Evaluating the clinical use of different breathing systems and assessing their effects on respiratory function in small dogs under anaesthesia

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Abstract

There is little consensus on the selection and use of breathing systems in small dogs. There is a wide array of systems available and several factors which govern breathing system selection. The current guidance for the use of breathing systems in 5–10 kg dogs is unclear. There is a trend to advise the use of more economical systems, however, the use of these has not been evaluated.

Survey study

This study aimed to investigate which breathing systems are available and why they are selected in 5–10 kg dogs. This was an anonymous online voluntary open survey. Research was approved by the University of Glasgow College of Medical, Veterinary & Life Sciences Ethics committee (Ref. 200220025).

An online survey, designed following CHERRIES guidelines (Eysenbach, 2004), was advertised through the American College of Veterinary Anesthesiologists - List (ACVA-List), Association of Veterinary Anaesthesia (AVA) and European College of Veterinary Anaesthesia and Analgesia (ECVAA) (February-March 2022). A convenience sample was taken.

Of the 256 responses received, 138 were completed. This included (*n* responses received) veterinarians (107) and veterinary nurses or technicians (29) actively involved in the anaesthesia of dogs.

The most prevalent breathing systems available to respondents were circle (99%), coaxial Bain (79%) and modified Ayre's T-piece (with adjustable pressure limiting valve) (72%). When recommending a dog weight range suitable for the use with these systems, respondents advised a median (interquartile range) of 5 (3–10) to 100 (100–100), 3 (0–8) to 20 (10–33) and 0 (0–0) to 10 (7–10) kg, respectively. Respondents agreed or strongly agreed that important factors in selecting a breathing system were the fresh gas flow requirement (92%), dog weight (91%), resistance (83%) and environmental pollution (79%). In clinical scenarios based on 5–10 kg dogs, the circle system was chosen by 58%

for a thin and 77% for a keel-chested *versus* 44% for an obese and 66% for a barrel-chested dog, respectively.

The circle system is the most commonly available breathing system. The minimum weight limit used for the circle system is less than previous surveys have reported (Nicholson and Watson, 2001). Several factors influence the choice of breathing system other than dog weight.

Clinical study

This study aimed to compare different breathing systems during spontaneous ventilation in anaesthetised 5–10 kg dogs. This was a randomised, non-blinded, crossover clinical trial. Ethical approval was obtained from the University of Glasgow School of Biodiversity One Health and Veterinary Medicine Ethics Committee (Ref EA34/21).

Thirty 5–10 kg dogs were anaesthetised for a range of procedures.

A Mapleson D T-piece system was used as a control in all dogs. The dogs were equally randomised to the test breathing systems: circle or Bain. All dogs received a standard anaesthetic protocol. Respiratory rate (f_R), end expired carbon dioxide ($P_{E'}CO_2$), tidal (V_T) and minute ($\dot{V}_E$) volume were compared using a paired student's t test or Wilcoxon rank test.

The circle $P_{E'}CO_2$ (6.04 ± 0.64 kPa), V_T (12.1 ± 3.9 ml kg^{-1}) and $\dot{V}_E$ (116.7 (97.5–166.0) ml kg^{-1}) were significantly higher (p = <0.001, 0.035 and 0.002 respectively) than the T-piece $P_{E'}CO_2$ (5.31 ± 0.78 kPa), V_T (10.6 (7.7–13.3) ml kg^{-1}) and $\dot{V}_E$ (107.8 (77.3‑131.9) ml kg-1). The Bain $P_{E'}CO_2$ (5.22 ± 0.98 kPa) was significantly lower (p = 0.032) and the V_T (7.1 ± 2.7 ml kg^{-1}) significantly higher (p = 0.041) than the T-piece $P_{E'}CO_2$ (5.61 ± 0.90 kPa) and V_T (6.6 (4.8‑7.0) ml kg^{-1}). Between the Bain and T-piece there was no significant difference in $\dot{V}_E$. Neither test system had a significant difference in f_R compared with the control.

Whilst differences were found between both test systems and the control, the clinical consequences appear minimal. Both circle and Bain appear suitable for use in healthy 5–10 kg dogs as overall ventilatory function was adequate.

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Alternative Format Preface

The manuscript contained in chapter 5 titled ‘A survey study on the availability of anaesthetic breathing systems and their use in 5–10 kg dogs’ has been published in *Veterinary Anaesthesia and Analgesia*.

> MURRAY, A. G, WOODHOUSE, K & MURISON, P. J. (2025) A survey study on the availability of anaesthetic breathing systems and their use in dogs weighing 5–10 kg. Veterinary Anaesthesia and Analgesia 52**,** 35-42.
>
> The material in chapter 5 has also been presented as a conference abstract at the Association of Veterinary Anaesthetists Autumn meeting in Warsaw, 2023.
>
> MURRAY, A. G., WOODHOUSE, K. & MURISON, P. J. (2023) A survey on the availability of anaesthetic breathing systems and their use in 5-10 kg dogs. Veterinary Anaesthesia and Analgesia 50, 548-548

The manuscript contained in chapter 7 titled ‘Comparing respiratory variables with circle, Bain and T-piece breathing systems in 5–10 kg dogs: randomised control trial’ is under review with *Veterinary Anaesthesia and Analgesia*.

The style of both manuscripts is reflective of the requirements of the individual journal with the exception that the referencing for both has been standardised with this thesis. When compiling this thesis, the figures, tables and references have been renamed according to their place in this document. Any appendices associated with the manuscripts have been placed at the end of this thesis.

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My anaesthesia colleagues from near and far also deserve acknowledgement and thanks for their participation in the survey.

I would also like to thank the dogs (and the owners who enrolled them) in the clinical study.

Author's Declaration

I, Andrew Gordon Murray declare that, except where explicit reference is made to the contribution of others, that this dissertation is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

Abbreviations

$\dot{V}E$	Minute volume
ρ	Fluid density
μ	Dynamic viscosity
η	Fluid viscosity
°C	Degrees Celsius
ΔP	Pressure difference
ΔV	Volume difference
ACVA	American College of Veterinary Anesthesia
APL	Adjustable pressure limiting
ASA	American Society of Anesthesiologists
AVA	Association of Veterinary Anaesthetists
BCS	Body condition score
BT	Bain test group
cmH_2O	Centimetres of water
CO_2	Carbon dioxide
CT	Circle test group
d	Distance
e.g.	For example
ECG	Electrocardiogram
ECVAA	European College of Veterinary Anaesthesia and Analgesia
ET	Endotracheal
F	Force

$F_{E'}ISO$	Fraction expired isoflurane
FGF	Fresh gas flow
Fig.	Figure
f_R	Respiratory rate
HR	Heart rate
Hz	Hertz
ICU	Intensive care unit
IQR	Interquartile range
kg	Kilogram
kPa	Kilopascals
L	Characteristic length
l	Length of tube
m	Metre
ml	Millilitres
mm	Millimetres
mmHg	Millimetres of mercury
n	Number
NIBP	Non-invasive blood pressure
P	Pressure
$P_{E'}CO_2$	Partial pressure of end tidal carbon dioxide
Pmax	Maximum airway pressure
Pmin	Minimum airway pressure
ppm	Parts per million

Q	Flow
Q	Dynamic pressure
R	Resistance
r	Radius
Re	Reynolds number
SpO_2	Saturation of peripheral oxygen
t	Time
T	Temperature
u	Speed of flow
UK	United Kingdom
USA	United States of America
V	Volume
v	Velocity
V_T	Tidal volume
W	Work
WOB	Work of breathing

Chapter 1 Introduction

The use of anaesthetic breathing systems is a fundamental part of small animal veterinary anaesthesia. From their origin in human medicine, breathing systems have been modified to suit various needs and requirements. When in use, a breathing system becomes intimately linked to the respiratory system of the animal. As such, the selection and function of the breathing system can directly impact the animal's ventilation and physiological status throughout anaesthesia. This introduction is constructed to provide an overview of breathing systems, their history and structure before examining the literature behind the following questions:

- What types of breathing system exist and how are they classified?
- How are breathing systems currently used?
- How are breathing systems selected?

To explore the potential of quantifying the impact of breathing system selection on the ventilatory function of a dog, the introduction will then describe normal respiratory function before examining the literature behind the following questions:

- What is resistance to breathing and how can it be measured?
- What are the complications of excessive resistance?
- How can respiratory function be measured?
- How does anaesthesia alter respiratory function?

1.1 Overview of breathing systems

The main purpose of an anaesthetic breathing system in veterinary anaesthesia is to deliver anaesthetic gases and vapours of known composition to the animal whilst preventing rebreathing of carbon dioxide. The breathing system may allow the anaesthetist to provide positive pressure ventilation to the animal's lungs. Lastly, the breathing system can provide the ability to safely scavenge waste or excess anaesthetic gases from the working environment (Hughes, 2016).

