Breathing systems

A Timothy Lovell

Abstract

Breathing systems are the fundamental components that couple the patient's respiratory system to the anaesthetic machine, and enable the intermittent respiratory pump to be fed by a continuous flow of gas. Although often consisting of only a few simple components, the correct functioning of these components is vital to the safe conduct of anaesthesia. Valve-based breathing systems have been the mainstay of adult anaesthetic practice for many years, whilst, historically, non-valved systems have been preferred in paediatric practice because of their lower imposed respiratory load. Various classifications of breathing systems are discussed, although that proposed more than 50 years ago by Mapleson remains the preferred choice. Whilst 'rebreathing' is often seen as a bad thing, some breathing systems preferentially allow the recycling of alveolar dead-space gas that has already been warmed and humidified and can hardly be considered to be undesirable. The use of 'circle-type' breathing systems is increasingly supplanting the use of more traditional breathing systems for the maintenance of anaesthesia because of their reduced environmental pollution and much greater economy.

Keywords carbon dioxide absorption; non-rebreathing systems; rebreathing systems

The classification of apparatus used to deliver inhalational anaesthetic agents to a patient has undergone numerous revisions over the years. The classical terms, open, semi-open, semi-closed and closed, were applicable to the use of ether and are now outdated. Small changes in geometry and gas flow rates can lead to conversion from one type to another, causing confusion.

The term breathing system is preferred to the old term breathing circuit, because gases do not flow in a circular path, with the exception of circle systems. A breathing system describes the components and its mode of operation. The terminology can be used generically (e.g. Mapleson A breathing system) or specifically (e.g. Magill breathing system).

Breathing systems are customarily divided into three groups:

- non-rebreathing systems
- systems in which rebreathing is possible
- systems using carbon dioxide absorption.

By convention, rebreathing in an anaesthetic system refers to inhalation of some or all of the previously exhaled gases, including carbon dioxide and water. This is often considered to be a bad thing, but some rebreathing systems allow for the rebreathing of the alveolar dead-space gas, which has already been warmed and humidified and contains no carbon dioxide; hardly an undesirable gas mixture.

Non-rebreathing systems

Non-rebreathing systems contain unidirectional valves to direct the exhaled gases away from the patient. These systems are seldom used during anaesthesia because of the problems inherent in valve design, but are often used in conjunction with a portable ventilator for transporting critically ill patients. The Ruben and Ambu valves are most commonly used during anaesthesia.

The simplest unidirectional valve circuit for spontaneous ventilation is shown in Figure 1. Two valves are required; during inspiration, one valve permits inhalation of fresh gas, while the other prevents inhalation of exhaled gases and ambient air. During the expiratory phase, the first valve closes, preventing contamination of the inspiratory gas supply, while the second valve opens allowing expiration. Theoretically, the dead-space of such a valve can be small and rebreathing can be reduced to perhaps 10–15 ml/breath. The design of the valves is complex, and they are prone to sticking in the open position, which results in rebreathing, or air dilution of the gas mixture. If fresh gas is supplied by a constant-flow anaesthesia machine then either the set flow must exceed the patient's peak inspiratory flow rate, which would be wasteful and tend to cause the valves to stick open, or a reservoir needs to be added to the inspiratory limb upstream

