

Anaesthetic Breathing Systems

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DEFINITIONS

The function of breathing is to maintain a supply of oxygen to the lungs for oxygenation of the tissues, and to remove carbon dioxide from the body. When used for spontaneous ventilation, a breathing circuit must enable a patient to breathe satisfactorily without significantly increasing the work of breathing or the physiological deadspace. It must also conduct inhalational anaesthetic agents to the patient. The volume of gas inspired and expired with each breath is the *tidal volume* (normally 6-10ml.kg⁻¹), the total volume breathed in a minute is the *minute volume* and the volume of gas in the lungs at the end of normal expiration is the *functional residual capacity* (FRC).

The concentration of carbon dioxide in an exhaled breath varies with time; the first portion contains no carbon dioxide and comes from the upper respiratory tract where no gas exchange takes place (the anatomical dead space, about 2ml.kg⁻¹). The *anatomical dead space* is 25-35% of each tidal volume. As expiration continues, the concentration of carbon dioxide then rises rapidly to a plateau of about 5kPa (5% of the expired gas mixture) as alveolar gas is breathed out. The volume of alveolar gas expired per minute is called the alveolar minute ventilation. Any areas of lung that are ventilated with gas but are not perfused by blood cannot take part in gas exchange and represent the *alveolar dead space*. The total dead space in the patient (anatomical + alveolar) is the *physiological dead space*.

The term *rebreathing* implies that expired alveolar gas containing 5% carbon dioxide (and less oxygen than normal) is inspired as part of the next tidal volume. Anaesthetic circuits are designed to minimise rebreathing as it may lead to significant elevations in blood CO₂ levels. The amount of rebreathing that occurs with any particular anaesthetic breathing system depends on four factors:

1. The design of the individual breathing circuit.
2. The mode of ventilation (spontaneous or controlled).
3. The fresh gas flow rate.
4. The patient's respiratory pattern.

Circuits may eliminate rebreathing by:

1. Ensuring an adequate flow of fresh gas, that flushes the circuit clear of alveolar gas or,
2. Using soda lime, in a circle system, that absorbs the CO₂ so that low fresh gas flows may be used.

For each of the circuits described below, fresh gas flow rates that ensure minimal rebreathing are suggested.

THE MAPLESON CLASSIFICATION OF BREATHING SYSTEMS

A number of classifications exist and the one introduced in 1954 by Professor WW Mapleson is most commonly used in the UK (Figure 1). It does not however, include systems with carbon dioxide absorption.

The Mapleson A (Magill) system has been in use since the 1930s and remains an excellent system for spontaneous ventilation (Figure 2). Fresh gas enters the system at the fresh gas outlet of the anaesthesia machine. The expiratory valve (Heidbrink valve) is very close to the patient to reduce the dead space. The respiratory cycle has three phases during spontaneous breathing; inspiration, expiration and the expiratory pause. During inspiration gas is inhaled from the two litre reservoir (breathing) bag which partially collapses giving a visual confirmation that breathing is occurring.

During expiration the bag and tubing are initially refilled with a combination of exhaled dead space gas (containing no carbon dioxide) and fresh gas flowing from the anaesthetic machine. Once the bag is full, the pressure within the breathing system rises and the expiratory valve near the patient opens allowing the alveolar gas (containing carbon dioxide) to be vented from the system. During the expiratory pause more fresh gas enters the system driving any remaining alveolar gas back along the corrugated tubing and out through the valve. If the fresh gas flow is sufficiently high all the alveolar gas is vented from the circuit before the next inspiration and no rebreathing will take place. With careful adjustment the fresh gas flow can be reduced until there is only fresh gas and dead space gas in the breathing system at the start of inspiration.

Summary

The delivery systems which conduct anaesthetic gases from an anaesthetic machine to the patient are known as breathing systems or circuits. They are designed to allow either spontaneous respiration or intermittent positive pressure ventilation (IPPV) and consist of a reservoir bag, anaesthetic tubing, and (in most cases) a pressure relief valve. A number of mechanical ventilators include a specific breathing system, for example the Manley series. Other ventilators have been designed to operate with existing breathing systems, for example the Penlon Nuffield 200. This article focuses on the breathing systems used with plenum anaesthetic machines (those with a supply of pressurized gas); drawover apparatus will be described in a future article.