Modern breathing systems attach to anaesthesia machines via a standard 22 mm female or 15 mm male connection at a common gas outlet (Subrahmanyam and Mohan, 2013). The output at the common gas outlet is the pre-set mixture of anaesthetic gas and volatile agent as selected by the anaesthetist on the anaesthetic machine.

Multiple methods of bridging the interface between the end of the breathing system and the animals' lungs exist. The standard method in dogs is the endotracheal tube which, is usually cuffed to prevent air leaks and aspiration (Mosley, 2024). Alternatives include a laryngeal mask airway or a tight-fitting facemask over the muzzle of the animal (Dugdale et al., 2020).

1.1.1 Components of a breathing system

Several components are common across different breathing systems. There are a few exceptions, and these are highlighted when discussing individual breathing systems.

Hoses or tubing are present in all breathing systems. This is usually corrugated to prevent kinking if it is bent (Davey, 2012). The tubing provides a conduit for the flow of gas between different breathing system components and between the animal and anaesthetic machine. The diameter of the tubing can vary depending on the breathing system and expected size of animal.

A reservoir bag is present in most breathing systems. This provides a compliant area of gas storage to allow for the changes in breathing system volume which occur during inhalation and exhalation. As the bag deflates during inspiration, it gives a visual indication of ventilatory function to the anaesthetist. Reservoir bags are also more distensible than the rest of the breathing system, so their incorporation provides an area of expansion in the case of pressure overload to reduce barotrauma in the lungs (Davey, 2012). Reservoir bags can be made from different materials, but these should be antistatic and impervious to inhalant anaesthetics (Miljenko, 2017). The size of a reservoir bag should be adequate to accommodate a maximal inspiratory volume of the anaesthetised animal. This prevents the creation of excessive negative pulmonary pressures if the bag were to empty. If an excessively large bag is used, the tidal volume of the animal will be too small to observe any meaningful movement of the bag. Various recommendations exist for the calculation of how big the bag should be. An estimation of between 2 and 6 multiples of the expected tidal volume is likely to be sufficient (Dugdale et al., 2020).

An adjustable pressure limiting valve is present in most breathing systems. It should be noted this valve has a myriad of other names, including pop-off valve, spill valve and relief valve. It is a one-way valve allowing for the escape of excess or waste gas from the breathing system whilst preventing entrainment of any room air (Davey, 2012). There are two main designs. The most common is a spring-loaded disc valve which includes a disk, light spring and control knob to alter the tension on the spring (Figure 1-1). The pressure at which the valve will open can therefore be adjusted. The minimum opening pressure of these is around 1.5 cmH_2O, so they add resistance to a system (Dugdale et al., 2020). In valves with a spring, it is common to have a maximum breathing system pressure limit which will allow for the release of pressure greater than this value. In human adult systems, this pressure is 60 cmH_2O (Davey, 2012). This limits barotrauma should the APL valve be left closed inadvertently, which can be a fatal mistake (DeLay, 2016). A more basic ‘stem and seat’ design is also available. With a stem and seat valve, the orifice between the stem and seat is opened or closed by the controlled knob. The stem and seat APL valve does not contain the spring. The breathing system reservoir bag is subject to collapse when the orifice is open unless an additional one-way valve is present. Additionally, positive pressure external to the breathing system (for example in the scavenging) can push air back into the breathing system; the additional one-way valve prevents this (Dorsch and Dorsch, 2008a).

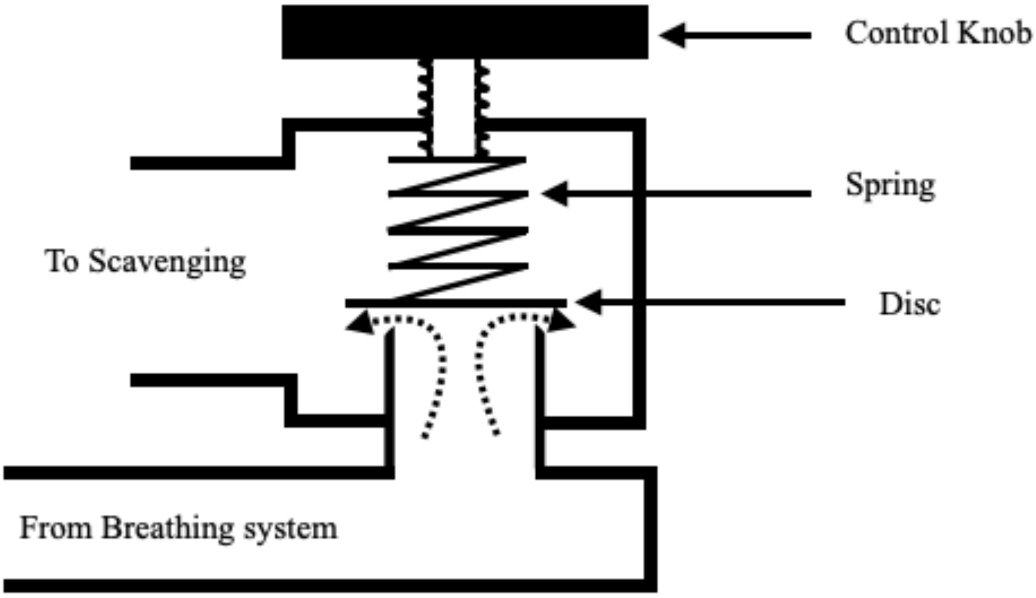


Figure 1-1 Schematic diagram of the components of a spring-loaded disc APL valve

Other apparatus and components can also be found in breathing systems or as attachments; these are discussed in more detail as they become relevant.

1.1.2 History of breathing systems

Without delving into excessive detail, this section is intended to convey the fundamental steps in the development of anaesthetic breathing systems. Breathing systems as they are today did not exist in the infancy of modern anaesthesia. Before the development of the anaesthetic machine, breathing systems were also required to vaporise the volatile agent. The first modern anaesthetic in people, carried out by Morton, used inhaled diethyl ether. The delivery of this anaesthetic was via a Morton inhaler, a spherical glass container with two ports, one for room air to enter and a mouthpiece for the patient to breathe from. Soaked sponges of ether were placed in the inhaler to emit ether vapour (Romero-Avila et al., 2021). This was the also described as the first apparatus where there was a defined tube for the patient to inhale from (King, 1946). This design of inhaler is shown in Figure 1-2.

Figure 1-2 Morton inhaler on display in the Science Museum London, UK

Alternatives to this device included the SchimmelBusch mask, a frame which sat over the mouth and held an agent-soaked cloth (Lo, 2014). None of these techniques allowed for accurate titration of the agent. Fluctuations in environmental temperature also caused significant variation in the quantity of volatile agent reaching the patient when using these inhalers. Through the mid to late 19th century, inhalers became more sophisticated with greater temperature regulation, driven by a need for increased accuracy. This period also saw the introduction of alternative inhalant agents such as chloroform, which had a faster uptake than ether (Romero-Avila et al., 2021). However, the systems of this time made no provision for the support of ventilation or scavenging of waste agent.

By the late 19th century, nitrous oxide had been compressed into a cylinder, thus allowing its use in the clinical setting for anaesthetic purposes. Oxygen had also been compressed into a cylinder by this stage, however, its utility during anaesthetic procedures was not appreciated at this time (Romero-Avila et al., 2021). The Hewitt apparatus, which combines nitrous oxide and oxygen for delivery via a facemask, shares a few components with a modern breathing system, namely the tubing and reservoir bag (Hewitt et al., 1897).

The first compressed gas anaesthetic machines became available at the start of the 20th century. Flowmeters were developed to allow accurate titration of each gas used. At this time, bubble vaporisers were incorporated into the machine to allow for delivery of volatile agents. The first Boyle anaesthetic machine was released in 1917. Through continual development into the 1950s, this design goes on to resemble most closely the anaesthetic machines in use today (Watt, 2007).

Early breathing systems in use with these anaesthetic machines include the Water's breathing system (Waters, 1926). Although absorbents had been used to remove carbon dioxide since the 1850s, the clinical use of a true circle or to-and-fro breathing system are not described until the 1920s (Waters, 1924). At this time, the absorbents were compounded into granular form to improve utility.

In the 1930s, Ayre developed the T-piece for hare lip operations in paediatrics. The use of this system reportedly resulted in reduced venous congestion and intraoperative bleeding. The rationale behind this was a reduced system resistance imposed by the T-piece vs the circle. The reduced resistance resulted in a lower intrathoracic pressure, allowing venous flow back to the heart and preventing any venous congestion (Ayre, 1937). Over the next 30–40 years, various other non-rebreathing systems were developed to fit a range of clinical uses (Mapleson, 1954).

