ANAESTHETIC BREATHING SYSTEMS

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The delivery systems which conduct anaesthetic gases from an anaesthetic machine to the patient are known as the 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 a pressure relief valve. A number of mechanical ventilators include a specific breathing system eg the Manley series. Other ventilators have been designed to operate with existing breathing systems e.g. the Penlon Nuffield 200.

The function of breathing is to maintain a supply of oxygen to the lungs for the blood to transport to the tissues and to remove carbon dioxide from the body. 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 6-10mls/kg), 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 - 2mls/kg). The concentration of carbon dioxide then rises rapidly to a plateau of about 5% as alveolar gas is breathed out. The volume of alveolar gas expired per minute is called the alveolar minute ventilation. The anatomical dead space is 25-35% of each tidal volume. 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 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 this occuring as it may lead to serious elevations in blood CO_2 levels. The amount of rebreathing that occurs with any particular anaesthetic breathing system depends on four factors; the design of the individual breathing circuit, the mode of ventilation (spontaneous or controlled), the fresh gas flow rate and the patient's respiratory pattern. Circuits may eliminate rebreathing either by ensuring an adequate flow of fresh gas which flushes the circuit clear of alveolar gas, or, in the case of a circle system by the use of sodalime which absorbs the CO_2 so that low fresh gas flows may be used. For each of the circuits described below, fresh gas flow rates that will ensure minimal rebreathing will be suggested.

Classification of breathing systems

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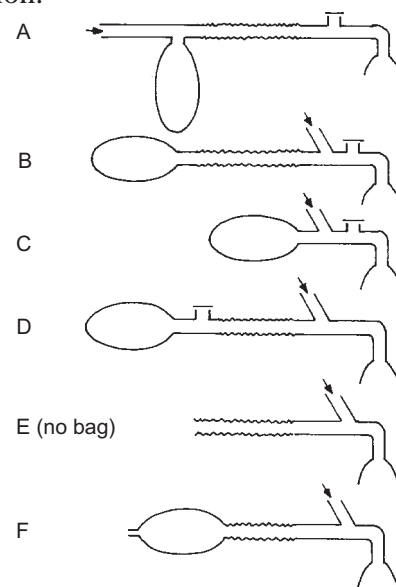

Figure 1. Mapleson classification of anaesthetic breathing systems. The arrow indicates entry of fresh gas to the system.

The Mapleson A (Magill) system was designed by Sir Ivan Magill in the 1930's 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 2 litre reservoir (breathing) bag which partially collapses giving a visual confirmation that breathing is occurring.
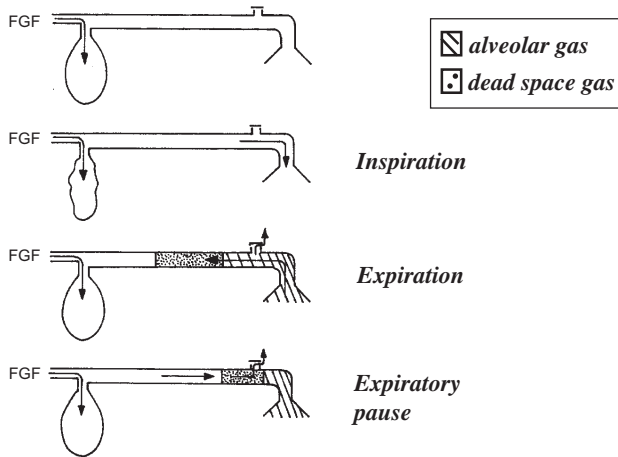
Figure 2. Mode of action of Magill attachment during spontaneous ventilation

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. When the system is functioning correctly, without any leaks, a fresh gas flow (FGF) equal to the patients alveolar minute ventilation is sufficient to prevent rebreathing. In practice however, a FGF closer to the patients total minute ventilation (including dead space) is usually selected to provide a margin of safety. An adult's minute volume is approximately 80mls/kg /min and thus for a 75kg man a FGF of 6 litres per minute will prevent rebreathing. 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. The inspiratory force 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 corrugated tubing and may reach the bag which will then contain some carbon dioxide. During the next inspiration when the bag is compressed alveolar gas re-enters the patients 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 (FGF of about 12-15 litres/min) which is obviously 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 that the patient's minute volume.

