Anaesthetic breathing systems: safe, efficient and economical use

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ABSTRACT: Registered Veterinary Nurses (RVN) play a crucial role in the preparation prior to and management of anaesthesia. It is vital that RVNs understand the proper use and function of the breathing system, and what system is most suitable for an individual, when preparing to anaesthetise or sedate any patient. In addition to this, RVNs are often responsible for the maintenance of breathing systems and therefore it is essential that troubleshooting and safety checks prior to use are understood to ensure the health and wellbeing of staff as well as patients.

Keywords: Anaesthesia; breathing systems; theatre practice; patient safety; safety checklists; ventilation

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Introduction

Hughes (2016) suggested that anaesthetic breathing systems are placed between the common gas outlet of the anaesthetic machine and patient via a facemask, endotracheal tube, or a supraglottic airway device. The breathing system aims to deliver oxygen and volatile agent safely to the patient with the addition of a scavenging device to remove waste gases such as excess anaesthetic agent and carbon dioxide (CO_2) exhaled by the patient. The correct use and optimal function of breathing systems is critical in any scenario that a patient is anaesthestised or sedated, as incorrect use or equipment malfunctions may negatively affect patient morbidity and increase risk of mortality. Both rebreathing and non-rebreathing systems have their advantages and disadvantages and may be suitable for different scenarios (Table 1).

Choosing a breathing system

There are numerous factors that may influence the RVNs choice of breathing system, such as;

- Patient size/weight
- Patient American Association of Anaesthesiologists (ASA) Physical Status Classification
- Method of respiration- Ventilation required or spontaneous
- Economical use of oxygen and volatile agents
- Can scavenging be performed with ease?
- Circuit drag
- Length and type of procedure
- Circuit resistance and mechanical dead space
- Where is the APL valve located?
- Personal preference
- Availability in practice

Non-rebreathing systems

Non-rebreathing systems are classified as those that do not absorb CO_2 and the removal of waste gases relies soley on an adequate fresh gas flow (FGF) (Dugdale, 2010). They were classified by Mapleson in 1954 with a letter from A to F depending on their composition (Table 2). They do not have unidirectional valves, but do possess a pressure-relief valve, known as an adjustable pressure-limiting valve (APL) or pop-off valve (Ferreira, 2018). A fresh gas flow calculation should always be performed in order to prevent rebreathing and this should be altered if the minute volume changes. However, Hughes (2016) suggested the use of capnography may be utilised to allow titration of oxygen to make the breathing system more economical and increase efficiency as the lowest possible FGF can be used, whilst ensuring the patient is not rebreathing CO_2. Using the waveform as a

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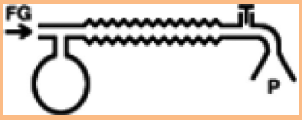
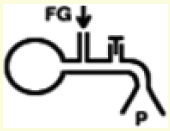
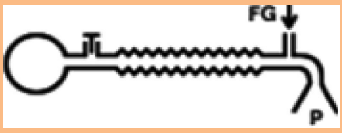
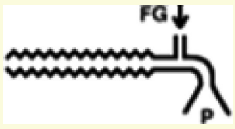
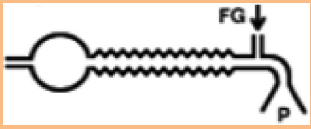
Table 1. Comparison of properties of non-rebreathing and rebreathing systems.

Rebreathing systems	Non-rebreathing systems
CO_2 absorbent canister for absorption of Carbon dioxide	Carbon dioxide removal is dependent on adequate fresh gas flow via APL valve and scavenging system
Unidirectional valves present	No unidirectional valves present
Low fresh gas flow and rebreathing of exhaled gases results in humidification and warming of inspired gas	High fresh gas flow results in drying and cooling of the patient's airway and may contribute to hypothermia in small patients.
Slower changes in anaesthetic depth when the vaporiser setting is changed due to inspired gas being rebreathed unless fresh gas flow is increased	Rapid changes in anaesthetic depth can be achieved when the vaporiser setting is changed due fresh inspired gas.
Economical and low levels of atmospheric pollution due to low levels of volatile agent and fresh gas use.	High fresh gas flow results in high levels of volatile agent and atmospheric pollution.
Higher resistance breathing system due to CO_2 absorbent canister, so may not be suitable for small patients unless specialised paediatric model is used.	Lower resistance to breathing – resistance will vary depending of breathing system

Adapted from Hughes (2016).

