Anaesthetic circuits: safe selection & use
Selection of an appropriate breathing system for the patient and the procedure plays an important role in patient safety during anaesthesia. In order to select an appropriate system, it is important to understand how each one works, its advantages, disadvantages and limitations. This is also important when performing safety checks. An understanding of some basic physiology and concepts such as dead space and resistance is essential, as is an understanding of how to calculate fresh gas flow for both rebreathing and non-rebreathing systems.

Tidal volume and minute volume
The tidal volume is the volume of air the patient inspires in a normal breath. The minute volume is the volume of air the patient inspires in one minute. This is equal to the minute volume multiplied by the respiratory rate.

Minute volume = respiratory rate x tidal volume

Tidal volume is roughly 10 to 20 mL/kg body weight. Minute volume is therefore about 15 x body weight x respiratory rate. Minute volume is used to calculate fresh gas flows for non-rebreathing systems.

Oxygen consumption
Oxygen consumption is the volume of oxygen used per minute by the body for metabolism. It is roughly 10 mL/kg/minute for dogs and cats. Oxygen consumption is used to calculate the minimum fresh gas flow requirement for rebreathing systems such as the circle.

Resistance
Resistance in anaesthetic breathing systems means resistance to gas flow. There are two types of flow when considering gas flow through a tube. In laminar flow, the gas flows smoothly in layers along the tube. When gas flow is turbulent, there are lots of whirlpools in the flow. Resistance is higher with turbulent flow than with laminar flow.
Factors increasing resistance: When flow is laminar, resistance increases with the length of the tube and the viscosity of the gas. Turbulent flow creates higher resistance and is promoted by corrugated tubing, bends in the tubing, soda lime and valves.

Factors decreasing resistance: Resistance decreases with a larger radius of the tube. Of these factors the radius of the tube is the most important thing. If the radius is halved the resistance is increased 16 fold. Resistance in breathing system can be substantially reduced by using smooth inner bore tubing.

Why is resistance important? If you try to breathe through a very narrow tube (i.e. a tube with high resistance) you have to use more effort, so you increase the work of breathing. Under anaesthesia this does not happen due to muscle relaxation, and instead the patient is prevented from ventilating properly (hypoventilation), resulting in increased arterial and end expired carbon dioxide levels. Larger and fitter patients have stronger respiratory muscles and can cope better with resistance in the breathing system.

Resistance in breathing systems is caused by narrow hoses, long hoses, corrugations, bends, kinks, valves and soda lime. Controlled ventilation overcomes breathing system resistance, so that during controlled ventilation high resistance systems can be used for smaller patients.

Dead space

Dead space is composed of three parts: anatomical, alveolar and mechanical (or apparatus). Anatomical dead space is the part of the respiratory tract where no gas exchange occurs. It extends from the incisors to the conducting bronchioles. Alveolar dead space refers to gas in a small number of alveoli which are ventilated but not perfused. Since no blood is delivered to these alveoli no gas exchange occurs there. Anatomical dead space and alveolar dead space together comprise physiological dead space. Mechanical dead space is the part of the endotracheal tube (measured from the incisors) and breathing system where inspired and expired gases mix. Dead space gas is the last part of the breath to be breathed in and the first part to be breathed out. Dead space is important because it reduces the proportion of each breath that takes part in gas exchange. Each breath the patient takes in (the tidal volume) consists of gas which reaches the alveoli and participates in gas exchange, plus gas which occupies the dead space (mechanical and physiological):

\[
\text{Tidal volume} = \text{dead space} + \text{alveolar volume}
\]

Therefore:\n
\[
\text{Alveolar volume} = \text{tidal volume} - \text{dead space}
\]

We said earlier that:

\[
\text{Minute volume} = \text{tidal volume} \times \text{respiratory rate}
\]
Therefore: Alveolar minute volume = (tidal volume - dead space) x resp rate

Obviously the more gas that reaches the alveoli, the better the patient’s gas exchange and the better the patient will ventilate and oxygenate. Decreased alveolar minute ventilation leads to CO$_2$ retention and possibly hypoxia. Keeping dead space to a minimum increases the proportion of useful gas per breath by maximising alveolar ventilation. The smaller the tidal volume the greater the significance of the mechanical dead space. A large volume of mechanical dead space compared to the patient’s tidal volume means CO$_2$ is retained and the end of each breath which the patient then rebreathes. This results in increased inspired CO$_2$ (FiCO$_2$), which should be zero, resulting in higher arterial and end expired CO$_2$ levels.

We cannot easily influence physiological dead space. But we can reduce mechanical dead space by ensuring that the ETT does not extend beyond the incisors and by selecting a breathing system with a small dead space such as a T piece.

