Breathing Systems in Anaesthesia

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QUESTIONS

Before continuing, try to answer the following questions. The answers can be found at the end of the article, together with an explanation. **Please answer True or False:**

1. **When managing a 70kg spontaneously breathing patient, the following fresh gas flows would be sufficient to prevent rebreathing:**
   a. 6 litres per minute in a Mapleson A system
   b. 6 litres per minute in a Water's system
   c. 12 litres per minute in a Bain system
   d. 9 litres per minute in a Mapleson B system
   e. 9 litres per minute in a Ree's T-piece

2. **Regarding Mapleson breathing systems:**
   a. The Bain system is a coaxial Mapleson A system
   b. The Mapleson D system is most efficient in ventilated patients
   c. A Mapleson C system has no adjustable pressure valve
   d. A Mapleson E (Ree's T-Piece) is suitable for use in patients up to 30kg
   e. The adjustable pressure valve requires a pressure of 1cm H_2O to open it at its minimum setting

3. **Regarding circle systems:**
   a. A high fresh gas flow rate is initially required to equilibrate the system
   b. The main component of soda lime is potassium hydroxide
   c. Compound A can be generated if low flow is used
   d. If the one-way valve becomes stuck, it leads to an increase in dead space in the system
   e. A closed circle system requires a lower fresh gas flow than a semi-closed system

Key Points

- Knowledge of anaesthetic breathing systems is essential for anaesthetists.
- Different breathing systems show varying efficiencies in spontaneously breathing and ventilated patients.
- Knowing the efficiencies of an individual breathing system enables the user to deliver fresh gas to a patient in a way that minimises rebreathing of carbon dioxide.
- Evaluating the performance of a breathing system requires an understanding of the positioning of individual components as well as the pressure changes during spontaneous and controlled ventilation.

INTRODUCTION

The function of breathing systems is to deliver oxygen and anaesthetic gases to patients and eliminate carbon dioxide. All breathing systems are composed of similar components but are configured differently. The common components include: fresh gas flow, tubing to direct gas flow, an adjustable pressure limiting valve to control pressure within the system & allow scavenging of waste gas and a reservoir bag to store gas and assist with ventilation.

Each breathing system receives three sources of gas: fresh gas, exhaled dead space gas and exhaled gas from the alveoli. The proportions of each within the system are most greatly influenced by fresh gas delivery. Gas is delivered to spontaneously breathing patients at sub-atmospheric (negative) pressure during inspiration and atmospheric pressure during exhalation. Conversely, ventilated patients receive gas at positive pressure during inspiration and atmospheric pressure during exhalation. In this tutorial, we will explore the different components and types of breathing systems used in common practice.

COMPONENTS OF BREATHING SYSTEMS

A breathing system is made up of components that connect the patient to the anaesthetic machine[1], and is usually composed of some or all of the following components:

1. The **Adjustable Pressure Limiting (APL)** valve allows a variable pressure within the anaesthetic system using a one-way, spring-loaded valve. At a pressure above the opening pressure of the valve, a controlled leak of gas is allowed from the system, which enables control of the patient's airway pressure. The minimum pressure required to open the valve is 1cm H_2O. A safety mechanism exists to prevent pressure from exceeding 60cm H_2O, however, be aware that pressures below this can lead to barotrauma.

2. The **reservoir bag** allows collection of fresh gas flow during expiration, which in turn minimises the amount of fresh gas required to prevent rebreathing. In addition, it allows the anaesthetist to monitor the breathing pattern of a spontaneously breathing patient. These are usually plastic or rubber, and can come in sizes between 0.5 litres to 6 litres. However, the most common size in the adult system is 2 litres. Laplace's Law states that pressure is equal to twice the radius divided by the radius of the bag. Therefore, as the bag increases, the pressure within it reduces. This is an important safety measure as the expansion of the bag to accommodate gas limits pressure within the system.

3. The **inspiratory limb** allows passage of fresh gas flow to the patient for inspiration. The **expiratory limb** allows passage of expired gas from the patient. Although tubing length varies depending on the system in use, the diameter is of standard size: 22mm for adult and 18mm for paediatric systems.

MAPLESON CLASSIFICATION

In 1954, Prof William Mapleson published an article in the British Journal of Anaesthesia first describing the Mapleson classification of breathing systems[2]. Although named after him, the 5 semi-closed systems which make up this classification were first drawn by his colleague Dr William Mushin[3].