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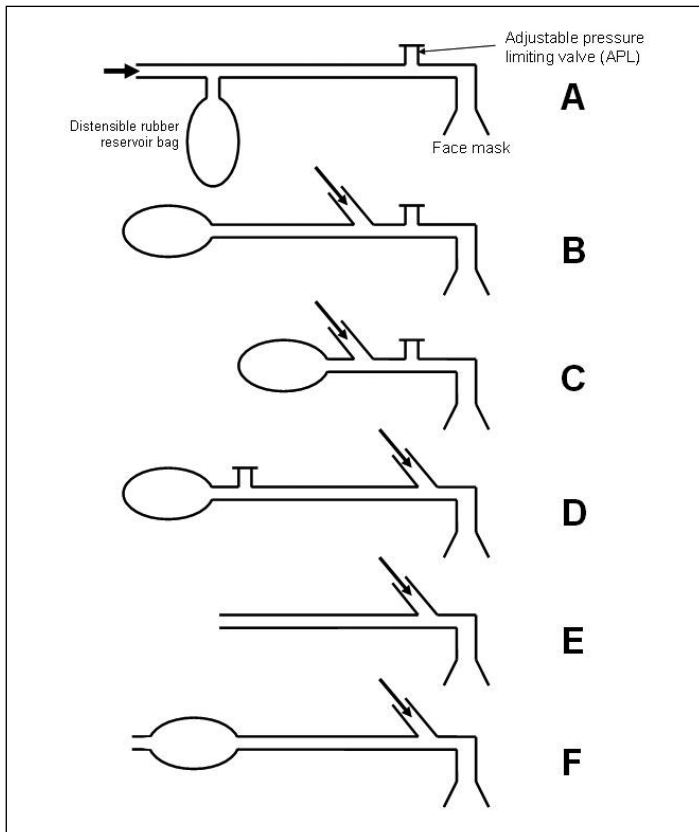


Figure 1. Mapleson classification of anaesthetic breathing systems. The arrows indicate entry of fresh gas to the system

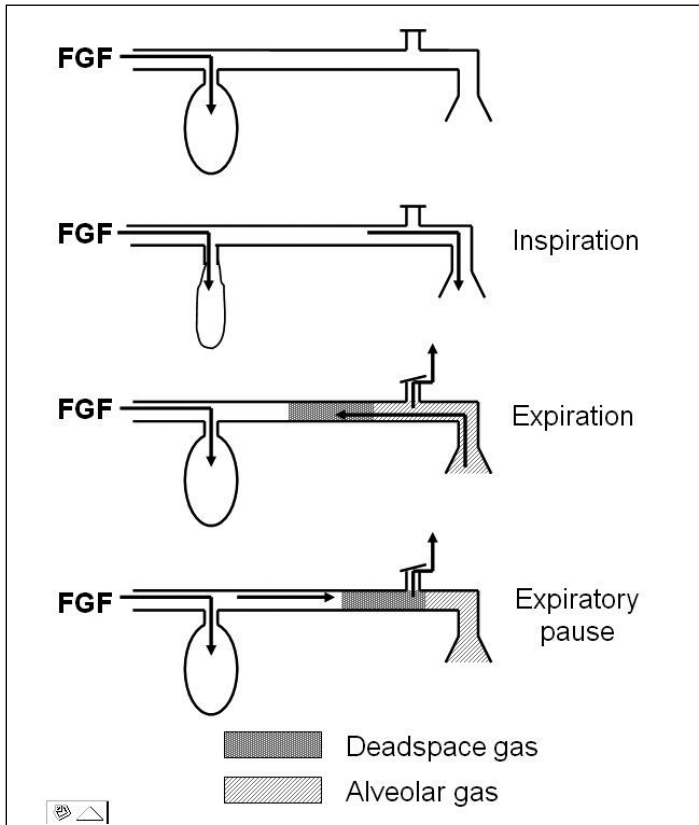


Figure 2. Mode of action of Mapleson A (Magill) breathing system during spontaneous ventilation