Adjustable pressure limiting valves are also known as pop off valves, APL valves or expiratory valves. These valves need to be closed for leak testing and sometimes to enable positive pressure ventilation. But they must be immediately opened otherwise pressure quickly builds up in the breathing system and this can damage the patient’s lungs (barotrauma). Valves on systems made by Intersurgical have a safety device so that once a certain pressure is reached they open and the patient’s lungs are protected (pressure relief valve).

APL of the mini Lack

Types of breathing system
There are two types of breathing systems: rebreathing and non-rebreathing systems. An understanding of how these systems work is essential for the safe and economical use of the systems.
Rebreathing systems:
With rebreathing systems, expired breath is recycled and rebreathed. The CO$_2$ is absorbed by soda lime. Fresh gas flows are calculated based on O$_2$ consumption, which is approximately 10 mL/kg/minute for small animals. So in theory a 10 kg dog could have a fresh gas flow of 100 mL/minute, but in reality technical issues make such low flows impractical.

Advantages The main advantage of these systems is the low fresh gas flow resulting in the use of less anaesthetic agent, making the system very economical for large animals. In addition, because the gas is recycled, expired moisture and heat are retained and there is less pollution. They can be used for spontaneous and controlled ventilation.

Disadvantages These systems have high resistance which smaller patients cannot cope with when spontaneously breathing. Regular replacement of the soda lime is required. The reaction between the soda lime and the inhalant agent is exothermic, and this, combined with the retention of heat can result in the patient becoming hyperthermic. The low fresh gas flow means that there is a slow response to changes in vaporiser settings. Because the gas is recycled and rebreathed, the concentration of anaesthetic agent which the patient breathes in is not the same as the vaporiser setting and is unknown unless there is agent monitoring.

When using nitrous oxide, it is possible to supply the patient with a hypoxic mixture of gases when using low flows. This is because the oxygen in the gas mixture is actually used up by the patient’s body for metabolism, but the nitrous oxide is not used up but is recirculated. You can use nitrous oxide with a rebreathing system with certain safety measures in place. If you are using pulse oximetry or have an oxygen analyser on the anaesthetic machine, you can ensure that the patient is saturating adequately and that you are providing enough oxygen. Or, you can use higher flow rates: 30 mL/kg/minute O$_2$ and 60 mL/kg/minute N$_2$O.

Denitrogenation: room air is 21% oxygen, 79% nitrogen, and our bodies are saturated with nitrogen in equilibrium with the atmosphere. When the animal is connected to a rebreathing system with 100% oxygen at the start of an anaesthetic, nitrogen flows down its concentration gradient to leave the patient and enter the breathing system. Oxygen flows in the other direction. This means that initially there may be high concentrations of nitrogen and low concentrations of oxygen in the system. Nitrogen must be purged from the system either by having relatively high fresh gas flows initially or by regularly dumping the bag contents.

Rebreathing systems are more expensive to buy and more difficult to clean than non-rebreathing systems.

Closed or semi-closed?
These terms refer to the way the rebreathing system is used, not the structure of the system. A rebreathing system can be run as closed or semi-closed. If it is closed, the fresh gas inflow is
equal to the $O_2$ consumption and the APL valve is kept closed. It is quite difficult to run a system this way. For gas flows less than about 250 mL/minute vaporisers become inaccurate and side stream capnographs remove up to 200 mL/minute for sampling. Also keeping the APL valve closed is potentially dangerous. Most people use the systems as semi-closed, where the fresh gas flow exceeds the patient’s requirement and the APL valve is kept partially or fully open depending on the fresh gas flow. Because of technical difficulties as above, normally a minimum flow rate of 500 mL/minute on patients up to 50 kg in body weight is suggested. The flow rate should be higher than this for the first 10 to 15 minutes to ensure adequate denitrogenation and also to increase the volatile agent concentration more rapidly.

**The circle system**

This consists of a circular system of hoses with 2 unidirectional valves, a patient connection, a fresh gas inlet, an APL valve, a soda lime canister and a reservoir bag. The bag should be 3 to 6 times the volume of the patient’s tidal volume, the soda lime canister should be at least twice the tidal volume. The unidirectional valves ensure that gas flows in one direction only so that the patient does not rebreathe $CO_2$-rich gas. Because these systems have soda lime, two unidirectional valves and an adjustable pressure limiting (APL) or pop off valve, they have high resistance which smaller patients cannot cope with.

