

Anaesthetic breathing systems

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Abstract

A breathing system is a series of components that allows the delivery of oxygen and other anaesthetic gases to the patient as well as aiding in the removal of carbon dioxide. There are key elements that feature in all anaesthetic breathing systems with numerous classification systems used. The layout of individual breathing systems determines their clinical application and use. All of the above will be discussed further in this article as well as a brief summary of the use of carbon dioxide absorbers and their function.

Keywords Carbon dioxide absorbers; circle system; Mapleson; non-rebreathing systems; rebreathing systems

Royal College of Anaesthetist CPD Matrix: 1A03, 1C02

Features of a breathing system

An ideal anaesthetic breathing system should have the following properties:

- safe, compact, lightweight and durable
- easy to clean and disinfect or, if disposable, have minimal environmental impact
- suited to spontaneous and controlled ventilation in all sizes and ages
- allow the effective removal of exhaled gas with no rebreathing.

All anaesthetic breathing systems consist of similar key elements but may be configured differently. The key elements of all anaesthetic breathing systems are:

- A fresh gas flow (FGF) supply.
- Connection to patient comprising an inspiratory and expiratory limb. Although tubing length will vary within each system, the diameter is of a standard size (22 mm for adult and 18 mm for paediatric systems).
- An expiration port or valve such as the adjustable pressure limiting (APL) valve. This allows a variable pressure within the anaesthetic system using a one-way, spring-loaded valve in order to safely vent waste gases. The minimum pressure required to open the valve is 1 cmH₂O and a safety mechanism exists to prevent pressure exceeding 60 cmH₂O.
- A reservoir bag (RB) of distensible material of a size adequate for the patient's peak inspiratory flow rate (0.5, 1

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Learning objectives

After reading this article, you should be able to:

- Outline an anaesthetic breathing system
- Describe the key elements of an anaesthetic breathing system
- Illustrate the Mapleson classification system with adaptations
- Discuss the advantages and disadvantages of each system

and 2 litre sizes commonly available). It allows collection of fresh gas flow during expiration and minimizes the amount of FGF required to prevent rebreathing.

- A carbon dioxide (CO₂) absorber if a rebreathing system is used.
- Corrugated tubing to connect all of the above components.

Rebreathing

The respiratory cycle consists of three phases: inspiration, expiration and the expiratory pause. Rebreathing occurs when an inspired tidal volume breath contains the CO₂ and reduced oxygen content from the previous exhaled breath – it can be quantified as an increase in the ratio of dead space (comprising parts of the upper respiratory tract not involved in gaseous exchange and equating to 2 ml/kg, as well as areas of the lung that are ventilated but not perfused) to tidal volume.¹

Factors influencing the degree of rebreathing include:

- design of the system
- FGF rate which is the prime determinant
- patient's respiratory rate
- duration of the end-expiratory pause
- ventilation pattern used: spontaneous ventilation (SV) or controlled ventilation (CV).

Rebreathing in a circuit can be eliminated by using fresh gas flow rates that are high enough to flush out and remove exhaled alveolar gas from the system and incorporating a CO₂ absorbing component (e.g. soda lime) within a circle system.

Classification of a breathing system

There are several ways anaesthetic breathing systems can be classified. Historical nomenclature includes:

- open system which uses solely atmospheric FGF
- semi-open system using FGF from atmosphere and other sources
- semi-closed system which is closed to the atmosphere. The FGF is greater than uptake with excess scavenged
- closed system which is closed to the atmosphere with FGF equivalent to uptake and CO₂ removed.

A more modern alternative classification, the Conway classification,² incorporates the rebreathing potential of a system and is shown in Table 1. We will discuss these in more detail using this classification.