1.2 What types of breathing system exist and how are they classified?

No single design for a breathing system has been adopted due to the advantages and disadvantages of individual variation within their design. As such, several different breathing systems have been produced, each with a different layout of the above components. Most veterinary anaesthetic breathing systems are either manufactured for human use or based on a design originally developed for use in human anaesthesia.

1.2.1 How are modern breathing systems classified?

Due to the wide range of systems now available, they have been classified into broad groups. Different methods exist for the classification of breathing systems based on how they work and their design. The two main categories are non-rebreathing and rebreathing systems. In non-rebreathing systems, the CO_2 is expelled from the system by an adequate fresh gas flow from the common gas outlet. Rebreathing systems contain an absorbent which removes the CO_2 from the system. Thus, in rebreathing systems the fresh gas flow is not required to expel the CO_2; it is only required to provide sufficient oxygen and anaesthetic agent (if the latter is being used) (Mosley, 2024).

Non rebreathing systems were classified further by Mapleson based on the design and layout of components (Mapleson, 1954). A category F was added later to the original categories A–E (Willis et al., 1975).

It would also be possible to group systems based on their suitability to provide positive pressure ventilation for a sustained period. This detail will be addressed with each system individually.

1.2.2 Non-rebreathing systems

The Mapleson classification of these systems is illustrated in Table 1-1.

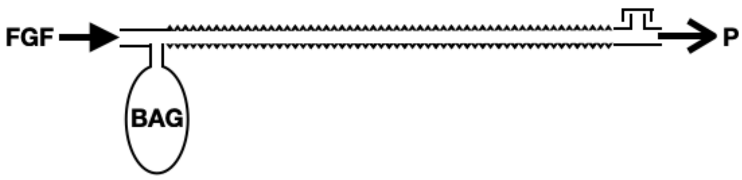
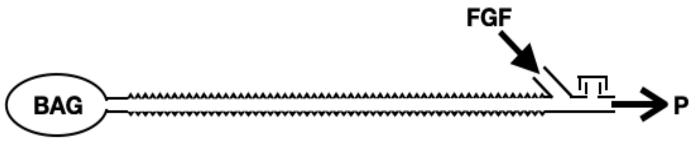
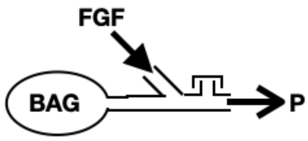
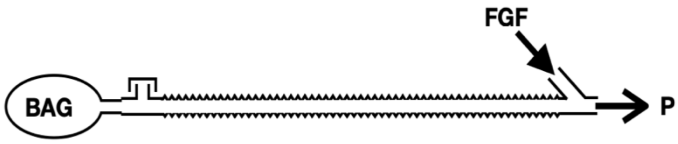
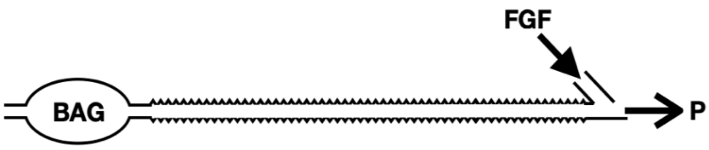
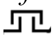
Mapleson Classification	Layout Diagram	Example Systems
Mapleson A		Lack, Mini-Lack, Magill
Mapleson B		(Not commonly used in anaesthesia)
Mapleson C		Water's breathing system
Mapleson D		Bain, Mapleson D T-Piece
Mapleson E		Ayres T-Piece
Mapleson F		Jackson Rees Modified T-Piece

Table 1-1 Mapleson classifications, layouts and examples of anaesthetic breathing systems. FGF= Fresh Gas Flow, P = Patient connection,  *= APL valve. (Mapleson, 1954, Willis et al., 1975)*

Mapleson A systems include the Magill, Lack and Mini-Lack systems. They are all characterised by the reservoir bag on the inspiratory limb next to the fresh gas connection and a length of tubing between the reservoir bag and the connection to the animal (Mapleson, 1954). With the Magill, the APL valve sits at end of the breathing system closest to the animal. Due to the additional drag this created and the difficulties accessing the valve during surgery, Lack moved the APL valve by adding a longer expiratory limb to the system (Lack, 1976). A coaxial arrangement was the original iteration of the Lack system, however, it went out of favour due to reported excessive resistance and potential significant complications if the inner tube leaked (Davey, 2012). A parallel Lack has since been described (Ooi et al., 1993). In the Lack breathing systems, the APL valve sits at the end of the expiratory limb, usually positioned ergonomically adjacent to the reservoir bag. The volume of the inspiratory limb is important, as if it is smaller than the tidal volume of the animal then exhaled gas may reach the reservoir bag. This cannot be cleared effectively by incoming fresh gas flow, thus creating a mix of fresh gas and expired gas, leading to rebreathing of CO_2 in the next breath (Davey, 2012). The flow of gas in these systems during spontaneous ventilation is highly efficient (Nott et al., 1982, Waterman, 2008), thus they can be used at fresh gas flows of 0.8–1 multiples of the minute volume (Hughes, 2016). A fresh gas flow lower than minute volume can be used as it is the physiological dead space gas which is exhaled into the system first. This volume of dead space gas then sits in the inspiratory limb and pushes the alveolar gas out to the scavenging due to the incoming fresh gas flow. The dead space gas is suitable for rebreathing as it will contain no CO_2. During controlled or mechanical ventilation, the efficiency reduces due to the escape of gas from the APL valve during inspiration resulting in the expired gas reaching a greater distance along the inspiratory tube (Davey, 2012). Thus, the Lack is not recommended for sustained positive pressure ventilation due to the risk of rebreathing (Hughes, 2016).

Mapleson B and C systems are not commonly used in veterinary clinical practice (Mosley, 2024).

Mapleson D, E and F are all similar. These systems all rely on the fresh gas flow to clear the exhaled CO_2 during the expiratory pause. As such they are inefficient compared to the Mapleson A systems during spontaneous ventilation requiring a fresh gas flow 1–3 multiples of minute volume. They become more efficient during positive pressure ventilation (Hughes, 2016).

The E classification is the simplest form of these breathing systems, consisting only of an inspiratory and expiratory limb. The clinical example of this system is the Ayres T-piece (Ayre, 1937). It has no other components, therefore there is no easy means by which to scavenge from this system and adequate ventilation of the operating environment is required if being used with volatile agents. Ventilation is possible with this system by intermittently occluding the expiratory limb and allowing the incoming fresh gas to inflate the animal's lungs. This method of ventilation has the potential to cause barotrauma as it is difficult to determine the pressure being applied to the respiratory system (Kaul and Mittal, 2013).

The Mapleson F classification incorporates an open-ended reservoir bag on the end of the expiratory limb furthest from the animal. The clinical example of this system is the Jackson-Rees modified T-piece. Ventilation of the lungs can be conducted by occluding or pinching the open end of the reservoir bag and squeezing the bag. This allows for a safer form of ventilation by giving the anaesthetist a more tangible guide for the pressures being applied to the respiratory system during each breath (Rees, 1950). Due to the open-ended bag, scavenging is still difficult.

The Mapleson D system has both an APL valve and a closed reservoir bag situated at the end of the expiratory limb furthest from the animal (Mapleson, 1954). This allows for effective and complete scavenging of excess gas and easy administration of positive pressure ventilation to the lungs (Hughes, 2016). Clinical examples of this type of system include the Mapleson D T-piece and the coaxial Bain. With the coaxial Bain system, the fresh gas runs through a narrower diameter inner tube which ends just prior to connection to the animal. The external tube is the expiratory limb of the system; the reservoir bag and APL valve are located at the end of this limb. Advantages of the coaxial system include the improved ergonomics of the system as well as the conservation of heat due to warming of the inspiratory limb by the enclosing expiratory limb (Bain and Spoerel, 1972).

1.2.3 Rebreathing systems

The two main systems that fall into this category are the to-and-fro breathing system and the circle system. Both these systems are characterised by the presence of an absorbent canister within the system. This absorbent is there to remove exhaled CO_2, thus preventing rebreathing (Hughes, 2016).

The most common CO_2 absorbent used today is soda lime. Soda lime consists predominantly of calcium hydroxide for the removal of carbon dioxide (Hughes, 2016). Potassium hydroxide and sodium hydroxide are also often present either solely or together to catalyse the reaction process (Davey, 2012). The stepwise chemical reaction with a sodium hydroxide catalyst is as follows:

$$CO_2 + H_2O \rightarrow H_2CO_3$$

$$H_2CO_3 + 2NaOH \rightarrow Na_2CO_3 + 2H_2O + HEAT$$

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

Water is required for the dissociation of carbon dioxide as the first step of the process. Therefore, water is a constituent of soda lime (Feldman et al., 2021). An indicator is present to signal the exhaustion of the soda lime which is detected based on a pH change (Dugdale et al., 2020). A hardener (for example zeolite or silica) improves the stability of the granules and prevents excessive dust formation (Davey, 2012). The optimum size of soda lime granules has been defined as between 4–8 mesh. This is to improve efficiency, maximising surface area for the reaction to take place without compacting. Excessively small granules would compact, leaving only small air spaces between them resulting in excessive resistance (Bracken and Sanderson, 1955).