Table 2. Mapleson classification adapted from Mapleson (1954).

Mapleson classification (Relevant to veterinary anaesthesia)	Diagram	Example of circuit
A		Magill, Lack & Mini Lack, Humphrey ADE (A mode)
C		Maybe be used in emergencies (Ambu-bag) but otherwise not relevant to veterinary anaesthesia
D		Bain, Paediatric Modified T-Piece, Humphrey ADE (D mode)
E		Ayre's T-Piece, Humphrey ADE (E mode)
"F"		Jackson Rees Modification of T-Piece

guide, rebreathing can be identified when the waveform does not return to baseline (Figure 1), accompanied by a figure above zero seen as the fraction of inspired carbon dioxide ($FiCO_2$) reading.

Fresh gas flow calculations

- The tidal volume (TV) of a patient should initially be calculated, this is the volume of gas entering or exiting the lungs in one breath.
  TV= 10–15 ml/kg, however it has also been cited by Hughes (2016) that TV may be 10–20 ml/kg at rest.
  When using TV for FGF calculations medium to large dogs will have a TV of 10 ml/kg and small dogs and cats will have a TV of 15 ml/kg (Orpet & Welsh, 2011).

- The minute volume (MV) is the total volume of gas entering or exiting the lungs in one minute. MV in ml is the TV multiplied by the respiratory rate (RR) and this calculation should be fairly fluid throughout the anaesthetic maintenance period as RR changes.
  MV (ml) = TV X RR

- The MV (ml) should then be multiplied by the circuit factor (CF), which is often between two numbers and therefore the range should be calculated to give the FGF in ml.
  FGF (ml)= MV x CF

- To convert the FGF to litres, divide the FGF (ml) by 1000.
  FGF (L) = FGF(ml) ÷ 1000

TV= Weight (kg) x 10–15ml
MV= TV x RR
FGF (ml) = MV x CF
FGF (L) = FGF (ml) ÷ 1000

The Lack system (Mapleson A)

The Lack systems can come as either a parallel (Figure 2), co-axial or mini modification (Figure 3). This breathing system has an inspiratory and expiratory limb, with the patient breathing fresh gas via the inspiratory limb from the reservoir bag. On exhalation, waste alveolar gas carrying CO_2 is pushed through the expiratory limb and into the scavenging system via the APL valve. If the co-axial is used, the inner tube is expiratory, and the outer tube is inspiratory. These systems allow rebreathing of dead space gas and therefore low FGF can be used and they have a low circuit factor (0.8-1). The parallel and co-axial Lack can be used for patients 10 kg and over, however they become uneconomical if patients are over 25 kg. The mini Lack is suitable for patients under 10 kg and is modified for smaller patients as the tubing is smaller and has a narrow tubing lumen (Walsh & Taylor, 2004). However, due to their low FGF they are unsuitable for patients that require prolonged intermittent positive pressure ventilation (IPPV) unless a higher fresh gas flow is used (Hughes, 2016).

The Magill system (Mapleson A)

Mapleson (2001) stated that the Magill system consists of a reservoir, wide bore corrugated tubing and an APL valve. This circuit also relies on rebreathing of dead spaces gases that do not contain CO_2 and can therefore have low FGF. The fresh gas fills the tubing and the reservoir bag so that when the patient inspires the bag empties and the initial dead space gas (not containing CO_2) is held within the tubing whilst the rest of the alveolar gas exhaled and CO_2 is vented via the APL valve that is close to the patient (Ferreira, 2018). Due to the position of the APL this increases the circuit drag and therefore may not be suitable to dental procedure or surgery on the head (Dugdale, 2010). The circuit factor is the same as the Lack system at 0.8-1.