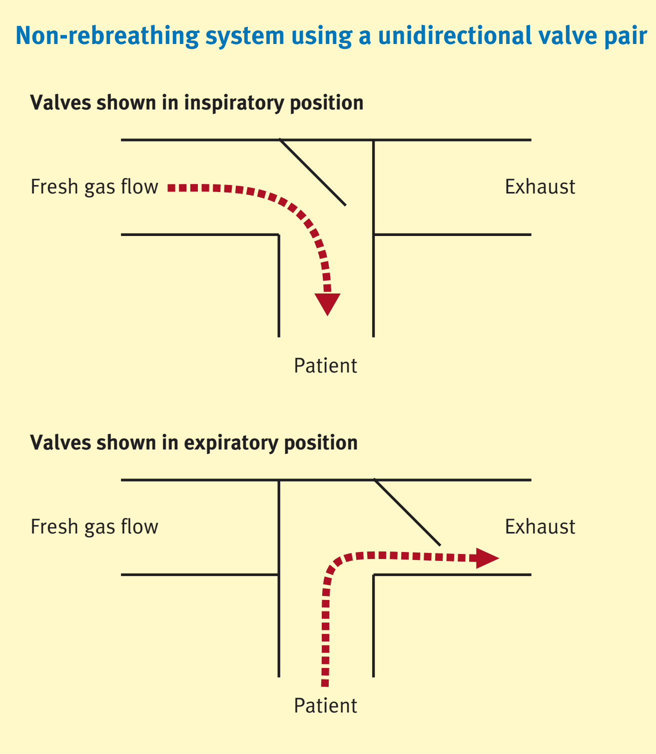

Figure 1

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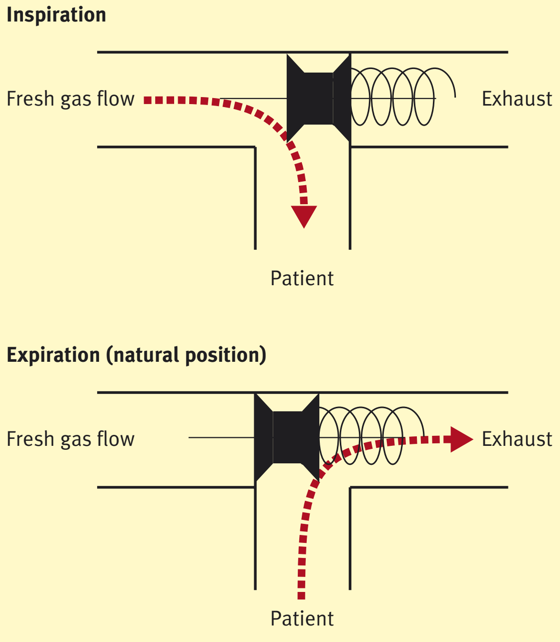
of the valve. This reservoir may be a conventional anaesthetic reservoir with an exhaust valve to avoid pressurizing the inspiratory valve, or an open-ended tube. The reservoir must exceed the size of the tidal volume. The minimum fresh gas flow that can be used with such a system is the patient's minute ventilation; any less leads to respiratory embarrassment or entrainment of air. However, such a system is hopeless for positive-pressure ventilation because any applied positive pressure opens the inspiratory and expiratory valves resulting in ventilation of the atmosphere rather than the patient.

Positive-pressure ventilation requires the inspiratory valve to remain open when the expiratory valve is closed. This is readily achieved by the Ruben and Ambu valves. The Ruben valve consists of a spring-loaded bobbin in the valve housing (Figure 2). The spring is weak and serves to occlude the inspiratory port and keep the valve in the expiratory position, providing relatively unhindered expiration. When the inspiratory limb is pressurized, by squeezing the reservoir bag on the inspiratory limb, the bobbin moves across, opening the inspiratory port and closing the expiratory port. With spontaneous respiration, the built-in differential resistance of the valve allows it to function in a similar manner, with the bobbin sliding across during inspiration and occluding the expiratory port. However, with high upstream pressures the valve has a tendency to stick in the inspiratory position, leading to lung over-inflation.

The use of these valved breathing systems is prone to problems at high fresh gas flow rates. It is possible for the valve to lock in the 'on' position, resulting in continual inspiration and preventing exhalation. During mechanical ventilation there is a tendency for some of the gas that should have been delivered to the patient to leak across the expiratory valve leading to inefficiency.