Other absorbent formulations have been produced. Newer varieties exclude the alkali metal hydroxide as this has been associated with the degradation of Sevoflurane into a nephrotoxic compound, known as compound A (Struys et al., 2004). Absorbents free of the alkali hydroxide also do not produce significant volumes of carbon monoxide which can be found when volatile agents are used with standard soda lime (Murray et al., 1999). Historically barium hydroxide was used as the alkali hydroxide, but this formulation has been discontinued due to the excessive production of carbon monoxide and compound A, especially when the absorbent became dehydrated (Kharasch et al., 2002).

The to-and-fro system (Waters, 1924) has the absorbent canister positioned adjacent to the animal. The reservoir bag is positioned at the other end of the canister. The proximity of the absorbent canister to the animal is inconvenient and increases the risk of inhalation of dust from the absorbent, which can be irritant to the lung tissue (Davey, 2012). As the absorbent closest to the animal becomes exhausted, the volume that it occupies becomes redundant and forms additional apparatus dead space. Thus, apparatus dead space in this system grows during prolonged use (Dugdale et al., 2020). Due to the settling of the absorbent with gravity, an area devoid of absorbent tends to develop at the uppermost part of the canister. If the canister is positioned horizontally, this allows channelling of gases in spaces devoid of absorbent, making for poor CO_2 removal (Davey, 2012). The disadvantages of this system mean it is not encountered frequently in current clinical practice.

The circle system (Sword, 1930) contains one-way valves to ensure that any expired gas must go through the absorbent prior to rebreathing of the gas by the animal. The one-way valves can be situated anywhere along the lengths of tubing between the animal and the absorbent, but one must be present in each of the inspiratory and expiratory limbs. The valves allow the absorbent canister to be placed at a site distant to the animal, which improves the ease of use compared with the to-and-fro system (Davey, 2012). The absorbent canister can also be placed vertically to avoid the previously described channelling (Dugdale et al., 2020). Most modern circles rely on anaesthetic agent being delivered in the fresh gas flow from the anaesthetic machine. However, a small number of circles allow for incorporation of an in-circuit vaporiser which are still in use in veterinary anaesthesia (Nicholson and Watson, 2001). Such in-circuit (draw over) vaporisers must be of a sufficiently low resistance to allow spontaneous ventilation (Boumphrey and Marshall, 2011). Due to the presence of one-way valves and absorbent in the circle, they are said to have a higher resistance than parallel (but not coaxial) non rebreathing systems (Davey, 2012).

1.2.4 Other breathing systems

A hybrid breathing system is one that can function in more than one of the different breathing system categories outlined above. The major veterinary example of a hybrid breathing system is the Humphrey ADE (Humphrey, 1983). This can be configured to function in Mapleson A mode during spontaneous ventilation to benefit from the more efficient fresh gas flow requirement. Should ventilation of the lungs be necessary, by repositioning a lever, the breathing system is configured into Mapleson D/E (Humphrey et al., 1986). In Mapleson D/E mode, a ventilator can be attached to allow the lungs to be ventilated. Both modes are recommended for animals less than 10 kg. For use with heavier animals, an absorbent canister can be fitted into the system which has one-way valves and converts the whole system into a circle system. This can be used for both spontaneous and mechanical ventilation with equal efficiency (Hughes, 2016).

A universal F system is described by Fukunaga (1978), which is a coaxial system. The F is an abbreviation of the surname rather than a Mapleson classification this system falls under. Like the Humphrey, the F system falls into multiple breathing system categories depending on the configuration. It can be attached to an absorbent canister to function as a circle and can function as a non-rebreathing system with the attachment of a reservoir bag (Fukunaga, 2019).

1.3 How are breathing systems currently used?

Before use, breathing systems should be visually inspected for cleanliness and any signs of damage. This visual inspection should also assess for any evidence of obstruction or occlusion of the tubes and other components. For systems with an absorbent, this should be assessed for evidence of exhaustion (Hughes, 2016).

Leak testing of the system should also be performed. In most systems, this can be completed by attaching to the fresh gas flow, occluding the connection to the animal and closing the APL valve or otherwise occluding the scavenging port. (In the Ayres T-piece a reservoir bag can be attached at the end of the expiratory tube to provide something to inflate.) With the fresh gas flow off, the oxygen flush should then be used to fill the system until visible distention of the reservoir bag occurs or to a set pressure on a manometer, should this be present within the system. If any evidence of deflation occurs, the system should be examined to identify the source of the leak and repaired or replaced depending on the severity of the problem and the nature of the system. The coaxial Bain system also requires separate testing of the integrity of the inner tube. This can be performed by setting a fresh gas flow and intermittently occluding the end of the inner tube (in which case there should be an observable bounce of the bobbin or ball bearing float in response to the backpressure imparted through the system and anaesthetic machine) (Dugdale et al., 2020).

Non-rebreathing systems should be used with a fresh gas flow around or above the minute volume of the animal. Over time this results in significant consumption of carrier gas and volatile agent, which will be dependent on the weight of the animal. Capnography allows for the titration of the fresh gas flow to the minimum flow required to prevent rebreathing of carbon dioxide (Hughes, 2016). With non-rebreathing systems, any adjustment to the vaporiser setting is transferred rapidly to the concentration of agent inspired by the animal. This occurs as there is no dilution of the fresh gas with expired gases when the incoming fresh gas enters the breathing system. Advantageously, this allows for more rapid adjustment of anaesthetic depth (Dugdale et al., 2020).

Rebreathing systems can be used in several different ways. These techniques can be classified as semi-open, semi-closed and closed. These terms are inconsistently applied between authors, as is demonstrated in Dorsch and Dorsch (2008a). Moyers' definitions (Moyers, 1953) of these terms will be used in this thesis. During the semi-open technique, the fresh gas flow is high and, in small animal anaesthesia, usually close to or above the animal's minute volume. The fresh gas flow prevents rebreathing of carbon dioxide. Semi-open use is commonly employed at the start of an anaesthetic (Herbert and Magee, 2017) to allow denitrogenation. Denitrogenation is the process by which any nitrogen, the major component of room air, is flushed from the breathing and respiratory systems. Nitrogen will also be present in the functional residual capacity and dissolved in the blood and tissues of the animal. This will be exhaled into the system when the concentration of nitrogen in the inspired gas is reduced by incoming fresh gas flow (as it moves down the concentration gradient). The higher fresh gas flow also allows the more rapid equilibrium of anaesthetic agent in the breathing system, with the concentration being delivered by the fresh gas flow (Mapleson, 1998). The disadvantages of semi-open use of the circle system include the loss of heat and moisture from the system to the scavenging as well as the relatively high consumption of anaesthetic gas and volatile agent.

During closed use, the APL valve can be shut as the volume of oxygen supplied is calculated based on the assumed metabolic demand of the animal. There is complete rebreathing of expired gases (Moyers, 1953). Closed use is difficult as the metabolic consumption of oxygen is not a fixed value, and can vary both between individuals and in the same individual over time. As such, titration of the fresh gas flow by the anaesthetist is required so the volume held in the breathing system does not increase or decrease over time. This is based on whether there is evidence of underfilling of the reservoir bag after exhalation or a build-up of pressure within the system (Boller et al., 2005). The excess pressure can be released by opening the APL valve. It requires much greater attention from the anaesthetist to use a circle in this manner (Dorsch and Dorsch, 2008b). It is important to note that only oxygen can be used as a carrier gas to prevent the excessive concentrations of other gases (e.g. nitrogen) in the breathing system. Using the circle in such a manner for dogs in the 5–10 kg weight range is complicated by the fact that most vaporisers are not calibrated for the fresh gas flow range that would be needed. As such, use of the circle in this manner in 5–10 kg dogs can result in an under delivery (most likely) or over delivery of volatile agent, so should be used with anaesthetic agent monitoring. Additionally, flowmeters, especially those in increments of 1 litre, do not have the accuracy to deliver such small volumes reliably. To illustrate this, a 5 kg dog needing flow rate of 5 ml kg^{-1} $minute^{-1}$ (estimated by rounding up from closed circle flow rates used by Boller et al. (2005)) would need a fresh gas flow of 25 ml $minute^{-1}$.