Breathing systems without a CO₂ absorber

Unidirectional flow

Non-rebreathing systems (e.g. the Ambu® bag) are mainly associated with patient resuscitation. The Ambu® bag consists

The Conway classification of anaesthetic breathing systems

Breathing systems without CO ₂ absorbers	Breathing systems with CO ₂ absorbers
Unidirectional flow: <ul style="list-style-type: none"> • Circle system without absorber • Non-rebreathing systems (Ambu®bag) 	Unidirectional flow: <ul style="list-style-type: none"> • Circle system with absorber
Bidirectional flow: <ul style="list-style-type: none"> • Mapleson A–F • Humphrey ADE • Enclosed Afferent Reservoir 	Bidirectional flow: <ul style="list-style-type: none"> • To-and-fro system

Table 1

of a one-way valve that prevents rebreathing by preventing mixing of fresh and expired gas. The bag is self-inflating so that when piped or cylinder gas is unavailable room air is entrained. This makes it a valuable back-up or emergency alternative. It is however, bulky, unable to provide humidification or heat conservation without an additional heat and moisture exchanger and requires a high FGF to deliver higher oxygen concentrations.

Bidirectional flow

Mapleson Classification (Table 2): In 1954 Mapleson described five different rebreathing circuits, collectively known as the Mapleson systems.³ Organized from letters A to E, each system's function and classification is determined by the positioning of its various components. The FGF requirements for each system vary and are determined by which form of ventilation is utilized: spontaneous or controlled. The Mapleson circuits are described below and the advantages and disadvantages of each are summarized in Table 3.

Mapleson A: This is the most efficient system for SV, as warm and humidified exhaled dead-space gas is reused. It is inefficient for IPPV as wastefully high FGFs are needed to prevent rebreathing.

- Spontaneous ventilation
 - Inspiration: the patient inhales fresh gas and partially empties the reservoir bag (RB).
 - Expiration: the patient begins to exhale, first anatomical dead space gas then alveolar gas, down the tubing towards the RB. As the bag fills, the pressure within the system opens the APL valve to vent the exhaled gases which are by now mainly alveolar.²
 - During the expiratory pause the FGF flushes the remaining alveolar gas away from the patient and out of the APL valve. If the FGF matches the alveolar ventilation (VA) then just as much gas flows into the system as

The Mapleson classification

System	Diagram	Spontaneous ventilation	Controlled ventilation
Mapleson A Lack/Magill		1 × minute volume (MV) 70 ml/kg/min	2.5 × MV
Mapleson B		2.5 × MV	2.5 × MV
Mapleson C Water's Circuit		2.5 × MV	2.5 × MV
Mapleson D Bain		2–3 × MV	1 × MV 70 ml/kg/min
Mapleson E Ayres T-piece		2 × MV	1 × MV 70 ml/kg/min or minimum 3 litres/min
Mapleson F		As Mapleson E	As Mapleson E

Table 2

Advantages and disadvantages of Mapleson systems

System	Advantages	Disadvantages
Mapleson A	Efficient during SV	Inefficient during CV APL positioned close to patient so difficult to operate
Mapleson B		Inefficient during SV and CV
Mapleson C	Compact and lightweight	Inefficient during SV and CV
Mapleson D	Efficient during SV APL position distal to patient Inspiration limb length can vary – useful for use in MRI suite	Inefficient during SV
Mapleson E	Low resistance: useful in paediatric setting	Difficult to scavenge waste gases Needs high FGF
Mapleson F	Low resistance: useful in paediatric setting RB allows ventilation	Difficult to scavenge waste gases Needs high FGF

Table 3

is exhaled, leaving only fresh and humidified dead space gas in the circuit.

- Intermittent positive pressure ventilation
 - Inspiration: with the APL valve closed the bag is squeezed generating an inspiratory breath which partially empties the bag.
 - Expiration: The subsequent expiratory breath fills the RB and tubing with both dead space and alveolar gas. If this is not flushed out with a high FGF rebreathing of exhaled CO₂ will occur.

A modification of the Mapleson A system is called the 'Lack' system. The Lack system uses an additional length of tubing, thereby moving the APL valve further from the patient and towards the RB. This runs either parallel to, or more commonly, inside the original corrugated tubing (co-axial) and eliminates the inconvenience of the APL sitting at the patient end. The FGF travels via the outer tube and the exhaled gas through the inner tube. There is a large amount of dead space present at the patient end, so the Mapleson A is not suitable for patients under 30 kg in weight.⁴

Mapleson B and C: These require a very high FGF to prevent rebreathing. The potential for mixing inspiratory and expiratory gases is due to the close proximity of the APL valve to the fresh gas port. The 'B' circuit has a length of corrugated tubing connecting the rest of the system to the reservoir bag and is highly inefficient, so much so that it is deemed to be impractical for clinical use for either SV or CV. The Mapleson C (often referred to as a 'Water's circuit without absorber') is used in resuscitation situations and for short patient transfers.