When the system is functioning correctly, without any leaks, a fresh gas flow (FGF) equal to the patient's alveolar minute ventilation is sufficient to prevent rebreathing. In practice however, a FGF closer to the patient's total minute ventilation (including dead space) is usually selected to provide a margin of safety. An adult's minute volume is approximately $80\text{ml.kg}^{-1}.\text{min}^{-1}$ and thus for a 75kg man a FGF of 6 litres per minute will prevent rebreathing. Where capnography is available this FGF can be titrated down, while watching for rebreathing, in order to limit gas use. This is an efficient system for spontaneously breathing patients, if carbon dioxide absorption is not available.

During controlled ventilation, the Magill circuit works in a different way and becomes wasteful and inefficient, requiring high fresh gas flows to prevent rebreathing (Figure 3). The inspiratory pressure is provided by the anaesthetist squeezing the reservoir bag after partly closing the expiratory valve next to the patient. During lung inflation some of the gas is vented from the circuit and at the end of inspiration the reservoir bag is less than half full. During expiration, dead space and alveolar gas pass down the system tubing and may reach the bag which will then contain some carbon dioxide. During the next inspiration, when the bag is squeezed, alveolar gas re-enters the patient's lungs followed by a mixture of fresh, dead space and alveolar gas. A FGF of two and a half times the patient's minute volume is required to vent enough alveolar gas to minimise rebreathing (a FGF of about

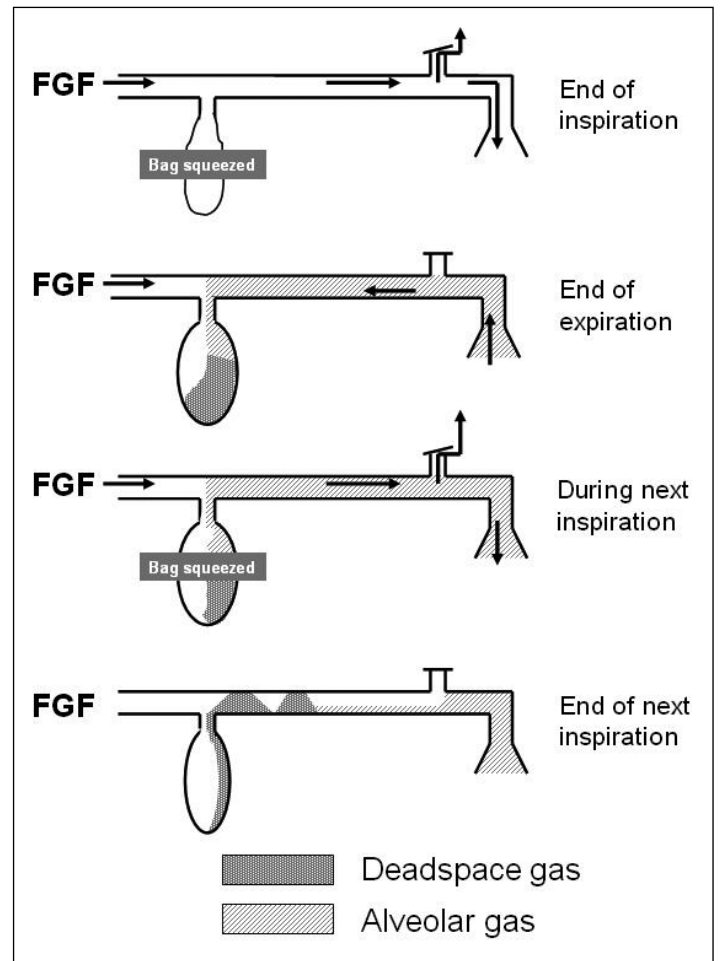


Figure 3. Mapleson A system with controlled or assisted ventilation

12-15l.min⁻¹) which is clearly very inefficient. In practice the Magill circuit should not be used for positive pressure ventilation except for short periods of a few minutes at a time.