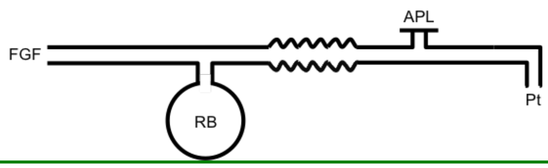
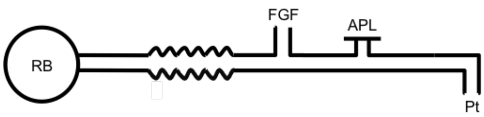
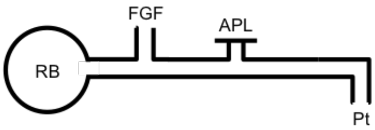
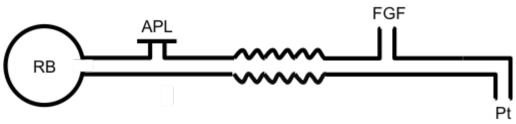
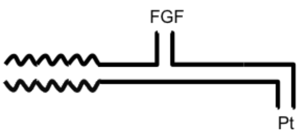
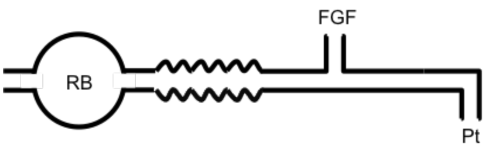
Mapleson Classification	**Diagram** FGF = fresh gas flow RB = reservoir bag APL = adjustable pressure limiting valve Pt = patient	**Volume of fresh gas flow to prevent rebreathing in spontaneously breathing patients** (multiples of MV)
A *Macgill Lack (coaxial)*		0.8 - 1.0
B		1.5 - 2.0
C *Water's*		1.5 - 2.0
D *Bain (coaxial)*		2.0 - 3.0
E *Ayer's T-piece*		2.0 - 3.0
F *Ree's T-piece*		2.0 - 3.0

Figure 1: The Mapleson Classification of breathing circuits

Mapleson A System

This breathing system consists of a reservoir bag at the anaesthetic machine and an APL valve at the patient end, separated by between 110-180cm of tubing.

During the first breath, all gases inhaled are fresh and do not contain any exhaled gas. As the patient expires, the dead space gases are exhaled first. As these have not undergone gas exchange, they contain the same gas mixture as was inhaled by the patient. These gases collect in the tubing. Meanwhile the fresh gas flow exiting the anaesthetic machine fills the remaining tubing and reservoir bag. As the pressure increases in the system and the patient continues to expire, the alveolar gases that have been used in gas exchange are forced to exit through the APL valve. As the patient takes the next breath, the dead space gases from the previous breath are inspired first, followed by fresh gas from the reservoir bag.

The Mapleson A system is most efficient when used in spontaneously breathing patients. In such cases, a fresh gas flow equivalent to minute volume is required as fresh gas can be accommodated in both the reservoir bag and the inspiratory limb tubing (550ml). However, if used for ventilated patients, the system is inefficient as the high pressure from the ventilator forces the fresh gas flow preferentially through the APL valve before the expired alveolar gas. It therefore requires a much high fresh gas flow in order to prevent rebreathing.

Due to the arrangement of the system, the weight and position of the APL valve at the patient end can be inconvenient. The co-axial system (Lack system) has been developed for this: it features the expiratory limb tubing inside inspiratory limb and therefore has both APL valve and reservoir bag away from the patient while still maintaining the Mapleson A arrangement.

Mapleson B & C Systems

The Mapleson B & C systems are similar apart from the B system having tubing between the reservoir bag and the fresh gas flow, which further acts as a reservoir. As the APL valve is between the fresh gas flow and the patient, fresh gas that has not been involved in gas exchange is vented during expiration along with the expired gases in the spontaneously breathing patient. A similar process happens when the patient is being ventilated: fresh gas is vented through the APL valve before it can be delivered to the patient. Neither system is efficient for spontaneously breathing or ventilated patients as 1.5 to 2 times the minute volume is required to prevent rebreathing.

Mapleson D System

The Mapleson D system features the fresh gas flow being introduced at the patient end of the system. The APL valve and reservoir bag are at the anaesthetic machine end of the system and are separated from the patient by 180cm of tubing. An advantage of this is that all the heavy components are away from the patient.

Mapleson D systems are most efficient when used for ventilated patients. As the ventilator delivers the breath, the patient inspires gas from the fresh gas flow and reservoir. As the patient expires, the waste gas travels along the tubing and exits the system through the APL valve. During the expiratory pause, the fresh gas flow fills the tubing, further pushing the waste gas out through the APL valve. By the time the next breath is delivered by the ventilator, the tubing is full of fresh gas. In this case, a fresh gas flow equivalent to minute volume is required to prevent rebreathing.