**The to and fro system**

Gas flows from the patient, through an absorbent canister to a reservoir bag and back again (to and fro). The canister may be vertical or horizontal. It has fairly high resistance due to the soda lime so should only be used in animals greater than 15kg. It is a low volume system, resulting in rapid denitrogenation. They are cheap, simple, portable and easy to sterilise. The APL valve and fresh gas flow inlet are near the patient’s head which can be inconvenient. They are heavy with a lot of drag. As the anaesthetic progresses, the soda lime nearest the patient becomes exhausted resulting in increased dead space as the soda lime is used up. It is possible for the exhaled gas to channel over or through the soda lime so that is does not come into contact with it and the $CO_2$ is not absorbed. Because the soda lime is so near the patient the patient can become hyperthermic. If a suitable filter is not present, the patient can inhale soda lime particles resulting in bronchiolitis.
<table>
<thead>
<tr>
<th>Malfunction</th>
<th>Problem</th>
<th>Prevention/ solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhausted soda lime</td>
<td>Inspired and expired gases mix, massive increase in dead space</td>
<td>Regularly check &amp; replace soda lime. Capnography will detect this problem</td>
</tr>
<tr>
<td>Faulty unidirectional</td>
<td>Inspired and expired gases mix, massive increase in dead space</td>
<td>Check proper valve function regularly. Capnography will detect this problem</td>
</tr>
<tr>
<td>APL valve closed</td>
<td>Pressure build-up in system, barotrauma to patient's lungs</td>
<td>Always check valve is open before connecting patient</td>
</tr>
<tr>
<td>High resistance</td>
<td>Patient hypoventilates if spontaneously breathing</td>
<td>Only use on patients of about 10 kg more</td>
</tr>
<tr>
<td>Leaks</td>
<td>Patient does not receive desired concentration of anaesthetic, pollution</td>
<td>Leak test the system before use</td>
</tr>
<tr>
<td>Nitrogen build up</td>
<td>Hypoxic mixture of gases</td>
<td>Denitrogenate the system, Monitor SpO₂, inspired oxygen</td>
</tr>
<tr>
<td>Using nitrous oxide</td>
<td>Hypoxic mixture of gases</td>
<td>Monitor SpO₂, inspired oxygen concentration or use high flows</td>
</tr>
<tr>
<td>Mechanical dead space</td>
<td>Rebreathing of CO₂</td>
<td>Cut ETT, choose alternative system. Capnography will detect this problem</td>
</tr>
<tr>
<td>too large for patient</td>
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</tr>
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</table>

**Potentially dangerous problems with the circle system**

**Non-rebreathing systems**

With non-rebreathing systems a continual high fresh gas flow from the anaesthetic machine flushes away expired gas containing CO₂ so that only fresh gas is inhaled. No soda lime is required. Gas flows are calculated based on the minute volume and the circuit factor of the individual breathing system.

The lack of valves and soda lime means that they have low resistance. They are cheap to buy and simple to use with no need to replace soda lime. There is a quick response to changes in anaesthetic concentration due to the high fresh gas flows used. There is no need for denitrogenation and it is easy to use nitrous oxide.

But the high fresh gas flow requirements and therefore use of more anaesthetic agent means they are much less economical than rebreathing systems and they are too inefficient for larger animals. Expired heat and moisture are lost resulting in cooling of the patient. The different systems have different properties and they may perform differently if using controlled ventilation.

**The Mapleson classification system**

The Mapleson system classifies non-rebreathing systems in order of fresh gas flow efficiency. Mapleson A is the most efficient (lowest fresh gas flow requirement), (Magill, Lack); Mapleson B...
and C are rarely used clinically; Mapleson D (Bain), E (Ayres T piece) and F (Jackson Rees modified T piece) are the least efficient.

Mapleson A systems (Magill, Lack) are the most efficient non-rebreathing systems but are still far less efficient than a rebreathing system. The fresh gas flow requirement is equal to the minute volume, therefore the circuit factor is 1.

Magill: Consists of a single hose with the expiratory valve at the patient end and reservoir bag away from the patient near the anaesthetic machine. The reservoir bag volume should be 3 to 6 times the tidal volume and the expiratory hose volume must exceed tidal volume. The patient breathes oxygen from the hose and bag. When the patient breathes out, the breath returns down the hose towards the bag following the path of least resistance. When the pressure in the bag reaches the pressure required to open the expiratory valve, gas is expelled through the valve into the scavenging. In this way the first part of the expired breath (dead space gas not containing CO₂) is retained in the system and rebreathed, but the last part of the breath (the alveolar gas containing CO₂) is expelled into the scavenging.

The Lack functions in the same way as the Magill except that the expiratory valve has been moved away from the patient for convenience, resulting in two limbs. These can be arranged in parallel or coaxially. The Lack and Magill can be used in patients of 5 -10 kg or above, but they have quite a large dead space. They should not be used for controlled ventilation unless the fresh gas flow is significantly increased. The mini lack is a low resistance system designed for cats and small dogs. However it has a relatively large dead space and there is no pressure relief system on the APL.