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 3) 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).
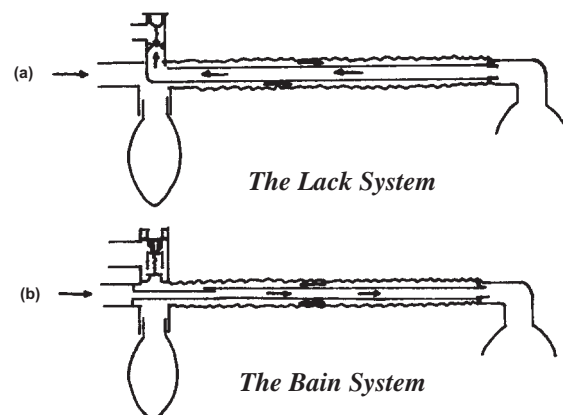

Figure 3. Coaxial anaesthetic breathing systems. (a) Lack system (Mapleson A). (b) Bain system (Mapleson D).

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.

The Mapleson B and C breathing systems (Figure 1) 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 used on intensive care units. High flows of gases are needed to prevent rebreathing of CO_2 and this system was at one time combined with a canister of sodalime to absorb CO_2 (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.
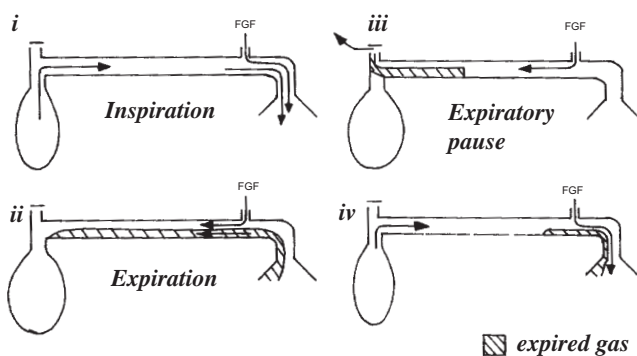

Figure 4. Mode of action of Mapleson D breathing system during spontaneous ventilation.

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 4). 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 will occur. A FGF of at least 8-10 litres/min (150mls/kg/min) 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/min is usually adequate for controlled ventilation; 100mls/kg/min will result in a degree of hypocapnia (lowered CO_2 level in the blood).

Modifications of the Mapleson D system
The Bain Circuit (Figure 3) is the most commonly used form of the Mapleson D system. It is a co-axial circuit which was introduced in 1972 by Bain and Spoerel. Unlike the Lack co-axial circuit described above, fresh gas flows down the central narrow bore tubing (7mm i.d.) to the patient and exhaled gases travel in the outer corrugated tubing (22mm i.d.). 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 green tubing should be occluded with a finger or the plunger of a 2ml syringe when a rise in gas pressure within the anaesthetic circuit should be observed.

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

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. This system is suitable for children under 20kg. Fresh gas flows of 2 - 3 times minute volume should be used to prevent rebreathing during spontaneous ventilation, with a minimum flow of 3 litres/minute, eg a 4 year old child weighing 20kg has a normal minute volume of 3 litres/min and would required a FGF of 6-9litres/min. During controlled ventilation in children normocapnia can be maintained with a fresh gas flow of 1000mls + 100mls/kg. e.g. a 4 year old weighing 20kg would need a total FGF of around 3litres/min.

Combination of the Mapleson A, D and E Systems - The Humphrey A D E Circuit. The Mapleson A circuit is inefficient for controlled ventilation as is

Figure 5.

the Mapleson D circuit for spontaneous ventilation. David Humphrey has designed a single circuit (Figure 5) 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 by-passed 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 a particular circuit. If the lever on the Humphrey block is moved from "up" to "down" whilst 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. This has led to anaesthetists ocasionally concluding that their endotracheal tube required changing.