Ruben valve



Inspiration

Expiration (natural position)

Figure 2

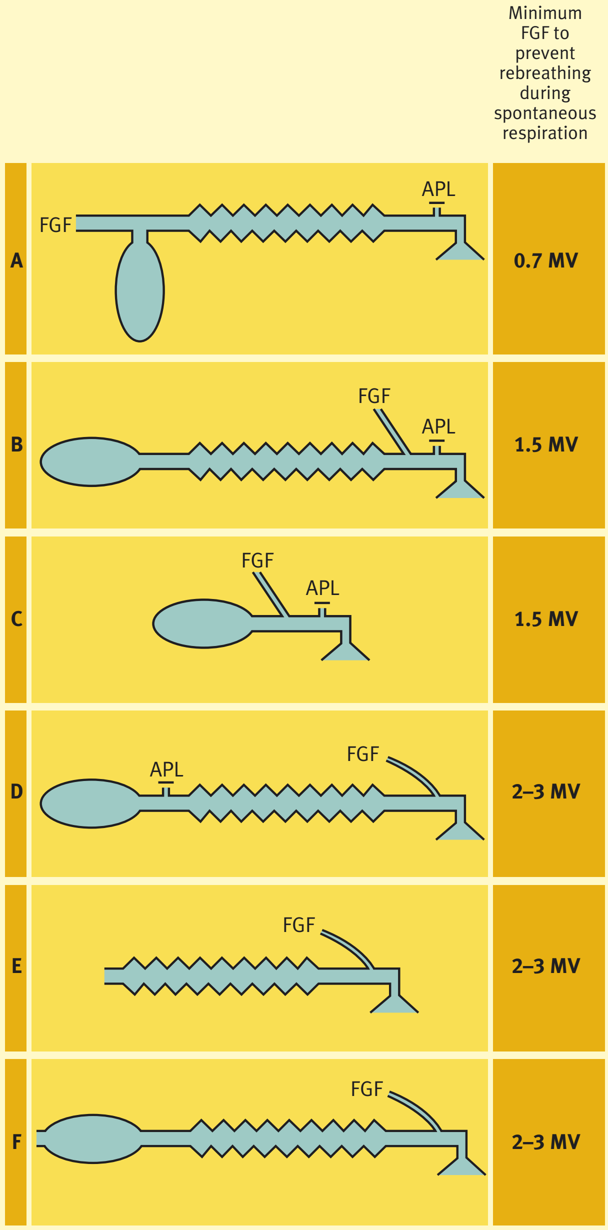
Mapleson classification

The physical properties of the rebreathing systems that are widely used in anaesthesia were first described theoretically by Mapleson 50 years ago. The original classification considered five different systems, the Jackson-Rees modification of the T-piece was added subsequently. The six different breathing systems are shown in Figure 3.

Mapleson A

Mapleson A is typified by the Magill attachment. The corrugated breathing hose is a minimum of 110 cm long with an internal volume of at least 550 ml.

Modified Mapleson classification of breathing systems



APL, adjustable pressure limiting valve; FGF, fresh gas flow; MV, minute ventilation.

Figure 3

During inspiration, the reservoir bag that had previously filled, together with gas stored in the corrugated hose is inhaled. This gas contains no carbon dioxide, and thus represents fresh gas. During early exhalation the reservoir bag is filled by gas flowing from the anaesthetic machine and gas displaced from the corrugated hose by gas exhaled by the patient. Initially the exhaled gas will have sat in alveolar dead-space only, it will have been warmed and humidified, but contains no carbon dioxide. Before the mixed alveolar gases that contain carbon dioxide reach the reservoir bag, the reservoir bag will have filled. Consequently, the pressure in the system rises and the adjustable pressure limiting (APL) valve opens, venting expired gas containing carbon dioxide. Subsequent expiration occurs with the gases being vented. At the end of expiration there is an expiratory pause. During this time, gas continues to flow in from the fresh gas flow, displacing any mixed alveolar gas that has found its way into the corrugated hose.