The Mapleson D and E systems work in a similar way and can be considered together. The Mapleson D is the Bain. This consists of an inner tube which delivers the fresh gas flow to the patient and an outer limb which takes the gas away from the patient to the bag and the APL valve. There is a continual flow of gas from the fresh gas outlet along the inner tube and back via the outer limb to the bag and the APL valve. The patient inspires gas mainly from the outer ‘expiratory’ limb, which should exceed the patient’s tidal volume. The expired gas also enters the expiratory limb. During the expiratory pause the CO₂ rich alveolar gas is flushed away by the fresh gas flow. Therefore if the patient’s respiratory rate increases, the expiratory pause shortens and the CO₂ may not be fully flushed away. The Bain has a circuit factor of 2.5. The Bain has relatively high resistance and can be used on patients of about 10 kg or above.

The Mapleson E is the Ayres T piece. This consisted of two hoses arranged as a T configuration with no bag or valves. Thus it had extremely low resistance and was used for paediatric human patients. But since it had no bag, controlled ventilation was difficult. Scavenging was also difficult.
Therefore the system was modified by Jackson Rees who added an open ended bag enabling controlled ventilation. But scavenging is still difficult with this system and can result in the bag becoming twisted and closed and over-inflation of the patient’s lungs.

The system most widely used now is a T-piece with an low resistance APL valve with a safety pressure limit. Confusingly, because it has an APL valve this is actually a Mapleson D with a T-piece configuration, but this is academic as the two sytems work in the same way anyway. The T-piece has a circuit factor of 2.5. It has low resistance and is suitable for very small patients, but is uneconomical for patients above about 8 kg.

The Humphrey ADE is a versatile system. Originally it comprised a Mapleson A, D and E system in one, but now it consists of a Mapleson A (parallel Lack) and a Mapleson E (T-piece), which can be selected by moving a lever. It is designed to use the Mapleson A (lever up) for spontaneous ventilation and the Mapleson E (lever down) for controlled ventilation using a mechanical ventilator. A soda lime canister can also be incorporated, in which case the system becomes a circle system.
Safety considerations for non-rebreathing systems. As with any breathing system, the APL valve should be open when before the system is attached to the patient otherwise there is a risk of barotrauma to the patient’s lungs. With coaxial systems such as the Bain, the inner tube may become damaged or disconnected. For small patients the volume of dead space of the equipment becomes important, and these systems vary in the amount of dead space they contain. Remember that the fresh gas flow requirement is high in order to flush away the CO\textsubscript{2}, and if the flow rate is too low the patient will rebreathe CO\textsubscript{2}. The fresh gas flow requirement is the minute volume of the patent multiplied by the circuit factor, and minute volume = tidal volume x respiratory rate. If the patient breathes more quickly under anaesthesia, e.g. during surgical stimulation, the minute volume increases and the fresh gas flow should be increased.

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<td>APL valve closed (especially mini Lack)</td>
<td>Pressure build-up in system, barotrauma to patient’s lungs</td>
<td>Always check valve is open before connecting patient</td>
</tr>
<tr>
<td>Mechanical dead space too large for patient</td>
<td>Rebreathing of CO\textsubscript{2}</td>
<td>Cut ETT, choose alternative system. Capnography would detect this problem</td>
</tr>
<tr>
<td>Bain: disconnection of inner tube</td>
<td>Inspired and expired gases mix, massive increase in dead space</td>
<td>Check inner tube before the anaesthetic</td>
</tr>
<tr>
<td>Fresh gas flow too low</td>
<td>Rebreathing of CO\textsubscript{2}</td>
<td>Calculate fresh gas flow based on the patient’s minute volume. Capnography would detect this problem</td>
</tr>
<tr>
<td>Twisted bag (Jackson Rees modified T piece)</td>
<td>Pressure build-up in system, barotrauma to patient’s lungs</td>
<td>Ensure scavenging cannot twist, or use alternative system</td>
</tr>
<tr>
<td>Leaks</td>
<td>Patient does not receive desired concentration of anaesthetic, pollution</td>
<td>Leak test the system before use</td>
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</table>

Potentially dangerous problems with non-rebreathing systems

Factors influencing breathing system selection
These include resistance and dead space, drag, how bulky the system is near the patient (especially for procedures near the patient’s head), ease of cleaning and mode of ventilation. For
small patients, the mechanical dead space should be minimised while for large patients mechanical dead space is not usually significant. Resistance of the system is important for small and weak patients and again not so important for larger animals. Non-rebreathing systems with their low resistance are suitable for smaller patients but are uneconomical for larger animals. Rebreathing systems are very economical especially is used as a semi-closed system at low flow rates (approximately 10 mL/kg/minute, with a minimum fresh gas flow of 500mL/minute for any patient). If controlled ventilation is used this overcomes resistance so that rebreathing systems can be used or smaller patients.