Semi-closed use of the circle is where the fresh gas flow used is less than the minute volume of the animal but higher than the oxygen consumption. There is partial rebreathing of expired gases (Moyers, 1953). During such use, the APL valve remains open or partially open. The semi-closed system provides the user the advantage of being able to perform anaesthesia using a lower fresh gas flow than with semi-open use, but saves considerable effort titrating the fresh gas flow to the minute oxygen consumption. With the APL valve open, there is a reduced risk of excessive pressure build up and barotrauma of the lungs. A wider variety of carrier gases can be used such as medical air.

1.3.1 Reported complications with anaesthetic breathing systems

Severe complications have been reported with the use of anaesthetic breathing systems. These are due to faults with the apparatus as well as incorrect use and mishap.

Breathing system leaks are relatively common, especially as breathing systems in the veterinary sector are reused for multiple anaesthetics. Leaks result in environmental contamination with anaesthetic vapours and gases, as well as the potential to under deliver fresh gas to the animal. Disconnection of the inner tube of the coaxial circuits is reported, potentially mixing expired gas with the fresh gas flow resulting in rebreathing (Normandale and Found, 1994, Szypula et al., 2008).

Occlusion of breathing systems can occur for various reasons. Some occlusions have been created during the manufacturing process (Gooch and Peutrell, 2004). It also could occur in the operating environment where objects have become lodged in the system (Foreman and Moyes, 1999), the system has filled with water (Kim, 2011), or there has been entrapment of the tubing by other equipment (Hughes, 2016).

Accidental closure of the APL valve can result in an accumulation of pressure in the system which the animal is unable to overcome. Some APL valves have a maximum pressure which they will allow to build in the system before releasing, even when fully closed (Davey, 2012). The results of APL valve closure can be catastrophic if unnoticed, resulting in barotrauma to the lung, rupture of the lung, pneumothorax and death (DeLay, 2016).

In bulky systems, if incorrectly supported or caught, they can pull the head of the animal out of position (Bain and Spoerel, 1972). This effect is sometimes known as system drag. It can also put excessive pressure on the airway device and lead to accidental extubation (Clutton, 1999).

Complications are reported specifically related to carbon dioxide absorbents such as soda lime. The dust of soda lime is caustic and can cause significant chemical injury if inhaled (Hughes, 2016). Failure to recognise exhaustion of the absorbent can result in significant rebreathing of carbon dioxide. Also reported is the degradation of volatile agents by soda lime. Compound A, a nephrotoxic compound, has been produced during the degradation of sevoflurane by soda lime (Morio et al., 1992).

In the circle system, insufficiency or leakage of the one-way valves can result in rebreathing of exhaled gas. This allows bidirectional movement of gas in the expiratory or expiratory limbs. Thus, exhaled gas can avoid passing through the absorbent canister, allowing rebreathing of carbon dioxide (Lee et al., 2013).

Significant respiratory depression or apnoea can occur should the resistance of the system be too high for the individual animal (Moore and Binger, 1927, Clutton, 1999). The concern surrounding breathing system resistance has been used to exclude the use of what are considered higher resistance systems in animals deemed unable to cope with this resistance. This includes animals with low body weights.

1.4 How are breathing systems selected?

Due the variety of breathing systems outlined, each with their own positive and negative attributes, the selection of a breathing system for each animal can be a complex decision-making process.

A starting point for this decision-making process is the suitability of the system for providing sustained positive pressure ventilation. Should positive pressure ventilation be indicated (for example during an intrathoracic procedure or to control end tidal carbon dioxide in the face of raised intracranial pressure), then a breathing system which is suitable for use with positive pressure ventilation should be used.

Beyond this point, most of the current guidance provided for the selection of breathing systems is focused on the weight of the animal. In particularly large dogs, systems which require a high fresh gas flow to operate without rebreathing become economically and environmentally unjustifiable. In other large species, e.g. adult horses, only the rebreathing systems are suitable for the clinical provision of anaesthesia. In dogs with a low body weight, there is concern regarding the ability of the animal to overcome the resistance imposed by the breathing system and therefore systems which are considered higher resistance, such as the circle, have been cautioned against (Clutton, 1999). There is a wide disparity between the recommendations of even the major veterinary anaesthesia reference texts as to the maximum and/or minimum weight of animal suitable for each breathing system. There are also areas of significant overlap where multiple different breathing systems would be suitable for the same animal (Dugdale, 2010, Hughes, 2016, Mosley, 2024). The weight limit at which anaesthetists decide to change between a rebreathing and non-rebreathing system has previously been examined in small animal practice in Australia. In this study, 10 kg was the most common response in 34% of respondents (Nicholson and Watson, 2001).

Due to the range of dogs which can be anaesthetised with certain breathing systems, it is common for veterinary practices to keep in stock only a limited selection of breathing systems for clinical use. In such circumstances the decision-making process becomes restricted to which systems the anaesthetist has available to them.

The inability to scavenge anaesthetic gases effectively has largely restricted the use of breathing systems which cannot be scavenged. Working environmental exposure limits for each agent are set in the United Kingdom – for isoflurane this is 50 ppm (parts per million) on an 8-hour weighted average (Health and Safety Executive, 2020). Harmful effects associated with the prolonged or excessive exposure to isoflurane include effects on cognitive abilities, reproductive health and motor skills (Burm, 2000).

Economic considerations have become a driving force behind recent changes to the recommended use of different breathing systems. Significant financial savings can be made by utilising a breathing system which requires a lower fresh gas flow (McMillan, 2021).

As well as economical savings, such breathing systems can be operated at lower flows, providing environmental benefits. The medical profession currently creates a substantial carbon footprint. A significant proportion of this is from volatile anaesthetic agents (Charlesworth and Swinton, 2017). All the volatile anaesthetic agents and the anaesthetic gas nitrous oxide have a significant global warming effect (Andersen et al., 2012). This is detailed in Table 1-2.

Volatile Agent	**100-year Global Warming Potential**	**Ozone Depletion**	**Atmospheric Lifetime (years)**
Carbon Dioxide	1	–	74
Isoflurane	510	0.03	3.2
Sevoflurane	130	0	1.1
Desflurane	2540	0	14
Nitrous Oxide	310	0.017	110

Table 1-2 Environmental effects of anaesthetic gases. 100-year global warming potential uses carbon dioxide as a reference of 1. (Campbell and Pierce, 2015, Dugdale et al., 2020)

By reducing the consumption of volatile agent and anaesthetic gas during the use of low flow anaesthesia, a significant reduction can be made to the environmental impact of anaesthesia. It is also worth noting that total intravenous anaesthesia with injectable anaesthetic agents has been recommended as a way of eliminating the need for volatile anaesthetic agents (Jones and West, 2019). Whilst total intravenous anaesthesia does not require a breathing system for the delivery of anaesthetic agent, they are still used for the delivery of medical gases and supportive ventilation if required.

1.5 Overview of the normal respiratory cycle

During spontaneous ventilation under anaesthesia, the breathing system must permit the normal respiratory cycle of the dog by providing sufficient oxygen and removing excreted carbon dioxide. Mammals must breathe to move gas from the external environment into their lungs, allowing the uptake of oxygen for aerobic cellular metabolism. Aerobic cellular metabolism is essential for cellular energy production. Breathing also allows mammals to exhale carbon dioxide, a waste product of metabolism, which must be excreted. The rate of cellular metabolism is not a fixed process and varies to match the animal's needs and requirements (Ewart, 2020b). For example, when exercising muscle cellular metabolism will increase resulting in greater carbon dioxide production. As carbon dioxide is a weak acid, it dissolves in water and dissociates to carbonic acid via the following equation:

$$CO_2 + H_2O \rightleftarrows H_2CO_3 \rightleftarrows HCO_3^- + H^+$$

Variations in the concentration of carbon dioxide in the blood therefore result in an alteration to the pH. Changes in pH have significant consequences for protein structure leading to changes in enzyme and cellular function (DiBartola, 2012). To maintain a relatively consistent blood pH during fluctuations in carbon dioxide production, it is important for the animal to control carbon dioxide excretion. As carbon dioxide readily diffuses into air, animals can do this by increasing or decreasing their minute ventilation (Pippalapalli and Lumb, 2023).

The concentrations of carbon dioxide present in the blood are detected peripherally by chemoreceptors in the carotid and aortic bodies. These feed information to the medulla oblongata via the vagus nerve. Central chemoreceptors, found on the ventral medulla, are more sensitive to changes in pH of the cerebrospinal fluid. These central chemoreceptors also influence ventilation via a negative feedback mechanism (Nattie and Li, 2012).

The information from the peripheral and central chemoreceptors is integrated in the respiratory centre of the brain. This consists of two centres in the medulla: the dorsal and ventral respiratory groups, as well as the pontine group in the pons. Each centre is paired, so there is a left and right. These centres regulate inspiratory and expiratory movements and maintain ventilation as an involuntary process.