Modifications of the Mapleson A system

A simple modification of the Mapleson A circuit is required to make it more efficient for controlled ventilation. This is achieved by substituting a non-rebreathing valve (such as an Ambu E valve) for the Heidbrink valve at the patient end of the circuit. Not only does this arrangement prevent rebreathing, but during manual ventilation the delivered minute volume will be the same as the desired FGF, which should be set at the rotameters. It is, however, a dangerous arrangement for spontaneous respiration because the valve may jam if the fresh gas flow is greater than the patient's minute volume.

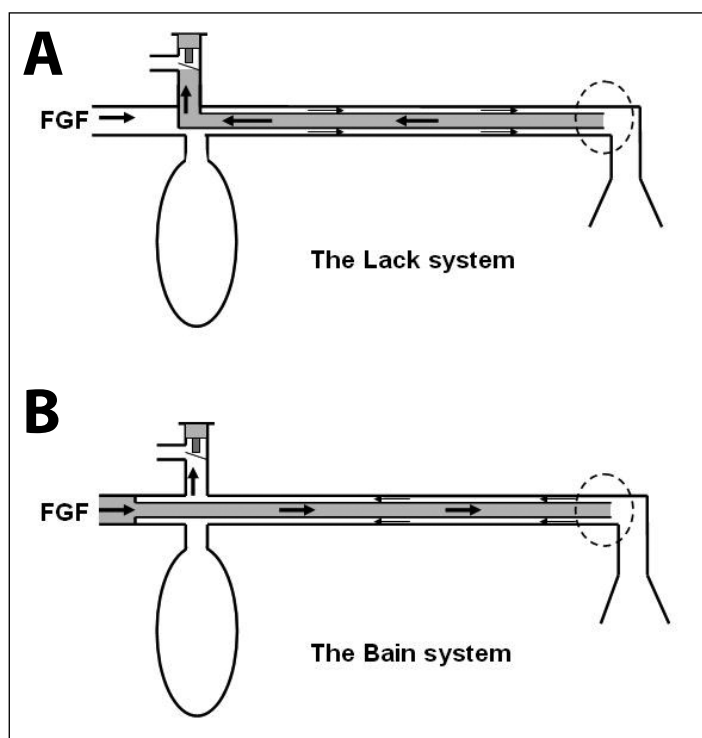


Figure 4. Coaxial anaesthetic breathing systems - the Bain (Mapleson D) and Lack (Mapleson A) systems. The coaxial tubing (shaded) avoids the need for fresh gas tubing (Bain) or an APL valve in the circuit near the patient. In the Bain system the coaxial tubing delivers fresh gas to a point in the system near the patient (dashed circle). In the Lack system it delivers expired gas to the APL valve

The Lack circuit

A disadvantage of the Magill system is that the expiratory valve is attached close to the patient making it awkward to use (particularly when a scavenging circuit is added). The Lack circuit (Figure 4A) is a Mapleson A system in which the exhaled gases travel down a central tube located within an outer corrugated tube towards the expiratory valve (co-axial system).

The inner tubing is wide enough to prevent an increase in the work of breathing and the expiratory valve is placed next to the reservoir bag, by the common gas outlet. The fresh gas flows required for both spontaneous and controlled ventilation are as described for the standard Mapleson A system.

Mapleson B and C breathing systems (Figure 1)

These systems are similar in construction, with the fresh gas flow entry and the expiratory valves located at the patient end of the circuit. They are not commonly used in anaesthetic practice, although the C system is commonly used on intensive care units (the Waters circuit), where it is used for IPPV or augmenting patient's spontaneous breaths during intubation and extubation. High flows of gases are needed to prevent rebreathing of CO₂ and this system was at one time combined with a canister of soda lime to absorb CO₂ (Waters' "to and fro" circuit). However the cannister proved too bulky for practical use and there was a risk of the patient inhaling soda lime dust.