Mapleson D: FGF is introduced at the patient end of the system with the heavy components, namely the APL valve and RB, sited away from the patient. It is mostly used in the coaxial form known as the 'Bain' system. The Bain system consists of narrow inner tubing that delivers FGF directly to the patient, who will then exhale down the outer corrugated tubing to the reservoir bag and APL valve. Disconnection of the inner tubing can result in an increased dead space which causes massive rebreathing. Therefore, one must to perform 'Pethick's test' before use to

assess for a disconnection. The inner tube of the Bain circuit is occluded at the patient end using the end of a 2 ml syringe plunger. If the tube is connected, this causes back pressure on the FGF and the flowmeter bobbin will dip. Alternatively, rapid flushing of FGF through an intact system leads to a venturi effect, causing the reservoir bag to collapse.

Mapleson D systems are most efficient when used during IPPV and will lead to rebreathing during SV.

- Spontaneous ventilation
 - Inspiration: The patient takes a breath from the fresh gas which has filled the outer corrugated tubing and reservoir bag.
 - Expiration: Exhaled gases, mixed with the continuous FGF, travel down the corrugated tubing towards the reservoir bag and APL valve. Once pressure within the system is high enough, the APL valve opens and vents exhaled gases.
 - The expiratory pause allows the FGF to flush out the exhaled gas and fill the corrugated tubing with any excess vented. High FGFs are required to prevent rebreathing.
- Intermittent positive pressure ventilation
 - Inspiration: The RB is squeezed, forcing its contents and all fresh gas distal to it into the patient.
 - Expiration: Exhaled gases, mixed with the continuous FGF, travel down the corrugated tubing towards the reservoir bag and APL valve. Once pressure within the system is high enough, the APL valve opens and vents exhaled gases.
 - Factors affecting rebreathing (e.g. minute ventilation and inspiratory flow rate) are controlled by the anaesthetist, allowing a lower FGF. This is consequently a more efficient system, requiring FGF of only 70 ml/kg/min, equal to VA.

Mapleson E: Introduced in 1937 as the Ayre's T-piece, this functions much like a Mapleson D, has minimal dead space, no valves and generates very little resistance to breathing. This makes it ideal for paediatric anaesthesia in children weighing less than 20 kg. The open-ended corrugated tubing

acts as an inspiratory reservoir and consequently must have a length that exceeds the tidal volume of the patient. During expiration the tubing fills with dead space and alveolar gas which is then flushed out by the FGF; the absence of an expiratory pause in small infants means that some rebreathing is inevitable at modest FGF. The FGF is ultimately the sole determinant of whether rebreathing occurs and directly influences the oxygen concentration of inspired gas. Therefore if the FGF is not equal to the inspiratory flow rate air will be entrained creating a dilutional effect.

Mapleson F: Mapleson described five systems in his classification but the Jackson Rees modification of the Mapleson E has led to an unofficial sixth. It is mainly used in paediatric anaesthesia. An open-ended valve-less bag is attached to the expiratory limb of a Mapleson D allowing the application of continuous positive airway pressure or hand ventilation whilst also providing a visual indicator of respiration. As with the Bain system, the reservoir bag can be replaced by a mechanical ventilator.

Humphrey ADE Circuit: In 1938 Dr David Humphrey invented this single system that incorporates both the Mapleson A and D systems and allows the user to alternate between them by the turn of a lever. The lever is moved upwards for SV and flow is directed through the RB and the APL valve, functioning like a Mapleson A. When IPPV is required the lever is moved down and the flow bypasses the RB and is instead directed through the ventilator, becoming a Mapleson D. If no ventilator is connected and the tubing is left open ended, then the system works as an Ayres T-piece (the 'E' of ADE).² The gas is then conducted to and from the patient via the inspiratory and expiratory limbs of anaesthetic tubing. The system is suitable for adult and paediatric use owing to its low resistance.