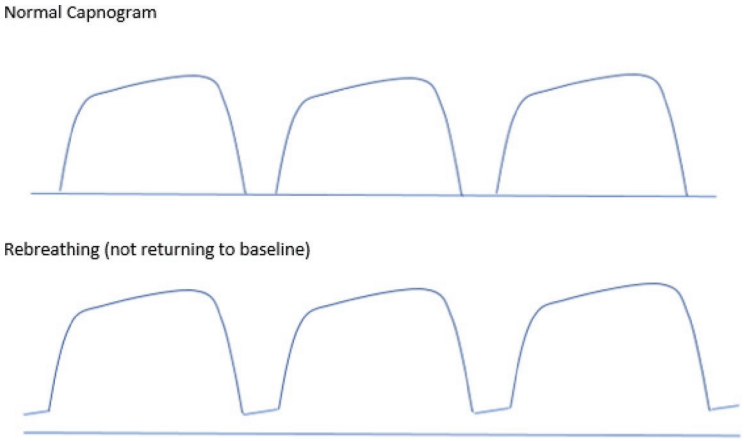


Figure 1. Normal and rebreathing capnography waveform.

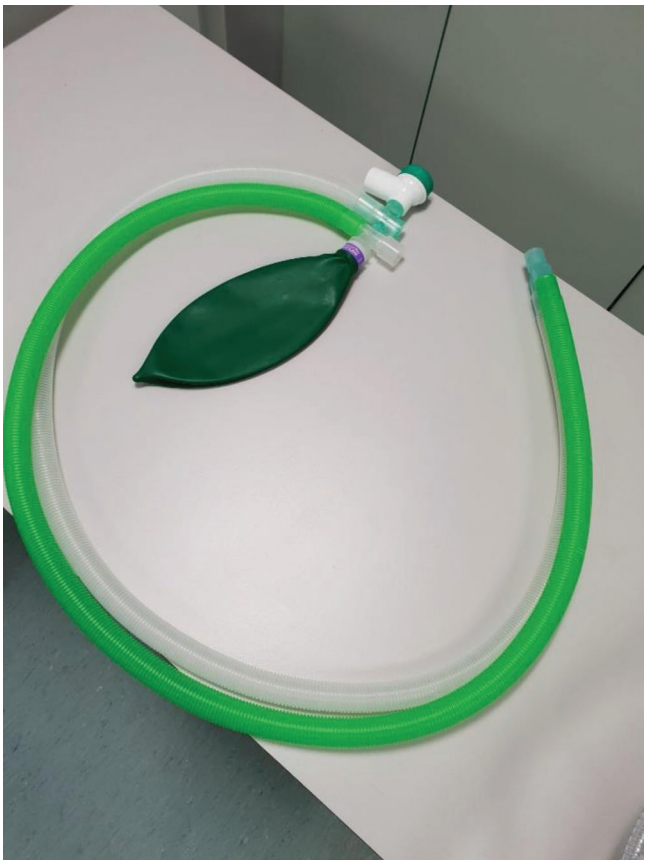


Figure 2. Parallel lack non-rebreathing system.

T-piece (Mapleson D,E,F)

There are various modification of the T-piece and each has slightly more resistance than the one before, the lowest resistance is the Ayre's T-Piece (Mapleson E) which has no APL or reservoir bag. The Jackson-Rees modified T-piece (Mapleson F) has the addition of an open-ended bag with a scavenging connector, IPPV may be performed by occluding the end of the bag to give a breath, however extreme caution should be taken to avoid accidental occlusion or twisting of the reservoir bag as this may result in volutrauma to the patient (Moseley & Shelby, 2018). Finally, the Paediatric Modified T-Piece (Mapleson D) (Dugdale, 2010; Hughes, 2016; Mapleson, 2001) is the most commonly used in practice as has both a reservoir bag and APL valve, it is easily scavenged and IPPV can be provided with ease.