Mapleson D breathing system

The Mapleson D, E and F systems are all functionally similar (Figure 1). They act as T-pieces with the FGF delivered to the patient end of the circuit and differ only in the presence of valves or breathing bags at the expiratory end of the circuit. These systems are all inefficient for spontaneous respiration (Figure 5). During expiration exhaled gas and fresh gas mix in the corrugated tubing and travel towards the reservoir bag. When the bag is full the pressure in the system rises and the expiratory valve opens venting to the atmosphere a mixture of fresh and exhaled gas. During the expiratory pause fresh gas continues to push exhaled alveolar gas down the tubing towards the valve. However, unless the FGF is at least twice the patient's minute volume, rebreathing of alveolar gas occurs. A FGF of at least 8-10l.min⁻¹ (150ml.kg⁻¹.min⁻¹) is required to prevent rebreathing in an adult.

When used for controlled ventilation the Mapleson D system functions more efficiently. During expiration the corrugated tubing and reservoir bag fill with a mixture of fresh and exhaled gas. Fresh gas fills the distal part of the corrugated tube during the expiratory pause prior to inspiration. When the bag is compressed this fresh gas enters the lungs and when the expiratory valve opens a mixture of fresh and exhaled gas is vented. The degree of rebreathing that occurs depends on the FGF. A FGF of 70ml.kg⁻¹.min⁻¹ is usually adequate for controlled ventilation; 100ml.kg⁻¹.min⁻¹ will result in a degree of hypocapnia (lowered CO₂ level in the blood).

Modifications of the Mapleson D system

The Bain co-axial circuit (Figure 4) is the most commonly used form of the Mapleson D system. Unlike the Lack co-axial circuit described above, fresh gas flows down the central narrow bore tubing (7mm internal diameter) to the patient and exhaled gases travel in the outer corrugated tubing (22mm internal diameter). The reservoir bag may be removed and replaced by a ventilator such as the Nuffield Penlon 200 for mechanical ventilation. Before use the Bain circuit should be carefully checked by the anaesthetist. The outer tubing of a Bain circuit is made of clear plastic and the inner green or black. If a leak develops in the inner tubing or it becomes detached from the fresh gas port, a huge increase in apparatus dead space occurs. In order to check for this, the lumen of the inner tubing should be occluded with a finger or the plunger of a 2ml syringe, demonstrating a rise in gas pressure within the anaesthetic circuit.

The degree of rebreathing that occurs during IPPV will depend on the FGF. In an adult, fresh gas flows of 70-80ml.kg⁻¹.min⁻¹ (6-7l.min⁻¹) will maintain a normal arterial carbon dioxide tension (normocapnia) and a flow of 100ml.kg⁻¹.min⁻¹ will result in mild hypocapnia.