During controlled ventilation, in the inspiratory phase, the APL valve has to be almost closed in order to fill the lungs. As well as filling the lungs, fresh gas is blown out of the APL valve. With the onset of expiration the patient exhales into the hose. The bag will be almost empty, therefore if the tidal volume exceeds 550 ml, dead-space gas and alveolar gas containing carbon dioxide enter the reservoir bag. The natural tendency is to start to squeeze again, allowing little if any expiratory pause. The expired gases in the hose are driven back into the lungs. Initially, airway pressure is low so the APL valve will not open. Later, as the lungs fill, the valve starts to open and this mixed gas is exhausted. The gas that initially entered the lungs was end-alveolar gas (i.e. rich in carbon dioxide).

Mapleson B and C

Mapleson B and C systems are seldom used during anaesthesia and have poor performance.

Mapleson D

At the onset of spontaneous inspiration, if the reservoir bag is initially full of fresh gas, then all that enters the lungs is fresh gas. With the onset of expiration, exhaled gases mixed with fresh gases pass down the hose. The initial gas exhaled has been only in the dead-space and contains no carbon dioxide. When the bag has filled, to an extent that the pressure exceeds the opening pressure of the APL valve, it opens. Further mixed, exhaled and fresh gases then leave via the APL valve. With the expiratory pause, the fresh gas washes out the end-tidal gases from the hose and out of the APL valve. This system is less efficient during spontaneous respiration because some of the fresh gases are lost from the APL valve during exhalation. With controlled ventilation, during inspiration, initially fresh gas enters the lungs from the bag and the fresh gas flow. As the pressure rises, the APL valve eventually opens and any further gases leaving from the bag are lost from the APL valve. At the same time, some of the gases stored in the hose are washed out of the APL valve by the fresh gas supply. During expiration, a mixture of fresh and exhaled gases enter the hose and then the bag. During the expiratory pause, mixed fresh and exhaled gases continue to be washed down the hose by the fresh gas. The longer the pause, the more of these gases are washed down to the bag. Eventually the pressure exceeds the APL valve opening pressure and this mixed gas is vented. The bag now contains a mixture of fresh and alveolar gases; subsequent breaths contain some alveolar gas (i.e. there is a degree of controlled rebreathing). As long as minute ventilation equals or exceeds fresh gas flow, the arterial carbon dioxide tension is determined by the fresh gas flow rate, the higher the flow rate the less rebreathing and *vice versa*.

Mapleson E and F

The Mapleson E and F systems are widely used in paediatric practice. Functionally they behave in the same way as a Mapleson D system, except that there is no valve. During inspiration, a mixture of fresh gas and the expiratory limb contents are inhaled. If the tidal volume exceeds the volume of the expiratory portion of the system and the fresh gas flow, then atmospheric air is inhaled, which dilutes the anaesthetic gases. During expiration, behaviour is identical to a Mapleson D system, the expiratory pause allows time for the fresh gas to displace the end-tidal gas down the expiratory limb far enough to avoid rebreathing. If the fresh gas flow rate is too low, the next inspiration contains a mixture of fresh and end-tidal gases.

Efficiency

For spontaneous breathing, the different Mapleson systems can be ranked in terms of economy of gas consumption in the absence of rebreathing. The most efficient is a Mapleson A, followed by a Mapleson D, E or F, which are functionally virtually identical. These are followed by the Mapleson C system and finally the B system. However, during controlled ventilation this order is different. The controlled rebreathing properties of the Mapleson D, E and F systems render them the most efficient. These systems are followed in order by the Mapleson B, C and finally the Mapleson A system. The efficiency of the Mapleson D, E, F systems during controlled ventilation, coupled with the fact that they are second only to the Mapleson A system in spontaneous ventilation have led some authors to consider them as the universal breathing systems.

Coaxial systems

One of the drawbacks of breathing systems such as the Magill attachment is that the APL valve is beside the patient's head, far away from the anaesthetic machine. This makes it cumbersome to adjust, and the relatively heavy APL valve and the weight of the scavenging system very close to the mask or tracheal tube may cause kinking and obstruction. During head and neck surgery, access to the APL valve is difficult.

