gas can enter the low-pressure compartment. The structure (5) shown at bottom is a safety release valve which is meant to open when the pressure in $L$ rises to excessive values owing to some malfunction of the system.

Balance of forces in a pressure-reducing valve. Area of diaphragm = $A$; that of the small, high-pressure orifice = $a$. When high-pressure gas flows into low-pressure compartment, the value of $R$ and the force $(R \times A)$ rises until it overcomes the compressed spring force $F_s$. For more accurate analysis the small force $(P_{mx} \times a)$ exerted by the high-pressure gas on the occluding plunger has to be taken into account. This, however, is small in comparison with the other two forces which may be of the order of 10 kg weight.
FIG. 7
Principle of water sight-feed meter. The flow rate is indicated by three of the vertically positioned holes passing gas bubbles through the water. Note also bypass stopcock at top of device which is used for supplying high flow rates.

FIG. 8
Variable area dry-bobbin meter. This diagram illustrates the constant pressure drop wherever the float may be situated. (Positions at 3 and 8 l./min are shown.)

FIG. 9
The use of a specific Rotameter for measuring the flow of a different gas. The actual flow rate of cyclopropane is 150 ml/min and is indicated as 90 ml/min by a carbon dioxide meter. Both tubes are meant to represent only the lower part of the complete tubes, where viscosity effects are predominant. The viscosity of cyclopropane is 40 per cent of that of carbon dioxide. The float position in the carbon dioxide meter is therefore 40 per cent less than the actual flow rate of cyclopropane.
In general it is possible to calibrate a Rotameter over a range of ten times, i.e. the lowest accurate reading will be one-tenth of the full scale measurement; cf. nitrous oxide flowmeters with a maximum reading of 10 l./min and a lowest scale marking of 1 l./min.

VAPORIZERS AND CIRCUITS

The more sophisticated vaporizers and inhalers built into anaesthetic machines are described in a separate section of this issue.

The now classical descriptions applied by Mapleson (1954) to the various circuits employed for semi-open anaesthesia—without carbon dioxide absorption—are set out by Sykes (1968) (p. 666). This nomenclature can also be applied to semiclosed circuits in which carbon dioxide absorption is employed (fig. 12), and similar considerations apply to the amount of rebreathing in them. Rebreathing is minimal in the lowermost circuit because the forward sweep of the fresh gases helps to push the carbon-dioxide-laden expired air from the space in front of the soda-lime outwards through the expiratory valve.

The pressure/volume characteristics of the reservoir bag are also of importance. On its elasticity depends the extent to which it will distend before the expiratory valve opens, and therefore the amount of rebreathing which occurs at this stage. In fact such bags readily distend up to nearly their nominal capacity (fig. 13). Above this level, however, they quickly resist any further deformation, with the result that rebreathing from this cause is limited.

FIG. 10
Variable area flowmeters with associated scales. The first two with rotating floats, the third with a ball float guided by parallel ribs (see also fig. 11). The first scale (a) shows the compression of graduations at the upper end which occurs even for a constant inner taper of the tube. (By permission of the Editor of Anaesthesia—after Binning and Hodge, 1967.)
BALL IS GUIDED BY THREE FLATS OVER THE WHOLE LENGTH OF TAPERED TUBE

TRI-FLAT TUBE for low flow rates

Fig. 11

Different flowmeter with ball float used for measuring low flows. Here the ball is guided by three flat parts of the inner walls, but the gap between ball and the other parts of the inner wall gradually increases from below upwards.

Fig. 12

Application to semiclosed apparatus of the nomenclature for semi-open systems. Special case of the to-and-fro apparatus. The upper two schemes correspond to Mapleson’s “C” and “D”, and the lowest to “A”. (A=absorber; B=rebreathing bag; E=expiratory valve; F=fresh gas flow; P=patient.)

(After Barth and Meyer, 1965.)

Fig. 13

Pressure-volume characteristics of a reservoir bag; nominal capacity 2 litres. If the opening resistance of the expiratory valve at the end of a tube leading from this reservoir to the patient (Magill attachment) were 5 mm H₂O, part of the expiration would flow back towards the reservoir until its contents exceeded 1500 ml; at the same time the fresh gas flow also enters the reservoir. The expiratory valve then opens, letting the remainder of the expiration escape to the outside. During this phase, fresh gases flowing into the breathing tube expel part of the expired gases contained in it.
**Fig. 14**

Draw-over inhaler adapted for use with "medical" gases. A connector fitted with a corrugated breathing tube is plugged into the inhaler inlet; the tubing acting as gas store is open to the room. Medical gases from flowmeters are admitted through the small side branch in the connector. There would be a non-return valve nearer to the patient to prevent any rebreathing.

**Fig. 15**

Inflating valve which avoids the use of any organic material or metal springs: Mitchell magnet pattern. During inflation the piston with centrally attached bar magnet is pressed by gas pressure against the expiratory opening of $S_e$ and fresh gases flow to patient through $I$. When the inflation ceases, the repulsion force of the fixed magnet on the left repels the piston which now seals $S_i$ and thereby prevents rebreathing; expired gas flows out through $E$ (Mitchell and Epstein, 1966).