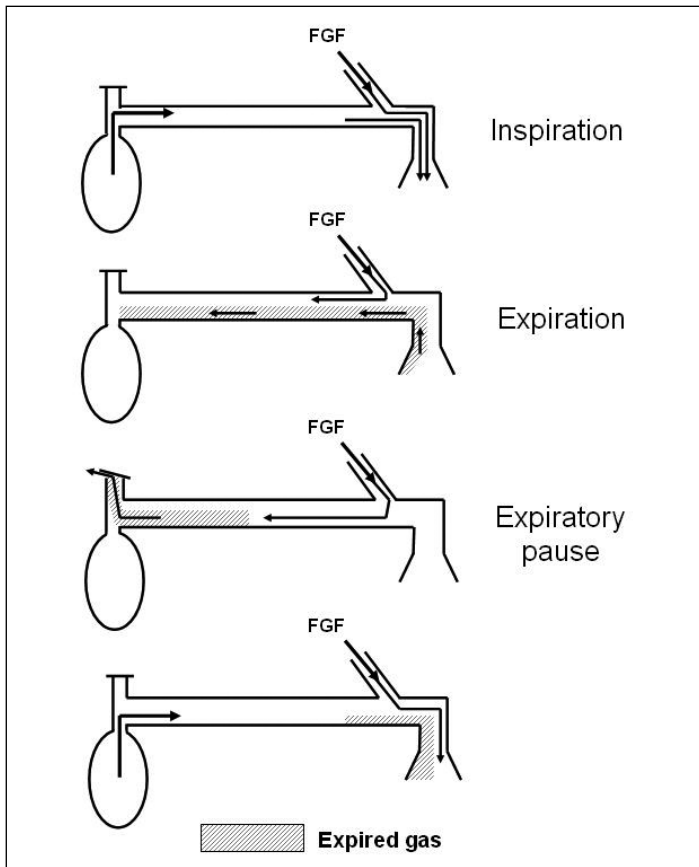


Figure 5. Mode of action of the Mapleson D breathing system during spontaneous ventilation

Mapleson E system

The Mapleson E system performs in a similar way to the Mapleson D, but because there are no valves and there is very little resistance to breathing it has proved very suitable for use with children. It was originally introduced in 1937 by P Ayre and is known as the Ayre's T-piece. The version most commonly used is the Jackson-Rees modification which has an open bag attached to the expiratory limb (classified as a Mapleson F system although it was not included in the original description by Professor Mapleson).

Movement of the bag can be seen during spontaneous breathing, and the bag can be compressed to provide manual ventilation. As in the Bain circuit, the bag may be replaced by a mechanical ventilator designed for use with children, such as a Penlon 200 with a Newton valve. This system is suitable for children under 20kg. Fresh gas flows of 2-3 times the minute volume should be used to prevent rebreathing during spontaneous ventilation, with a minimum flow of $3\text{l}\cdot\text{min}^{-1}$. For example, a 4-year-old child weighing 20kg has a normal minute volume of $3\text{l}\cdot\text{min}^{-1}$ and would require a FGF of $6\text{-}9\text{l}\cdot\text{min}^{-1}$. During controlled ventilation in children normocapnia can be maintained with a fresh gas flow of $1000\text{ml} + 100\text{ml}\cdot\text{kg}^{-1}$ - the 4-year-old weighing 20kg would need a total FGF of around $3\text{l}\cdot\text{min}^{-1}$.

The Humphrey ADE circuit

The Mapleson A circuit is inefficient for controlled ventilation, as is the Mapleson D circuit for spontaneous ventilation. David Humphrey designed a single circuit that can be changed from a Mapleson A

system to a Mapleson D by moving a lever on the metallic block, which connects the circuit to the fresh gas outlet on the anaesthetic machine. The reservoir bag is situated at the fresh gas inlet end of the circuit, and gas is conducted to and from the patient down the inspiratory and expiratory limbs of the circuit. Depending on the position of the control lever at the Humphrey block, gases either pass through the expiratory valve or the ventilator port. When the lever is 'up' the reservoir bag and the expiratory valve are used, creating a Mapleson A type circuit. When the lever is in the 'down' position the bag and valve are bypassed and the ventilator port is opened, creating a Mapleson D system for controlled ventilation. If no ventilator is attached and the port is left open the system will function like an Ayre's T piece (Mapleson E).

Like all pieces of equipment, it is essential that the anaesthetist fully understands the function of this circuit before using it. If the lever on the Humphrey block is moved from 'up' to 'down' while gases are flowing, the breathing bag will remain full of gas but manual ventilation of the patient's lungs by compressing the bag will be impossible and may resemble complete obstruction of the breathing circuit.

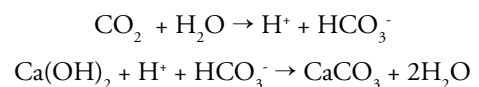


Figure 6. The Humphrey ADE circuit

CIRCLE SYSTEMS

An alternative to using high flow circuits is to absorb CO_2 from the expired gases which are then recirculated to the patient. These circuits, known as circle systems, were first used in 1926 and require smaller amounts of fresh gas each minute.