Pulmonary stretch receptors feedback to the pons and have a negative impact on the apneustic centre via the Hering Breuer reflex. Activation of these receptors therefore stops further inspiration and limits tidal volume (Ewart, 2020a). This reflex also increases expiratory time, thus decreasing respiratory rate (West, 2021).

During normal inspiration, sub-atmospheric pressure is generated in the pleural space due to the outward movement of the diaphragm and the thoracic wall by the intercostal muscles. This is an active process requiring coordinated movement of the muscles. The negative pressure expands the lung parenchyma creating sub atmospheric alveolar pressure. Sub-atmospheric alveolar pressure allows entrainment of air down a pressure gradient from the external environment through the airways. Once the pressure gradient reaches equilibrium, movement of gas stops (Lumb, 2017d).

During expiration, the recoil of the lung parenchyma, thoracic wall and diaphragm creates positive pressure in the pleural space and in turn positive pressure in the alveoli. The gas then moves from the alveoli through the airways to the external environment down the pressure gradient. At rest in the healthy dog this is a passive process, but during exercise there is an active component of expiration where the chest and diaphragm are employed to generate a greater positive intrapleural pressure. This allows expulsion of a larger volume of gas (Ewart, 2020b, Lumb, 2017d).

1.6 What is work of breathing and how can it be measured?

The work of breathing is the amount of energy the body expends during each breath and is given in joules. As such, it is the energy expended by the respiratory muscles to move the volume of gas of each breath in and out of the body (Lumb, 2017d).

Work in its purest form is the product of force and distance as determined by Galileo:

$$W = Fd$$

W = work

F = force

d = distance

However, for work of breathing we are examining a gas. Gases exert pressure on their surroundings. Pressure is the quotient of force and area:

$$P = \frac{F}{A}$$

P = pressure

F = force

A = area

Combining the two equations provides the formula for work of breathing, which is the product of pressure and volume.

$$W = PV$$

W = work

P = pressure

V = volume

To allow the calculation of the work done during both inspiration and expiration of a tidal volume where there will be variation in pressure, pressure can be integrated with respect to the volume as demonstrated in Cabello and Mancebo (2006):

$$W = \int P\, dV$$

W = work

P = pressure

V = volume

The work of breathing can be visualised as the area under the curve of a pressure volume loop. This is demonstrated in Figure 1-3 (based on Marval (2006)).

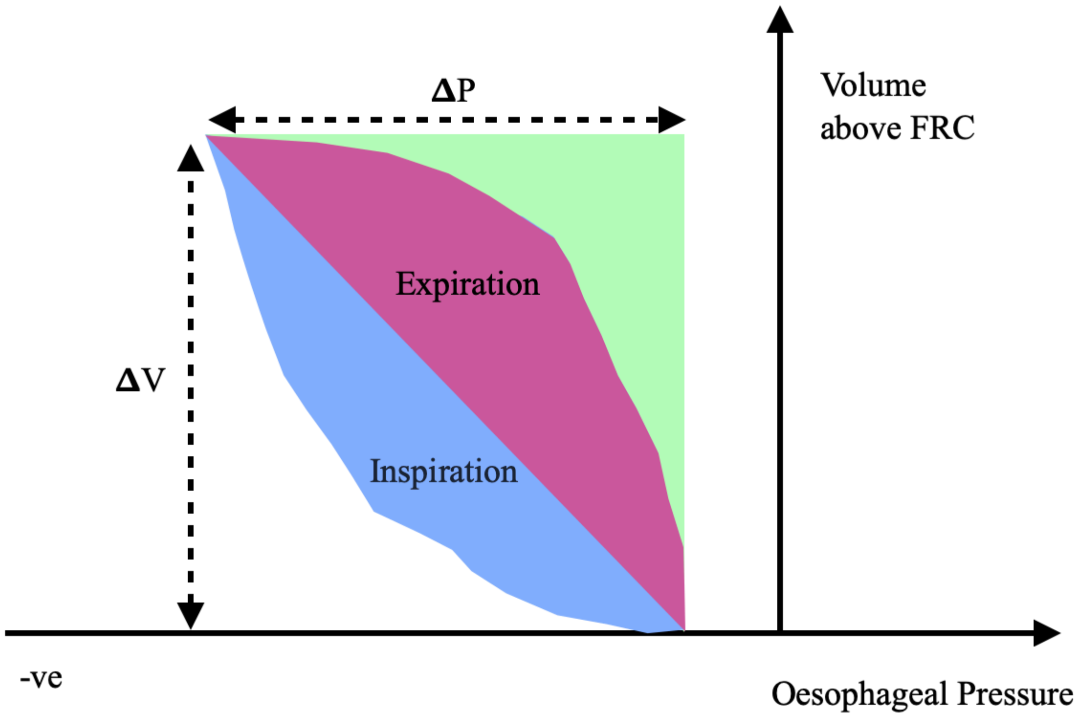


Figure 1-3 Graphical representation of oesophageal pressure plotted against volume for a single breath. The blue area represents the resistive inspiratory work. The purple area represents the resistive expiratory work. The green area represents the elastic work of breathing. FRC = functional residual capacity, ΔP = pressure difference, ΔV = volume difference

Work of breathing consists of elastic and resistive elements. The resistive work is the energy needed to overcome the inherent resistance of deforming the chest and moving respired gas through the airways and any additional apparatus (Lumb, 2017d). Other resistive aspects which need to be considered when calculating work of breathing include the energy required to overcome inertance (Otis et al., 1950) and the compression of intrathoracic gas (Ingram and Schilder, 1966).

Elastic work of breathing is comprised of the work required to overcome the recoil of both the chest and the lung. Elastic work will increase with increasing tidal volumes (Lumb, 2017e). The elastic recoil of the chest and lung parenchyma is also variable depending on the age (Mauderly, 1974) and disease status of the animal (King et al., 1991).

1.6.1 Measurement of work of breathing?

There is no ideal method currently available to measure work of breathing. This is due to the fact it cannot be directly measured and instead must be calculated based on at least two separate measurements. In the simplest form, calculation of the work of breathing can be performed using an oesophageal pressure transducer and simultaneously measuring tidal volume. The values for these measurements can be plotted and integrated to calculate the work of breathing (Cross et al., 2021).

The integration method may underreport work of breathing mainly as it fails to incorporate elastic work during inspiration (Cross et al., 2021). Thus, other more comprehensive techniques have been developed. These include the use of the Hedstrand (Hedstrand, 1969) or Otis diagrams (Otis et al., 1956). The advantage of these diagram methods is the ability to distinguish the different components of the work of breathing. The construction of the Otis diagram requires transpulmonary pressure (the pressure difference between the intrathoracic pressure measured in the oesophagus and the pressure at the mouth). The Otis diagram therefore fails to include apparatus resistance in any work of breathing calculation (Cross et al., 2021).

The most complicated and arguably the most accurate way to calculate work of breathing is with the use of a modified Campbell diagram, depicted later by Cross et al. (2021). The Campbell diagram method also requires prior measurement of the chest wall compliance. To effectively use the Campbell diagram clinically, pressure transducers must be placed in the trachea and oesophagus, as well as at the breathing system to endotracheal tube interface (airway opening). The measurement of volume and flow should also occur at the airway opening (Banner et al., 1994).

The major limitation of all methods described above is the assumption that no work is done in any other cavity during the process of respiration. It is unlikely that no work is exerted on the abdominal contents by the diaphragm (Cross et al., 2021). All methods require additional equipment above and beyond what is routinely found on veterinary anaesthetic monitors (Richardson and McMillan, 2019), so the clinical usability is currently limited.

1.7 What is resistance to breathing and how can it be measured?

Resistance is one of the major components which contributes to work of breathing. If the thoracic compartment is considered alone, the pressure to move air in and out of the lungs must overcome three things (Kaminsky, 2012):

1) The change in volume of the lung and thorax, termed elastance
2) The change in flow of the gas, termed resistance
3) The change in acceleration of lung, thoracic wall and gas, termed inertance.

Elastance, the reciprocal of compliance (Fry and Hyatt, 1960), is altered by changes in both the lung and chest wall. Obesity (Lazarus et al., 1997) or interstitial lung diseases are examples of conditions which will increase elastance (or decrease compliance). A degree of compliance is present in breathing systems (Mosley, 2024) which must be overcome by the animal. In human anaesthesia, the levels of compliance are governed and limited by international standards ISO 5367:2023.

Inertance becomes increasingly significant at higher respiratory rates. This is demonstrated in puppies which have a higher respiratory rate (Lanteri et al., 1999). In a breathing system, inertance is added due to the extra volume of gas; this is mentioned with respect to diving apparatus (Moon et al., 2009).