**Fig. 16**

Modern double-purpose valve: Ambu "E" pattern. During inflation the moulded silicon rubber structure $A$ is stretched and occludes the seat and duct leading to a similar structure $C$ which forms the expiratory valve. At the end of inflation $A$ contracts, $C$ expands and permits escape of expired gas. (By courtesy of Testa Laboratorium A/S, Copenhagen, Herlev.)
The T-piece circuit is also described in detail in this issue (Sykes, 1968). A T-piece with large limb volume also finds a place in portable anaesthetic apparatus based on draw-over inhalers (vide infra). These are often designed for atmospheric air as carrier of the anaesthetic vapour, but can be adapted for medical gases (oxygen, nitrous oxide) as follows (fig. 14). A connector fitted to a corrugated breathing tube is plugged into the inhaler inlet; this tubing acts as gas store and is open to the room at its far end. Medical gases are admitted through a small side branch in the connector. The patient inhales anaesthetic vapour mixed with medical gases and air; the proportion of the latter is determined by the ratio of respiratory minute volume to gas flow. As the continuous flow accumulates at atmospheric pressure in the storage tube while the patient exhales through an expiratory valve, this arrangement prevents any pressure fluctuations at the inhaler inlet which could possibly affect the vapour concentration delivered from the inhaler.

**EXPIRATORY VALVES**

One of the factors determining the extent of rebreathing is the opening pressure of the expiratory valve; for this reason it should be as low as possible. Mushin and Mapleson (1954) suggest an ideal value of 0.5 to 1.0 cm H₂O for such valves, though in one hospital where their resistance in actual use was measured, a standard Heidbrink-type of valve fell short of this level of performance (Hunter, 1960).

Modern expiratory valves with better characteristics, and often incorporating a non-return valve, are now available both for artificial ventilation alone (fig. 15) and for the dual purpose of use in both spontaneously and artificially ventilated patients (figs. 16, 17).

**INTERMITTENT FLOW APPARATUS**

Intermittent flow apparatus of the "demand-type" now finds a very limited application, except in dental anaesthesia and in obstetric analgesia (Cole, 1968). The McKesson, the Walton and the A.E. machines were described in some detail recently in relation to dental work (Thompson, 1968). Figure 18 will, however, serve as a reminder of the principles involved.
Certain demand devices incorporate a safety mechanism which stops the flow of nitrous oxide should the oxygen supply fail. Owing to the more complicated structure of intermittent compared with continuous flow apparatus, they need greater attention and are more prone to deliver wrong concentrations (Nainby-Luxmoore, 1967). On the other hand, observations on a Walton V machine have yielded close agreement between the dial reading and the nitrous oxide/oxygen concentrations obtained under various conditions (Smith, 1961).

MODERN PORTABLE APPARATUS

Portable draw-over anaesthetic machines have progressed far from the Oxford ether vaporiser which was described in 1941 by Epstein, Macintosh and Mendelssohn, though this apparatus, with its wide breathing tubes, its vaporizer in which ether was kept at a constant temperature and its reservoir bellows was in many ways a model for all which followed. However, the thermostatic principle has since been abandoned in most modern appliances and has been replaced by thermo-compensation; as its name implies the effect of temperature changes of the liquid anaesthetic are compensated automatically so that the output concentrations remain uninfluenced by the temperature of the liquid anaesthetic. A modern version of a draw-over inhaler is illustrated in figure 19.

The Fluoxair apparatus (fig. 20) delivers halothane, air and oxygen. It is built round a special version of the Tecota inhaler originally designed for trichloroethylene analgesia; it offers an acceptably low resistance to the intermittent flow of gases through it (Mackay, 1965). As in the case

![Figure 19](image_url)
Portable anaesthetic apparatus for use with oxygen-enriched air acting as carrier for halothane vapour. The Fluoxair inhaler, visible at the back, is a development of the Tecota analgesia apparatus. The double purpose expiratory/inflation valve structure in transparent plastic requires the use of double breathing tubes. Concertina bellows for performing controlled ventilation. (By courtesy of Cyprane Ltd., Keighley, Yorkshire.)

of all normal draw-over apparatus, there is no rebreathing as long as the non-return valve on the breathing tube to the patient functions correctly.

An extreme example of a portable, continuous-flow machine (fig. 21) using a premixed gas cylinder (50 per cent nitrous oxide, 50 per cent oxygen) in conjunction with the OMV—an induction unit for halothane (Parkhouse, 1966)—was recently described by Latham and Parbrook (1967). A narrow tube leads from the reducing valve on the Entonox cylinder to the adjustment valve of a small flowmeter unit which is plugged into the inlet of the miniature halothane vaporizer. A Magill attachment is formed by a

Lightweight continuous flow machine using a premixed gas cylinder in conjunction with the OMV induction unit for halothane (after Latham and Parbrook, 1967).
tubular T-piece plugged into the tapered outlet from the vaporizing appliance. The system is completed by breathing tube, mask and expiratory valve; apart from the cylinder, the weight of this apparatus is below 3 kg.

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REFERENCES


ASSOCIATION DES ANESTHESIOLOGISTES FRANÇAIS

POST-UNIVERSITY TEACHING COURSE

SEPTEMBER 14-15, 1968

HOTEL HILTON, AVENUE DE SUFFREN, PARIS

Preliminary Programme

SATURDAY, SEPTEMBER 14

12.30 p.m. Reception lunch
2.00 p.m. Working Session

ANTI-REFLEX DRUGS (NEUROPLEGIA),
Chairman: Prof. P. Huguenard
4.00 p.m. Break
5.00 p.m. Working Session
6.00 p.m. Film:

"GENERAL ANAESTHESIA WITH TARACTAN PALFIUM"

9.00 p.m. Dinner and entertainment.

SUNDAY, SEPTEMBER 15

9.00 a.m. Working Session

PRESENT-DAY ASPECTS OF ARTIFICIAL VENTILATION IN ANAESTHESIOLOGY, Chairman: Prof. M. Cara

1.00 p.m. Lunch

Simultaneous French-English translation

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