Fresh gas enters the system at a T-junction near the patient, fills the tubing and is inspired by the patient, then the exhaled air fills the larger bore tubing during expiratory pause and is eventually pushed out of the system by the high FGF via the an APL valve or open-ended bag. The Mapleson F and D allow easy provision of prolonged IPPV to the patient as they require high fresh gas flows and have a circuit factor of 2.5-3 (Hughes, 2016). Due to their small lumen

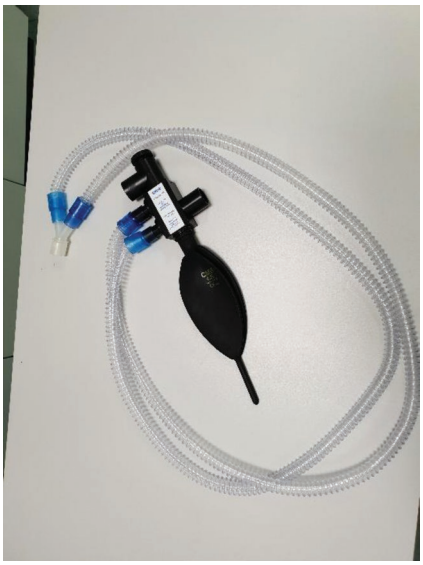


Figure 3. Mini parallel lack non-rebreathing system.

tubing, low resistance and low mechanical dead-space, they are suitable for patients under 7 kg including paediatric patients and small mammals.

The Bain system (Mapleson D)

The co-axial Bain system is similar to the co-axial Lack in the fact that fresh gas is carried along the inspiratory tubing within and exhaled gas passes via the surrounding outer expiratory tubing, however it works in a similar way to the T-piece. The inner tube if filled with fresh gas, with some overspill into the end of the outer tubing where it is inhaled. Exhaled gas is then pushed through the outer tubing to the reservoir bag and out of the APL valve and therefore a small amount of fresh and waste gas is mixed. However, with an adequate FGF, rebreathing should not occur. The Bain system is suitable for patients up to 70 kg (Mapleson, 2001), however it often becomes uneconomical for patients over 15 kg (Dugdale, 2010). Hughes (2016) suggested that flowmeters used in veterinary practice may not be able to provided adequate FGF for patients at the high end of this weight range and therefore breathing systems such as a rebreathing system may be more applicable for use in these large patients. Due to the higher FGF and circuit factor (2.5-3) the Bain system is suitable for prolonged IPPV (Hughes, 2016), but care should be taken to prevent volutrauma when high FGFs are used due to a quick build-up of pressure within the circuit with the APL valve closed.

The Humphrey ADE system

This is a hybrid breathing system that can be adapted depending on patient requirements by altering a lever and is therefore

extremely versatile. The main component is the Humphrey block which attaches at the gas outlet on the anaesthetic machine. It has a lever that alters the passage of gas so that it can be used as a Mapleson A, D or E, or can be used as a rebreathing circuit with the addition of a CO_2 absorbent canister (Gale et al., 2015). Due it versatility this breathing system is becoming popular in veterinary practice. This circuit can also be easily attached to a ventilator for patients where required as there is a specialised attachment port.

The manufacturers provide thorough guidance for veterinary use (Anaequip UK, 2019) and discuss the advantages of this breathing system over others. This includes lower fresh gas flow in D and E setting when compared to a Bain system and T-Piece making it economical, flexibility of use as non-rebreather in various modes and rebreathing system. This system also has a unique self-regulating four phase expiratory valve that has extremely low resistance and states that it has been used in patients as small as 1 kg. Overall, this breathing system is becoming more popular in veterinary practices as it works extremely efficiently and is simple to use with training. It also allows veterinary practices to help reduce pollution and increase efficiency and economy of anaesthetic gas usage using capnography.