The original Lack breathing system brought the APL valve back to the machine using a coaxial breathing system. The patient inspired through the outer lumen, and exhaled through the inner limb with the APL valve at the machine end. Because all that has happened is to extend the length of tubing between the end of the supply hose and the APL valve, and gas flow in this limb is unidirectional, away from the patient, the Lack system is classed as a Mapleson A system. Because the patient is respiring through both tubes, this makes a bulky breathing system. In common with the Magill attachment, it is efficient during spontaneous respiration and grossly inefficient during controlled ventilation, requiring extremely high fresh gas flow rates to maintain a reasonable arterial carbon dioxide tension. Because of the bulk of the coaxial Lack system, a parallel Lack system has been developed that uses two standard 22 mm hoses arranged side by side rather than coaxially. This parallel Lack circuit functions indistinguishably from the coaxial version.

The Bain breathing system (Figure 4) has similarities to the coaxial Lack system, but respiration (inspiration and expiration) occurs through the outer tube. The inner 6 mm tube is connected directly to the common gas outlet at the machine end. Because the inner tube is only 6 mm, it is possible to accommodate this coaxial system in the same space as a conventional 22 mm breathing system hose. Care needs to be taken before use to verify that the inner tube has not disconnected from the mount at the machine end, since such a disconnection would produce a breathing system with a dead-space exceeding the magnitude of tidal ventilation. Extreme care must be taken to ensure that the anaesthetic machine has a back bar pressure relief valve, before testing the integrity of the inner lumen by occluding it. In the absence of a back bar pressure relief valve, the pressures generated in the back bar could be high enough to blow the seals on the flow-meter tubes. Several studies have shown that the resistance properties of the Bain system are satisfactory even with very long lengths. The functional behaviour of the Bain system is identical to that of a Mapleson D system, with the advantage that the weight of the APL valve is supported by the common gas outlet of the anaesthesia machine. Given that the Bain functions as a Mapleson D system, it is unsurprising that it is widely used as a universal breathing system.

The Humphrey attachment

Some authors consider the Mapleson D, E and F systems to be universal systems but they are inefficient during spontaneous ventilation. The advantage of having the APL valve at the machine end of the breathing system is illustrated by the success of the Lack and Bain breathing systems. These two concepts led Humphrey to design the ADE attachment shown in Figure 5. A standard anaesthetic Y-hose is attached to the patient end of the valve block. With the switch in the upper position, the breathing system is configured as a Mapleson A system, with consequent high efficiency during spontaneous ventilation. With the switch in the lower position, the internal gas pathways in the valve block are changed, and the system behaves as a Mapleson D system, with high efficiency during controlled ventilation. Claims have been made that by using smooth-walled tubing it is possible to reduce the fresh gas flow in the Mapleson A mode to the alveolar ventilation, rather than the minute ventilation, the theoretical minimum for a Mapleson A system. In an attempt to allow further reduction in fresh gas requirements an add-on carbon dioxide absorber can be added to the valve block (Figure 6). With the attached absorber, the ADE is converted into a circle absorber system, with all of its advantages in terms of economy of fresh gas consumption and reduction in pollution.

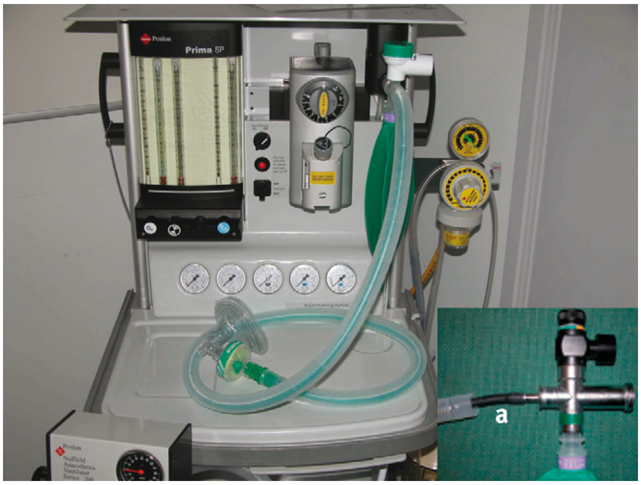


Figure 4 A coaxial Bain breathing system. Fresh gas is supplied to the patient end via the small inner tube. The inner tube connection **(a)** is shown in the inset figure.