Carbon dioxide is removed from the expired gas by passage through soda lime, a mixture of 94% calcium hydroxide, 5% sodium hydroxide, and 1% potassium hydroxide which reacts with CO_2 to form calcium carbonate:



Soda lime also contains small amounts of silica to make the granules less likely to disintegrate into powder and a chemical dye which

changes colour with pH. As more carbon dioxide is absorbed the pH decreases and the colour of the dye changes from pink to yellow/white. When around 75% of the soda lime has changed colour it should be replaced. The soda lime canister should be mounted vertically on the anaesthetic machine to prevent the gases passing only through a part of the soda lime (streaming).

Fresh soda lime contains 35% water by weight which is necessary for the reaction between carbon dioxide and soda lime to take place. This generates considerable heat. The soda lime may rise in temperature to 40°C. This is an additional advantages of circle systems - the gases within the circle are warmed and humidified prior to inspiration. Baralyme is a commercially available CO₂ absorber which contains 5% barium hydroxide instead of sodium hydroxide.

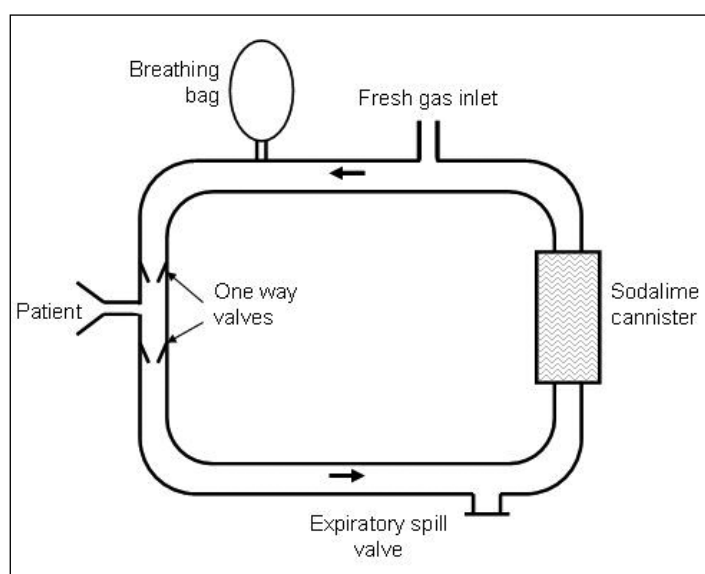


Figure 7. Schematic diagram showing the basic components of a circle breathing system

Design of circle systems

A circle system (Figure 7) is composed of two one-way valves (one on the inspiratory limb of the circuit from the patient and one on the expiratory limb), a reservoir bag, a fresh gas inlet, a canister of soda lime and an expiratory spill valve. Although there may be slight differences in the positioning of these components, all the systems function in the same way.

Vaporiser position

The vaporiser may be placed either outside the circle (VOC) on the anaesthetic machine in its conventional position, or rarely within the circle itself (VIC). Normal plenum vaporisers, with high internal resistance, cannot be used within the circle and a low internal resistance type vaporiser (such as the Goldman) is required. Drawover vaporisers such as the OMV are not recommended for use within the circle because of the risk of achieving dangerously high levels of inhalational agent. Since the gases are recirculated, if the vaporiser is placed in the circle, gas already containing volatile anaesthetic agent will re-enter the vaporiser and the resulting output will exceed the vaporiser setting. This is a particular danger during controlled ventilation. Vaporisers should only be placed inside the circle when inspired volatile anaesthetic

agent monitoring is available. It is safer to use conventional plenum vaporisers mounted on the anaesthetic machine outside the circle. In this case the maximum volatile anaesthetic agent concentration achievable within the circle cannot exceed that set on the vaporiser.

Practical use of circle systems - reducing the fresh gas flow

During the first five to ten minutes of anaesthesia using a volatile anaesthetic agent in oxygen and air, a large amount of the agent (and nitrous oxide, if used) is taken up by the patient, causing a reduction in the agent concentration within the system. In addition the total volume of the circle system (tubing and soda lime canister) is around 3 litres and this volume is also a reservoir of room air that needs to be replaced with anaesthetic agent and fresh gas. High fresh gas flows (roughly equivalent to the patient's minute volume) ensure that this wash-out of air from the system and the patient's functional residual capacity occurs rapidly. Wash-out of air from the patient's lungs is also dictated by the patient's minute volume. After 10 to 15 minutes, provided suitable agent monitoring is available, the fresh gas flow can be reduced to low flows.