Rebreathing systems

Davey (2012) stated that rebreathing systems recycle the exhaled gases whilst absorbing the CO_2 so that it is safe for the patient to inhale. This results in low FGF to be used, however an initial FGF of 100 ml/kg/minute should be provide for the first 10-15 minutes with the pressure-relief valve open to allow for denitrogenation to occur and filling the breathing system with fresh gas to allow for rapid patient stabilisation to allow for an appropriate depth of anaesthesia to be achieved. Once the patient is stablised the FGF can be reduced to as low as 10 ml/kg/minute however 0.5-1 L is most suitable as many vaporisers will not deliver accurate levels of volatile agent below this level (Hughes, 2016).

When using low-flow anaesthesia (0.5-1 L/min), environmental pollution is reduced and anaesthesia is more economical as it reduces the amount of volatile agent and oxygen used. However, extreme caution should be taken to avoid undesirable effects such as rebreathing of CO_2, hypoxia, build-up of nitrogen within the circuit and unexpecting changes in anaesthetic depth. Therefore, it should be only practiced with the use of a capnograph and the monitoring of inspired oxygen concentration end-tidal anaesthetic agent may also be beneficial (West, 2020). Rebreathing systems use CO_2 absorbents such as soda lime (Figure 4) to absorb excess CO_2 via a chemical reaction. This reaction uses and produces water with the addition of heat, helping to humidify the gas that is delivered to the patient and can help reduce the risk of hypothermia (Herbert & Magee, 2017). CO_2 absorbents should be checked for any signs of colour change as this will occur when exhausted and should be changed immediately to prevent patients rebreathing CO_2. Unfortunately, some CO_2 absorbents may return to its original colour when exhausted if it is not used, and it is essential that the RVN is aware of original colour and exhausted colour as this may differ between brands of CO_2 absorbents. In addition to this, soda lime should be handled with caution and appropriate personal protective equipment as it can be caustic.

Circle system

Herbert and Magee (2017) stated that the circle system is named as such and may also be called a "circuit" because it involves a circular unidirectional flow of gases. There are two unidirectional valves (Figure 5), one allows the patient to inhale gases via the inspiratory limb a Y-connector, the other allows exhaled gas to enter the expiratory limb via the Y-connector. The breathing system also has a pressure relief valve, CO_2 absorbent canister and reservoir bag as standard, however some models also have a manometer to measure pressure which can help when leak testing or performing IPPV. The circle circuit allows the patient to inspire a mixture of fresh gas and previously exhaled gas (with CO_2 removed) and with a low FGF to be used as previously discussed.

The standard circle circuit is suitable for patients over 15 kg due to increased resistance of the CO_2 absorbent, canister and unidirectional valves. However, modern modifications such as the paediatric circle circuits are extremely lightweight, have smaller CO_2 absorbent canisters, small lumen tubing and the Y-connector may also have a septum to reduce mechanical dead space and can therefore be used on patients as small as 7 kg (Sager & Norkus, 2019). Although it is recommended that patients less than 7 kg are maintained on a non-rebreathing circuit, this is at the discretion of the anaesthetist and Robertson et al. (2018) stated that paediatric rebreathers can be utilised effectively for feline patients over 3 kg.

Safety checks

Performing safety checks and leak testing is paramount in maximising successful patient outcomes and preventing exposure of volatile agents to veterinary personnel. The Association of Veterinary Anaesthetists (2014) developed a safety checklist with the aim to increase awareness and reduce

Figure 4. Circle rebreathing system with CO_2 absorbent canister.

human error to improve patient safety (Figure 6). This checklist helps to ensure that the anaesthetic machine and breathing system are in good working order and are safe to use prior to induction of the patient. McMillan (2014) supported this idea and stated that the use of anaesthetic safety checklists can improve patient safety, ensure critical steps have been performed prior to anaesthesia and improve communication and collaboration between team members.