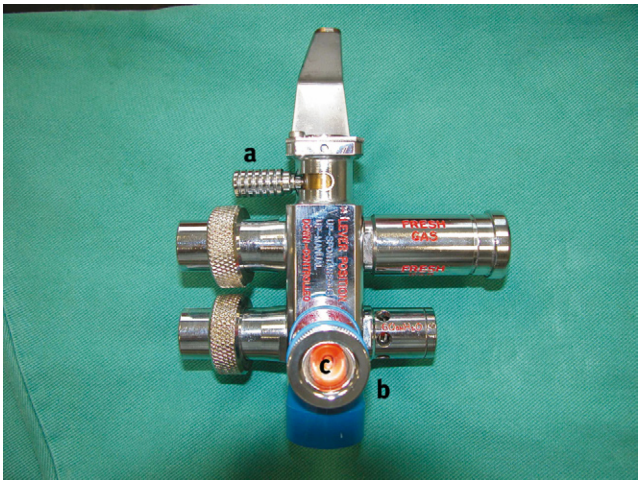


Figure 5 The Humphrey ADE attachment. **a** The mode switch, **b** the APL valve, **c** the central orange bar in the middle of the APL valve facilitates transient user closure of the APL to deliver assisted breaths while in Mapleson A mode.

Carbon dioxide absorption systems

To function with fresh gas flows of less than the alveolar minute ventilation, it is necessary to rebreathe some of the exhaled gas. The carbon dioxide in the exhaled gas is removed by reaction of carbon dioxide and water to produce carbonic acid, which in

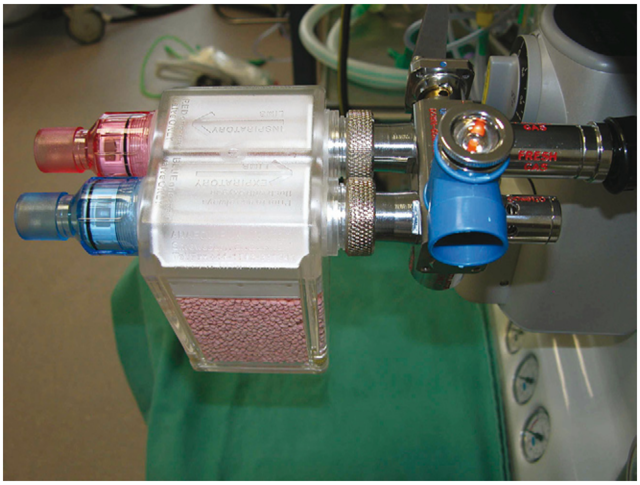


Figure 6 The Humphrey ADE with attached carbon dioxide absorber.

turn is removed by reaction with calcium hydroxide. Two types of absorber are widely used. Soda lime consists of about 80% calcium hydroxide, 4% sodium hydroxide and 14–20% water. Baralime, which is more commonly used in the USA, consists of 80% calcium hydroxide and 20% barium hydroxide octahydrate. Newer carbon dioxide absorbers have come on to the market during the past few years that avoid the use of strong bases such as sodium and potassium hydroxide. Different manufacturers add different indicator dyes to the absorber, some change from pink when fresh to white when exhausted, other dyes change from white to purple. Soda lime absorbs up to 25 litres of carbon dioxide per 100 g. In continuous use, the indicator changes colour before this amount of carbon dioxide has been absorbed. When the soda lime is left to stand for a few hours, it appears to regenerate as hydroxide ions migrate to the surface of the granules, diluting the calcium carbonate produced on absorption of carbon dioxide. The reaction is exothermic and produces water, and it has been claimed that at low gas flows this is beneficial in that it will warm and partially humidify the anaesthetic gases. This needs to be contrasted with the greater degree of humidification that is possible with the Bain circuit. When gases are repeatedly recirculated, there tends to be a gradual accumulation of various waste products that would normally be excreted via the lungs. A greater issue is the use of oxygen concentrators to provide the source of oxygen. Under low flow conditions, once steady state is reached, the gases in the circle may contain as much as 13% argon. The past 10 years have seen increasing concerns about the production of toxic metabolites under 'low flow' conditions. This is more of a problem with baralime than with soda lime.