Inspired anaesthetic gases should contain no carbon dioxide and a minimum of 30% oxygen. Exhaled alveolar gas contains a lower concentration of oxygen and around 5% carbon dioxide which is removed from the exhaled gas on passage through the soda lime. A small amount of fresh gas is added before the next breath. At low fresh gas flow rates (<1000ml.min⁻¹) the oxygen concentration within the circle is unpredictable, particularly when used with nitrous oxide, often dropping to 27%, or even to below 21%, at flows less than 0.5l.min⁻¹. Circle systems should preferably not be used at low flow rates without an oxygen analyser in the inspiratory limb. The lowest fresh gas flow rate of oxygen and nitrous oxide which can be used, whilst ensuring that the inspired oxygen concentration remains at a safe level, is 1500ml.min⁻¹ (nitrous oxide 900ml.min⁻¹ and oxygen 600ml.min⁻¹).

The margin of safety is far greater if only oxygen and a volatile agent is used in the circle system. Under these circumstances there is no risk of oxygen dilution and the flows may be reduced to 1000ml.min⁻¹. With flows of >1500ml.min⁻¹ the inspired concentration of volatile agent will be similar to that set on the vaporiser. With flows <1500ml.min⁻¹ the volatile agent concentration may fall within the circuit and the setting on the vaporiser may need to be increased. This occurs because vaporisers function less efficiently at low fresh gas flows, but also because recycled gas in the circle contains less agent (after some has been taken up by the patient), and so dilutes the agent joining the circle in the fresh gas.

Halothane, isoflurane and enflurane are all safe to use in circle systems with soda lime, however trichloroethylene (no longer used in the USA or UK) produces a toxic metabolite and must not be used. When the circle system is not in use all fresh gas flows should be turned off to avoid wastage and to prevent the soda lime from drying out.

Several paediatric circle systems have been developed using smaller bore tubing and a one litre reservoir bag. The work involved in breathing through these systems is no greater than with a conventional Mapleson F system.

CONCLUSION

There are many different continuous flow breathing systems available, and this review has concentrated on those that are most commonly used.

With patient safety in mind, it is essential that the anaesthetist

routinely checks the anaesthetic circuit before use.

It is important to have a thorough understanding of the function and pitfalls of a particular system, as well as the minimum fresh gas flows for each system, before using it.

SI UNITS

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The International System of Units was eventually defined in 1971 by the CGPM (Conférence Générale des Poids et Mesures) and is based on the metric system. It includes seven base quantities which are mutually independent:

Base quantity	Name	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

Other quantities are derived quantities and can be defined by equations using the base units, for example:

Derived quantity	Name	Symbol
area	square metre	m ²
volume	cubic metre	m ³
speed, velocity	metre per second	m.s ⁻¹
acceleration	metre per second squared	m.s ⁻²
specific volume	cubic meter per kilogram	m m ³ .kg ⁻¹
current density	ampere per square meter	A.m ⁻²

There are 20 SI prefixes which form multiples of the SI units:

Factor	Name	Symbol	Factor	Name	Symbol
10 ²⁴	yotta	Y	10 ⁻¹	deci	d
10 ²¹	zetta	Z	10 ⁻²	centi	c
10 ¹⁸	exa	E	10 ⁻³	milli	m
10 ¹⁵	peta	P	10 ⁻⁶	micro	μ or mc
10 ¹²	tera	T	10 ⁻⁹	nano	n
10 ⁹	giga	G	10 ⁻¹²	pico	p
10 ⁶	mega	M	10 ⁻¹⁵	femto	f
10 ³	kilo	k	10 ⁻¹⁸	atto	a
10 ²	hecto	h	10 ⁻²¹	zepto	z
10 ¹	deka	da	10 ⁻²⁴	yocto	y