When performing safety checks it is vital that all components of the breathing system are present and assembled appropriately with no obvious signs of damage or disconnection of inner tubing (if present) prior to leak testing. As many of the breathing systems used in veterinary medicine are designed single use for humans, they are not suitable for prolonged use and therefore as a consequence, damage will occur when repeatedly used. Therefore, it is vital that safety checks are performed prior to use to address wear and tear on the systems and dispose when appropriate according to practice protocol. CO_2 absorbent canisters should be checked before and after each use and changed if there is any evidence of exhaustion present, however capnography is the most sensitive way to test if the soda lime needs to be changed. Regardless of technique used, it is recommended that even if there is no colour change present that the CO_2 absorbent is changed after a specified amount of time. CO_2 absorbent manufacturers recommend changing after 6-10 hours of active use (Crump, 2019) and active usage can be tracked by using a chart.

APL valves and pressure-relief valves should always be checked prior to attaching a patient, as previously mentioned when high FGFs are used, the risk of high airway pressures and volutrauma is significant if the APL is left closed. Each APL has a maximum pressure limit as a safety mechanism; however these breathing systems are used in humans and may not be suitable for veterinary patient safety in this case. For example the APL on a Bain system or Lack system will likely have an APL with a maximum pressure of 60cmH_20. Hammond and Murison (2016) stated that inflation pressures over 30cmH_20 may result in lung capillaries becoming compressed and cause a reduction in alveolar blood flow.

Figure 5. Unidirectional valves on circle rebreathing system.

Leak testing

Leak testing is a simple procedure that should be performed before connecting to a patient and after each use (Grubb et al.,