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 are known as circle systems, were first devised by Brian Sword 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 and 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
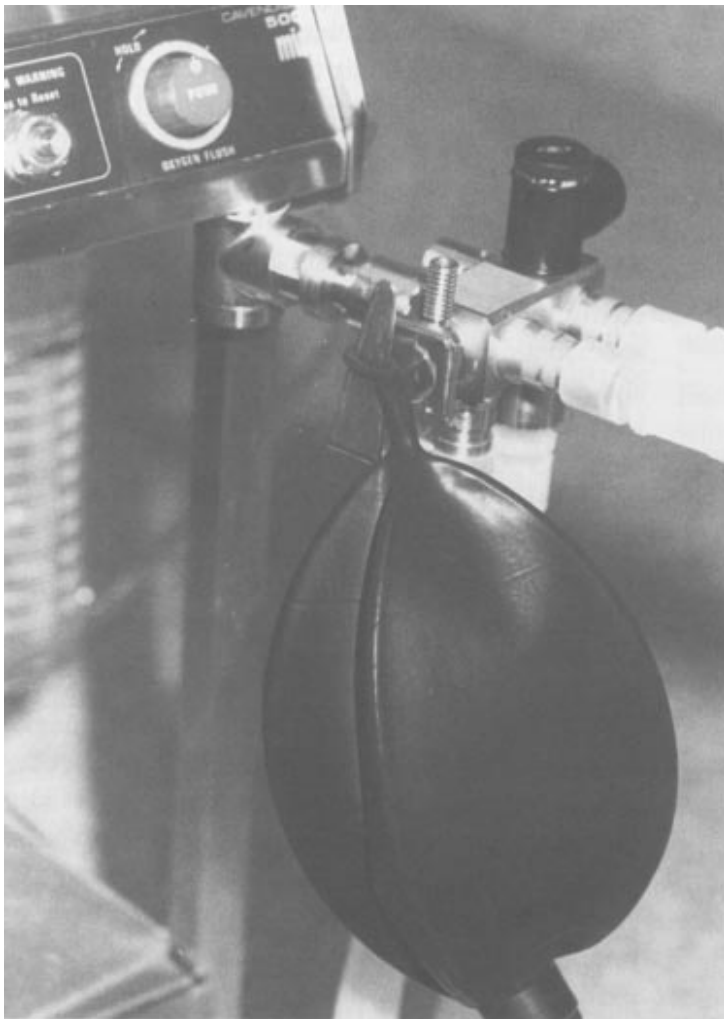
pH decreases and the colour of the dye changes from pink to yellow/white. When around 75% of the soda lime has changed colour it should be replaced. The soda lime canister should be mounted vertically on the anaesthetic machine to prevent the gases passing only through a part of the soda lime (streaming).

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° centigrade. There are therefore additional advantages of using circle systems in that the gases within the circle are warmed and humidified prior to inspiration. (Baralyme is a commercially available CO_2 absorber which contains 5% barium hydroxide instead of sodium hydroxide.)
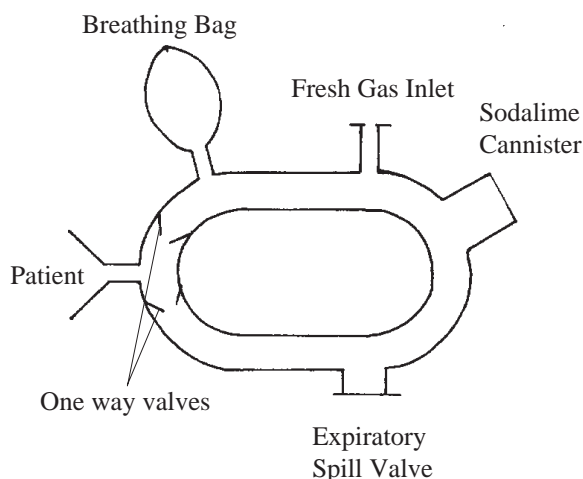

Figure 6. Arrangement of circle system.

Design of Circle Systems. A circle system (Figure 6) is composed of two one way valves (one inspiratory and one expiratory), 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 over-dosage. 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 when dangerously high concentrations can build up. Vaporisers should only be placed inside the circle (VIC) 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. During the first 5 - 10 minutes of an inhalational anaesthetic using a volatile anaesthetic agent in oxygen and nitrous oxide, large amounts of the anaesthetic agent and nitrous oxide will be taken up by the patient, and the nitrogen contained in the patient's lungs and dissolved in their body will be washed out. If low fresh gas flows are used immediately the patient is connected to the circuit the nitrogen will not be flushed out of the circle system and will dilute the anaesthetic agent concentration. This may be prevented by using conventional fresh gas flows of 6litres/min for the first 5-10 minutes of each anaesthetic before reducing the flow rates.

Reducing the fresh gas flow rates. 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 (<1000mls/min) unless 40 - 50% oxygen is supplied to the circle, the oxygen concentration within the circle can fall to unacceptably low levels due to the greater uptake of oxygen compared with nitrous oxide. 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 to ensure that the inspired oxygen concentration remains at a safe level is 1500mls/min (nitrous oxide 900mls/min and oxygen 600mls/min). Conventional flow meters and vaporisers become

unreliable if flows are set lower than these levels.

These comments are less important if only oxygen and a volatile agent is being used in the circle. Under these circumstances there is no risk of oxygen dilution and the flows may be reduced to 1000mls/min.

With flows of >1500mls/min the inspired concentration of volatile agent will be similar to that set on the vaporisers. With flows <1500mls/min the volatile agent concentration may fall within the circuit and the setting on the vaporiser may need to be increased.

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 breathing systems available, and this review has concentrated on the most commonly used ones. It is essential for the safety of patients that an anaesthetist routinely checks the anaesthetic circuit before use and has a thorough understanding of the function and pitfalls of a particular system before using it.