In fluids and gases, resistance is the frictional drag which occurs as opposition to flow. For flow to occur between two places, a pressure gradient must exist between the start and end point. The resistance governs how large this pressure gradient must be to provide a certain flow (Lumb, 2017e). Resistance to breathing is defined as the pressure difference between the alveoli and the mouth or nose divided by inspiratory or expiratory gas flow (Kaminsky, 2012). This can be expressed as a modified version of Ohm's law:

$$R = \frac{\Delta P}{Q}$$

Q = flow

R = resistance

ΔP = pressure difference

Apparatus resistance is a term used for the resistance imposed by any equipment the animal must inhale and exhale from to move gas in to and out of its lungs (Smith, 1961). The resistance imposed by anaesthetic breathing systems is apparatus resistance.

1.7.1 Resistance to flow in a tube

The airways and a major component of the breathing systems are tubes. Resistance to flow of gas in a tube occurs for two reasons (Al-Attar and Harrison, 2023, Lumb, 2017e). Firstly, there is friction created with the gas moving in contact with the wall of the tube. Secondly, resistance is imparted by the gas on itself.

Flow of gas can be laminar or turbulent. Both forms of flow are illustrated in Figure 1-4. In laminar flow, all the gas moves in the same direction with the central portion moving faster. The speed of travel of the centre component of the flow is proportional to the viscosity of the fluid or gas. The more viscous the substance, the faster the centre area travels compared to the area in contact with the wall of the tube, however, the overall flow is reduced. The external volume, which is in contact with the tube, moves slower due to friction and loss of energy (Lumb, 2017e).

In turbulent flow, the organisation of the pattern of flow appears chaotic (Williamson and Henderson, 2023) and results in the formation of areas of unstable flow, for example eddies and vortices. Unstable areas of flow result in energy loss, making turbulent flow a less efficient form of flow requiring a greater pressure difference to overcome (West and Theron, 2015).

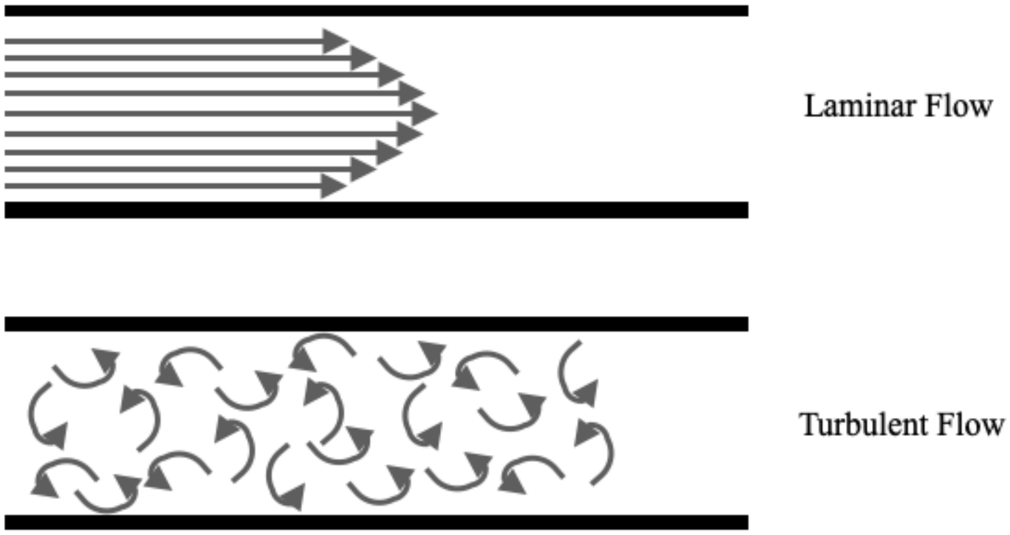


Figure 1-4 Representation of both laminar and turbulent flow in a tube based on Ebrahim et al. (2019)

It is therefore useful to be able to predict whether the flow of gas is expected to be laminar or turbulent. This is predicted by Reynolds number (Reynolds, 1997), which is determined from the following equation as quoted by Ebrahim et al. (2019):

$$Re = \frac{\rho u L}{\mu}$$

Re = Reynolds number

ρ = fluid density

u = speed of flow

L = characteristic length

μ = dynamic viscosity

Where the Reynolds number is <2000, laminar flow is more likely, whereas when the number is >2000, turbulent flow becomes more likely. However, there is no precise cut-off for this transition between laminar and turbulent flow.

The resistance to flow during laminar flow can be calculated based on Poiseuille's law, quoted by Bates (2016), which states:

$$R = \frac{8\eta l}{\pi r^4}$$

R = resistance

η = fluid viscosity

l = length of tube

r = radius

For turbulent flow, the calculation of resistance is more complex due to the nature of eddy and vortex formation. A form of the Blasius equation has been used to examine the resistance to flow in human endotracheal tubes (Lofaso et al., 1992). This has not been transferred to evaluate breathing systems. The calculations required to predict the resistance of breathing systems at different flows and pressures are more complex than those looking at endotracheal tubes due to the number of different constituents which make up each breathing system type.

1.7.2 Physiological resistance

The physiological resistance to breathing is not a fixed value and will vary based on several factors. It is comprised of both airway resistance and the resistance of tissue deformation (Lumb, 2017e).

Airway resistance is a relatively minor component of physiological resistance. The airways terminate in very narrow tubes which, by Poiseuille's law, would result in a high resistance if the entire tidal volume was required to pass though the individual airway. This, however, is not the case, as tens of thousands of individual bronchioles exist, summing to a much larger cross-sectional area which reduces resistance. The result of this is that the airways which contribute the greatest resistance to breathing are usually considered the large airways, e.g. trachea and bronchi. It is worth noting that due to the complex branching and changes in airway diameter through the lung, there is usually a mixture of turbulent and laminar flow. Due to the higher flow rates in the higher order airways, turbulent flow dominates here. As the flow of gas reduces as it approaches the alveoli, laminar flow becomes more prevalent. This contributes to the greater resistance of the large airways compared to the smaller ones (Lumb, 2017e).

Changes in airway resistance throughout the respiratory cycle are also worth considering. At the end of expiration, the airways which are not fixed due to cartilage will be at their smallest diameter. Unfixed airways increase in diameter, reducing resistance to flow throughout inspiration. Therefore, resistance at the initiation of inspiration will be higher than later in the inspiratory cycle. The closing capacity describes the volume at which the airways begin to close. Once the airways close, gas remaining in the alveoli which has a higher concentration than present in the blood is absorbed rapidly, thus absorption atelectasis develops. The resistance of a closed airway is much greater than that of an open one (Lumb, 2017e).

1.7.3 Apparatus Resistance

The resistance imposed by breathing systems is apparatus resistance. As each breathing system is composed of multiple components, apparatus resistance is the combination of the resistance of all the different parts. When individual components are combined, there is the potential for a change between laminar and turbulent flow at their interface. It is therefore difficult to predict the total resistance when all the individual components are put together and, when determining resistance, the system should be studied as a whole (Martin et al., 1989).

In the anaesthetised animal, any airway device is also a component of apparatus resistance. The most common airway device used in dogs is the endotracheal tube. When used in human anaesthesia, an endotracheal tube is seen as the biggest contributor to apparatus resistance (Shandro, 1982). This statement is unlikely to be transferable directly from humans to dogs. The most common ET tube size used in adult humans is between 7 and 8.5 mm depending on sex and individual size (Farrow et al., 2012). The selection of ET tubes in dogs varies based on size and conformation, however, based on experience, an 8 mm tube can be used in a 10 kg dog. Given the tidal volume of the 10 kg dog is at least one fifth of that of the adult human, the flow required through the tube will also be lower, reducing resistance.

1.7.4 Measurement of resistance

Like work of breathing, resistance to breathing cannot be directly measured and requires calculation based on indirect methods and other principles.

Integration of the pressure difference between the alveolus and atmospheric pressure with respect to inspiratory or expiratory flow (instead of volume which was used to calculate work of breathing) allows calculation of resistance (Engstrom and Norlander, 1962). Here, oesophageal balloon pressure can be used as a substitute for alveolar pressure. Using oesophageal balloon pressure allows calculation of both apparatus and physiological resistance. To discern only apparatus resistance, the pressure can be measured at the level of the airway opening (i.e. between the breathing system and airway device) (Banner et al., 1994).

Whole body plethysmography is described as the gold standard method for calculating resistance, however, this requires bulky equipment not compatible with the veterinary clinical environment (Kaminsky, 2012).

Forced oscillation is another alternative which has been used in anaesthetised humans to measure respiratory impedance. It measures impedance due to the fact it utilises an alternating pressure frequency (Ntima and Lumb, 2019). To generate and deliver the oscillating frequency requires significant modification of the anaesthetic breathing system (Crago et al., 1972).

1.8 What are the complications of excessive resistance?

Excessive resistance of a breathing system can be present during inspiration, or expiration or both phases of ventilation. In human medicine, excessive respiratory resistance has been attributed to serious complications which, if untreated, could result in death (Davies et al., 1919).