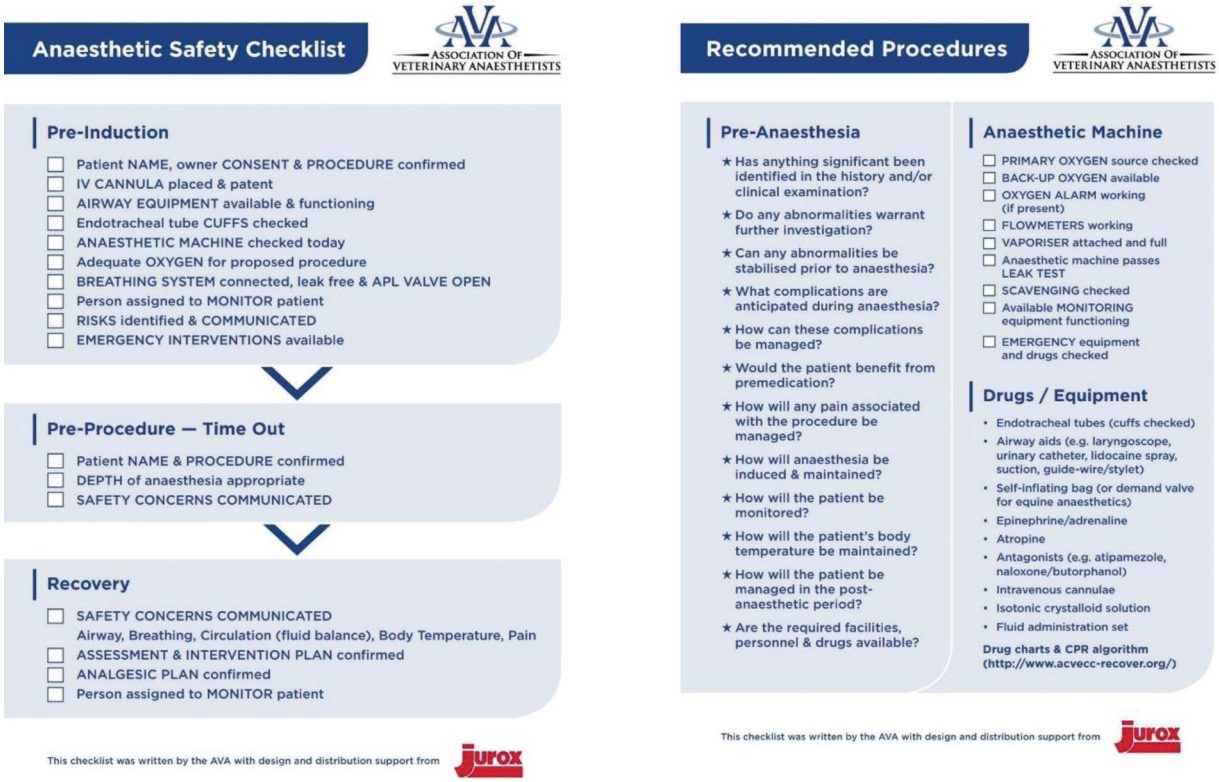


Figure 6. Anaesthetic safety checklist developed by the Association of Veterinary Anaesthetists, with design and distribution support from Jurox UK. Accessible online from: www.ava.eu.com/resources/checklists.

Figure 7. Parallel lack non-rebreathing system being leak tested with APL valve closed and reservoir bag turgid.

Figure 8. Paediatric APL Valve removed from Paediatric modified T-piece non-rebreathing system.

2020). However, different circuits need to be leak tested using different techniques;

- Attach the circuit to the gas outlet ensuring this connection is secure.
- The APL valve should be closed or open-ended bag occluded.
- The end of the breathing system should be occluded with a hand or plugged.
- The system should then be filled with oxygen to a pressure of 30-40cmH_20, however if a pressure gauge is not present, the reservoir bag should be filled until turgid (Figure 7).
- The reservoir should hold its pressure for at least 10 seconds with the oxygen turned off.
- The APL valve should be opened and the pressure should be released immediately and the end of the breathing system can be released or unplugged.

When leak testing a Paediatric Modified T-Piece, it is important to consider that the pressure required to open the APL valve is small (2-3cmH_20) (Hughes, 2016) and therefore the APL valve should be removed from the circuit during leak testing (Figure 8) and an alternative method should be performed;

- Remove the APL valve and replace the reservoir bag onto the end of the expiratory limb, occlude or plug the end of the breathing system.
- Fill the system with oxygen until the reservoir bag is turgid and monitor for any decrease in pressure caused by leaks (Figure 9).

Figure 9. Paediatric modified T-piece non-rebreathing system leak test with APL valve removed and end of tubing occluded.

- Release or unplug the end of the breathing system and replace the APL valve.

If the unidirectional valves require testing on a rebreathing circuit, the same steps should be carried out with the addition of;

- Squeeze the reservoir bag when turgid to ensure the valves flutter open and closed freely.

When testing a co-axial Bain system, the inspiratory inner tubing should be checked for integrity and can be performed two different ways (Robertson et al., 2018).

Foex Crampton-Smith test or the occlusion test

- Set the FGF to approximately 4L/minute.
- Occlude the inner tubing with the device provided by the manufacturer or the plunger from a 2ml syringe (Figure 10).
- The reservoir bag should remain deflated.
- Watch the bobbin or ball on the flowmeter, as this should drop and a high-pressure alarm should sound.

Figure 10. Foex Crampton-Smith test on a Bain system. Photo courtesy of Kassy Jones RVN, University of Liverpool Small Animal Teaching Hospital.

Pethick test

The APL valve should be closed, and the end of the breathing system should be occluded or plugged.

- The breathing system should be filled with oxygen and then the occluded end should be released or unplugged whilst pressing the emergency oxygen flush.
- The reservoir bag should deflate.

Conclusion

Although the *RCVS Code of Professional Conduct for Veterinary Surgeons* (2012) states that the veterinary surgeon is ultimately in control of the maintenance of anaesthesia, RVNs play a critical role in preparation and use of the anaesthetic machine, breathing systems and ancillary equipment. Through the selection of an appropriate breathing system and a solid understanding of their maintenance, an RVN can promote safe anaesthesia for patients and personnel. The addition of using of FGF calculations and capnography can also help ensure that the use of volatile agents and fresh gases are used economically and efficiently.

Disclosure statement

No potential conflict of interest was reported by the author.

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