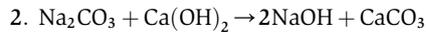
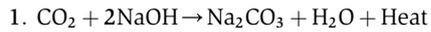
Enclosed Affluent Reservoir system (EAR): This system (described by Miller and Miller in 1988) was designed to work efficiently for both SV and IPPV.⁵ It performs as a Mapleson A, but has the reservoir bag and APL valve within a non-distensible container. A piece of corrugated tubing and a further reservoir bag is connected to this container and this second bag is squeezed during hand ventilation, forcing air into the container and compressing the enclosed reservoir bag to deliver a breath. The APL valve is opened during passive expiration to allow ventilation of alveolar gas. During SV there is no pressure within the container and the APL valve remains fully open as for a Mapleson A. FGF requirements are the same for each mode of ventilation, namely 70–100 ml/kg/min.

Breathing systems with CO₂ absorber

Carbon dioxide absorbers

For a system to be efficient, the removal of CO₂ from the exhaled gas is an essential process. The chemical reaction between CO₂ and either soda lime [94% Ca(OH)₂, 5% NaOH, 1% KOH] or Baralyme [80% Ca(OH)₂, 20% Ba(OH)₂] and a dye indicator allows CO₂ to be safely and efficiently removed. This is an exothermic reaction, with water as a by-product, and warms and humidifies the system. Soda lime is presented as dyed granules, size 4–8 mesh, with small amounts (0.2%) of silica to prevent

disintegration of the granules. The dye changes the colour of the granules once they have become exhausted. NaOH and KOH act as catalysts and are regenerated at the expense of the Ca(OH)₂.⁴



To prevent channelling of gases via a settling process, and consequent inefficiency, the canisters are used in the upright position.

Bidirectional flow

To-and-fro breathing system: No longer widely used, this system initiated the development of the circle system. It consists of a Mapleson C system with a horizontal soda lime canister positioned between the RB and APL valve. The canister serves to warm and humidify the gases, but it is cumbersome and inefficient as the granules nearest the patient are exhausted first, thus increasing dead space with channelling likely as the canister is horizontal.⁴

Unidirectional flow

The circle system (Figure 1): By using soda lime to absorb the patient's exhaled CO₂, this system allows the exhaled gases, including the volatile agent, to be re-circulated. Lower flows are possible making this system more efficient and less polluting, as well as warming and humidifying inspired gases. Gas analysers are essential at low flows to ensure adequate volatile and oxygen are administered and that rebreathing does not occur via absorbent exhaustion. The system consists of:

- two one-way valves
- a reservoir bag
- APL valve
- a soda lime cannister
- a Y-piece patient connector
- a source of FGF.

The positioning of the vaporizer can either be outside the circle (VOC), e.g. on the anaesthetic machine backbar, or inside

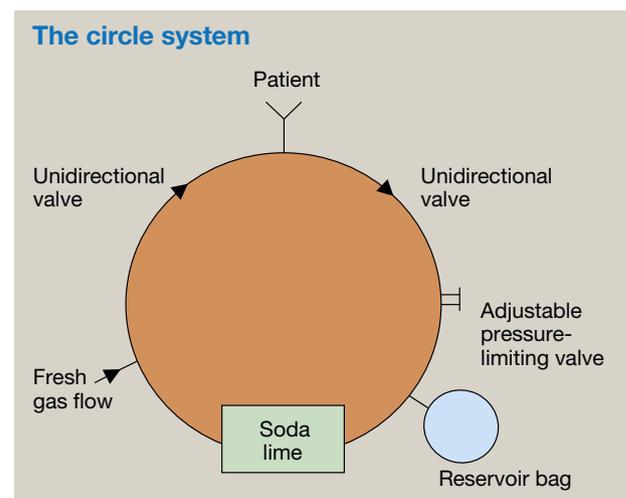


Figure 1

the circle (VIC). In order for a VIC to work, the vaporizer must have an extremely low internal resistance to allow easy passage of the gas.⁴ There is also an increased risk of high volatile concentrations owing to vapour containing gas to-and-froing through the vaporizer, so inspired anaesthetic gas monitoring is essential. In a spontaneously breathing patient, VIC can lead to inadequate anaesthesia as the concentration of the volatile anaesthetic will be dependent on the patient's inspiratory flow rate. VOC allows the required volatile concentration to be achieved by adjusting the vaporizer; the maximum volatile concentration can never be greater than that set. ◆

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