Historically two types of carbon dioxide breathing systems have been used. For many years the to-and-fro system introduced by Waters was popular. However, it was cumbersome in use, required the absorber to be directly next to the mask or tracheal tube, and allowed the patient to inhale soda lime dust. Its advantage over the circle systems, which are widely used today, was the ease with which it could be cleaned and sterilized.

Circle absorber systems have been extensively used in North America for more than 30 years. Their use for the maintenance of anaesthesia is rapidly increasing in much of the developed world, driven by a desire to reduce the cost of expensive inhalational anaesthetic agents as well as to reduce the extent of environmental pollution. Although frequently seen as an integral part of the anaesthesia machine, disposable, single-use, circle-type breathing systems are also available. In a circle system the two one-way valves are housed in clear chambers so that it is possible to confirm their correct operation. The three common places to locate the APL valve are shown in Figure 7. For many years it has been practice in the USA to have the APL valve at the Y-piece (position 1, Figure 7) arguing that this would preferentially vent alveolar carbon dioxide during exhalation, thereby extending the life of the absorber. With increased concerns over pollution, the inconvenience of having the scavenging on the Y-piece has gradually led to an abandonment of this location for the APL valve. The most common location for the APL valve now is downstream of the expiratory valve (position 2, Figure 7) before the gas enters the absorber.

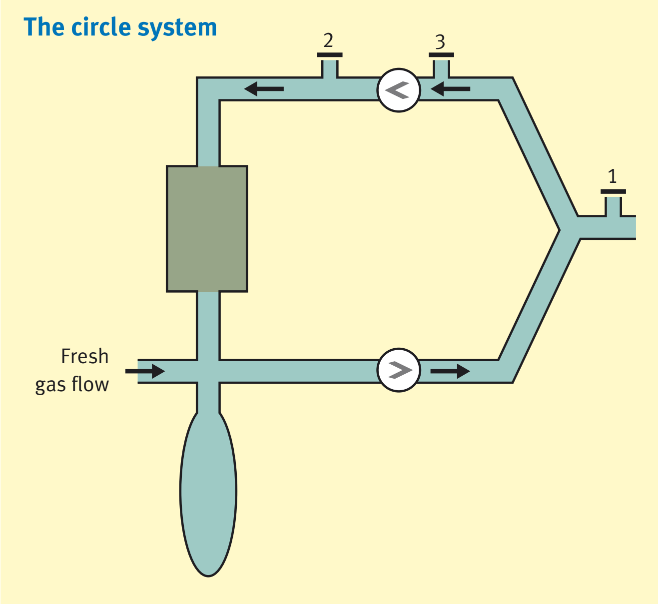


Figure 7 The APL valve can be located in position 1, 2 or 3.

The resistance to gas flow, while higher than that seen in the original Mapleson classified systems, is less than that seen with coaxial systems such as the Bain. This is because of the presence of two one-way valves, together with the absorber. High inspiratory flow rates, while reducing the inspiratory resistance have been associated with an increase in expiratory resistance, the converse occurring at low flows. Low fresh gas flow rates have been associated with an increase in the relative humidity in the breathing system. This water vapour leads to an increase in the degree of stickiness of the unidirectional valves. Very prolonged use of very low flow can be associated with a not inconsiderable amount of water deposition within the breathing system. ◆

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