If a Mapleson D system is used for spontaneously breathing patients, the patient's expired gases collect in the tubing and reservoir bag before the pressure generated is enough to open the APL valve. This causes significant rebreathing unless 2 to 3 times the minute volume is used.

A commonly used configuration is the coaxial Mapleson D system, also called the Bain system, where the fresh gas flow is delivered via the inner tube, and waste gases are removed via the outer tube. This reduces clutter around the anaesthetic machine, however, the internal tube can kink, leak or become disconnected, resulting in hypoxia. This is a disadvantage of all coaxial systems.

Mapleson E & F Systems

The Mapleson E & F systems are valve-less systems which offer low resistance to breathing and are therefore used in paediatric patients up to 30kg. Both systems have the fresh gas flow near the patient, connected to an open-ended tube. In the Mapleson F system, there is a double-ended reservoir bag at the end of this tube.

During inspiration, the patient inhales fresh gas directly from the fresh gas flow and gas which has collected in the tubing. The patient then exhales dead space gas followed by gas that has been used in gas exchange. During the expiratory pause, the pressure from the fresh gas flow pushes all of this expired gas out of the open-ended tube. In the Mapleson F system, some of this mixed gas collects in the reservoir bag. A high fresh gas flow of 2 to 3 times minute volume is required to prevent rebreathing.

These systems have some disadvantages. Since no APL valve is present, it is not possible to scavenge waste gas: this is vented directly into the theatre environment. In addition, it is not possible to generate positive pressure in the Mapleson E system, which means that CPAP cannot be used. Also, the lack of reservoir bag makes hand ventilation of these patients more difficult.

CIRCLE SYSTEMS

A circle system improves the efficiency of anaesthetic gas delivery by recycling gas that is expired from the patient and thus reducing the amount of fresh gas flow required.

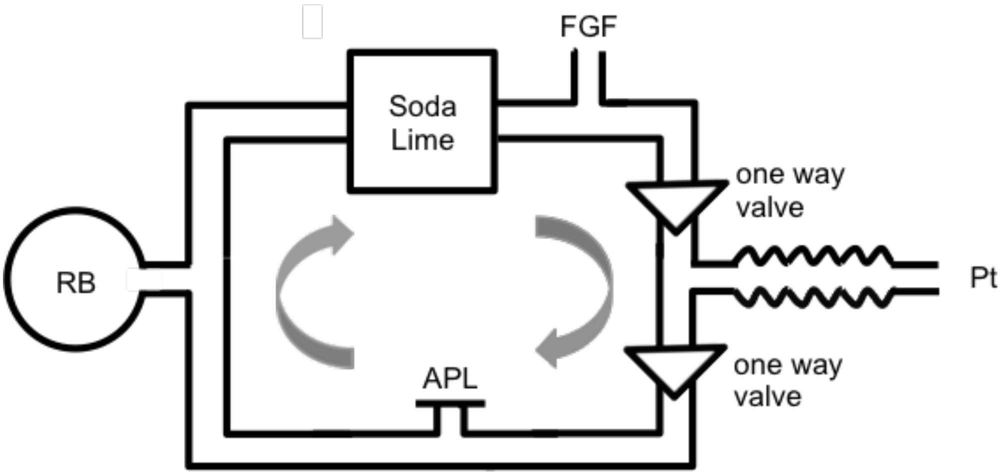


Figure 2: A circle system

Fresh gas flow leaves the anaesthetic machine and passes to the patient via a one-way valve during inspiration. As expiration occurs, the exhaled gases from the patient pass via a one-way valve to the APL valve, then on to the reservoir bag (or ventilator). Before this expired gas is mixed with the fresh gas flow and delivered to the patient, it passes through soda lime, which absorbs carbon dioxide. Initially, a high fresh gas flow is required in order to fill the breathing system with the desired mixture and to equilibrate the system, after which a minimal flow of 0.5 litres per minute can be used.

A circle system can be semi-closed or closed. In a semi-closed circle, the APL valve is opened, and allows excess gas to be removed from the system and reduce the risk of barotrauma. However, the relatively high fresh gas flow allows a vaporiser outside circle (VOC) to be used, which can introduce a higher percentage and more precise anaesthetic gas into the mixture.

In a closed circle, the APL valve is completely closed. Although this is the most efficient anaesthetic breathing system, it leaves little margin for error as the fresh gas flow must meet the exact patient requirements, and the soda lime must absorb all expired carbon dioxide. The minimal flow in this system only allows the use of a vaporiser inside circle to be used. A detailed description of vaporisers is beyond the scope of this article.

One of the most important components of the circle system is soda lime. This is a mixture of 80% calcium hydroxide, 4% sodium hydroxide, and 16% water. It also contains a pH-sensitive dye, which indicates when the granules are exhausted. Soda lime granule are described as 4-8 mesh, which means that each granule will fit through a mesh that has 4 openings per inch, but not one that has 8. The following exothermic reaction occurs:

$$CO_2 + 2NaOH \rightarrow Na_2CO_3 + H_2O$$
$$Na_2CO_3 + Ca(OH)_2 \rightarrow 2NaOH + CaCO_3$$

Important facts to note about circle systems:

- The one-way valves can become stuck by water vapour within the system leading to an increase in dead space.
- The one-way valves increase the resistance to breathing in the system.
- The lower the fresh gas flow rate, the longer it takes for changes made to the anaesthetic gas mixture to occur.
- Monitoring the gas composition within the circle is essential.
- Use of sevoflurane at low flow rates below 1 litre/minute can generate Compound A by reaction with soda lime. Although this is nephrotoxic in rat models there is currently no evidence of harm in humans.
- One must be familiar which the colour of the pH-sensitive dye as different manufacturers use different colours to indicate that the soda lime is exhausted.

Uneven distribution of soda lime granules in the canister causes gas to flow unevenly and reduces the efficiency of the soda lime.

System	Advantages	Disadvantages
Mapleson A	Efficient for spontaneously breathing patients.	Inefficient for ventilated patients. APL valve at patient end can be difficult to operate.
Mapleson B		Inefficient for both spontaneously breathing & ventilated patients.
Mapleson C	Lightweight and compact.	Inefficient for both spontaneously breathing & ventilated patients.
Mapleson D	Efficient for ventilated patients. Heavy components are away from patient. Can have a long inspiratory limb: good for use in MRI setting.	Inefficient for spontaneously breathing patients.
Mapleson E	Useful for patients under 30kg as low resistance due to lack of valve.	Difficult to scavenge waste gas. Requires high fresh gas flow.
Mapleson F	Useful for patients under 30kg as low resistance due to lack of valve. Reservoir bag allows ventilation.	Difficult to scavenge waste gas. Requires high fresh gas flow.
Semi-closed circle	Efficient for maintenance of anaesthesia. Relatively high fresh gas flow allows use of vaporiser outside circle.	Less efficient than closed circle.
Closed circle	Highly efficient, can be used at minimal flows.	Fresh gas flow must match patient demands at all times.

Figure 3: Summary of advantages & disadvantages of various breathing systems

ANSWERS TO QUESTIONS

1) When managing a 70kg spontaneously breathing patient, the following fresh gas flows would be sufficient to prevent rebreathing

a) **True**. A 70kg patient has a tidal volume of 7ml/kg multiplied by a respiratory rate of 12, giving 5.8 litres per minute. A Mapleson A system requires a fresh gas flow equivalent to the minute volume to prevent rebreathing
b) **False**. A Waters system is a Mapleson C system, which requires 1.5 to 2 times the minute volume, which is at least 8.8 litres per minute
c) **True**. A Bain system is a coaxial Mapleson D
d) **True**. The Mapleson B system needs a FGF of at least 9 litres per minute
e) **False**. A Ree's T-piece is a Mapleson F system, which requires a fresh gas flow of 2 to 3 times the minute volume to prevent rebreathing.

2) Regarding Mapleson breathing systems:

a) **False**. The Bain system is a coaxial Mapleson D. A coaxial Mapleson A system is also known as a Lack system
b) **True**. The Mapleson D system is most efficient in ventilated patients
c) **False**. The Mapleson C system features an APL valve between the fresh gas flow and the patient. The valveless systems are the Mapleson D and E systems.
d) **False**. While a Mapleson E system is only suitable for use in patients up to 30kg, it is an Ayre's T-Piece. A Ree's T-Piece is a Mapleson F system
e) **True**. The adjustable pressure valve requires a pressure of 1cm H_2O to open it at its minimum setting

3) Regarding circle systems

a) **True**. A high fresh gas flow rate is initially required to equilibrate the system
b) **False**. The main component of soda lime is calcium hydroxide
c) **True**. Compound A can be generated by reaction of sevoflurane with soda lime at low flows
d) **True**. If the one-way valve becomes stuck, it leads to an increase in dead space in the system
e) **True**. A closed circle system requires a lower fresh gas flow than a semi-closed system

References and Further Reading

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