The effects of inspiratory and expiratory resistance on ventilation have been individually studied in dogs (Moore and Binger, 1927). Inspiratory resistance was reported to cause an increase in respiratory rate with a corresponding decrease in tidal volume. In severe cases, a reduction in minute volume occurred with a corresponding hypoxaemia, hypercarbia and acidosis. Expiratory resistance produced a reduction in minute volume and respiratory rate.

The hypercarbia, acidosis and any hypoxaemia were less pronounced than occurred with inspiratory resistance.

Serial investigation took place in the 1940s studying the effects of additional pressure in the breathing system. The effect of this is resistance to expiration. An examination of the effects of 10 cmH_2O positive pressure in the breathing system of anaesthetised dogs was found to result in reduced systolic, diastolic and mean blood pressures (Beecher et al., 1943). This also corresponded with a drop in blood flow to the femoral artery, as well as an increase in venous pressure. These findings are supported by a subsequent study where 7 mmHg was applied to the breathing apparatus of dogs (Knoefel et al., 1945). This resulted in a fall in arterial pressure and 41% drop in cardiac output. The second study also reports a period of apnoea developing after the additional pressure was applied into the system. The reduction in cardiac output, blood pressure and blood flow were explained as being a consequence of the reduction in preload, due to the congestion of the venous system created by the increased thoracic pressure.

1.8.1 Breathing system adaptations and modifications to minimise resistance

To minimise resistance to breathing, adaptations have been made to breathing systems and their components.

Smooth bore tubing has been developed which has a smooth internal surface in addition to a corrugated exterior. This reduces resistance to flow internally whilst maintaining the structure of the tube to prevent kinking (Davey, 2012). Such tubing can be of a smaller diameter, which will reduce breathing system volume but increase resistance according to Poiseuille's law. Smaller diameter tubing commonly connects to the patient via a 15mm external diameter connection (Davey, 2012). The reduced diameter of interface between the breathing system and airway device helps to reduce apparatus dead space which becomes more significant at smaller tidal volumes (Dugdale et al., 2020).

One-way valves, a component of the circle system, have evolved over time. The trend is for lighter weight materials to be used in manufacturing these to reduce the force required to move them, thus reducing their resistance (Dugdale et al., 2020). The discs in modern one-way valves are usually composed of a hydrophobic material (Parthasarathy, 2013). This reduces the build-up of water condensation on the valve. Any condensation on the valve disc will increase its weight. The force required to open the valve may also increase due to the surface tension of the condensation, if it bridges the disc and the seat of the valve (Dorsch and Dorsch, 2008b).

It has been demonstrated that the absorbent canister size which has the greatest efficiency is one which has an airspace equal to that of the tidal volume of the anaesthetised subject when full. More than this volume results in excessive resistance due to the passage of gas through a larger volume of soda lime. Less than this volume and there may be incomplete removal of carbon dioxide (Adriani and Rovenstine, 1941). Due to the wide range of sizes of dog which are encountered in veterinary practice, the soda lime canisters tend to be larger than would be required for some animals. This results in smaller animals encountering needless resistance. Recently, several small animal veterinary circle breathing systems have been developed and a common feature of these is a smaller canister size (Dugdale et al., 2020).

The development of soda lime granules was key to minimising resistance and improving absorption efficiency for carbon dioxide (Bracken and Sanderson, 1955). The soda lime structure and volume make up the substantial component of the canister resistance. Granules which were too small tended to cake together reducing the diameter of any airflow channels. On the other hand, if the granules were too large there was greater potential for channelling and lack of carbon dioxide absorption. The resistance of soda lime can also be altered by changing particle shape and surface (Adriani and Rovenstine, 1941).

1.9 How can respiratory function be measured?

Previously described measurements of work of breathing and resistance frequently require measurement of volume and flow. Measurement of the volumes of gas as they move in and out of the lung also provides some quantification of respiratory function. The volume of gas moved in and out of the lung during each normal breath is called the tidal volume. If this volume is multiplied by the number of breaths the subject takes in a one-minute period, this becomes the minute volume (Lumb, 2017b).

Flow is the change in volume over time and is given by the equation below (as quoted by Gilbey and Wilson (2021)):

$$Q = \frac{\Delta V}{t}$$

Q = flow

ΔV = volume difference

t = time

Flow rates can vary considerably during each breath it is therefore more practical to obtain flow by integrating volume with respect to time (Gilbey and Wilson, 2021).

The composition of gases in the blood and expired gases can be quantified to measure the effectiveness of ventilation in terms of gas exchange. The main gases examined in terms of gas exchange are oxygen and carbon dioxide (Nunn and Pouliot, 1962).

1.9.1 Measurement of tidal and minute volume

The volume of gas held in the lungs can be broken into different components (Quanjer et al., 1993). The focus here is on static lung volumes which exist at times where there is no flow of gas in or out of the lung. As well as the tidal volume introduced above, there are both inspiratory and expiratory reserve volumes. These reserve volumes are the volumes of gas that can be forcibly inhaled or exhaled respectively beyond what would constitute the normal tidal volume. Even after complete expiration (including the expiratory reserve volume), a volume of gas remains in the lung which cannot be expired; this volume is termed the residual volume (Lumb, 2017b). A graph representing these volumes is shown in Figure 1-5. This graph also shows the lung capacities, which are calculated values based on the volumes. The total lung capacity is the sum of all the volumes. The vital capacity is the sum of the two reserve volumes and the tidal volume. The functional residual capacity is what remains after a normal breath. It is calculated based on the sum of the residual volume and the expiratory reserve volume (Lumb, 2017b). It is worth noting that as expiration is a passive process in the dog, the functional residual capacity is obtained at the point when the atmospheric and intrapleural pressures are equal (Ewart, 2020b).

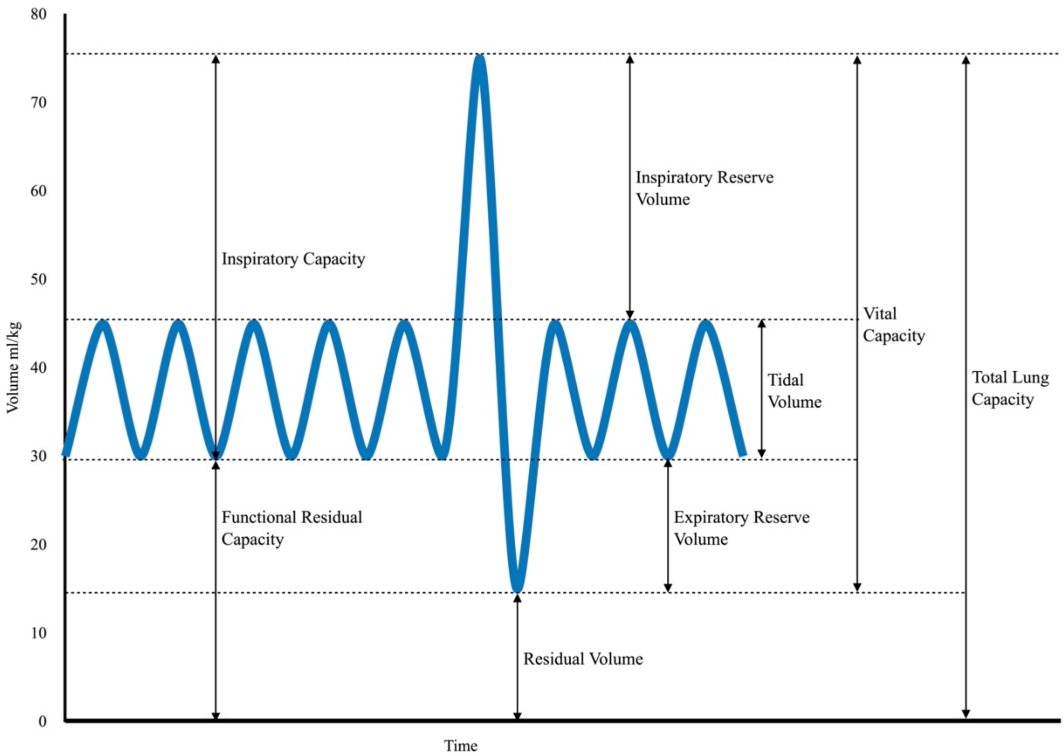


Figure 1-5 Graphical representation of the volumes and capacities of the lung (based on Lumb (2017b)). Volume in ml/kg is approximate and will vary between individual animals.

The tidal volume, inspiratory and expiratory reserve volumes can all be measured in a cooperative human. In dogs and anaesthetised subjects, only tidal volume can be measured without the use of invasive apparatus due to the inability to achieve a maximal expiration or inspiration voluntarily (Beecher and Bradshaw, 1933).

Measurement of tidal volume can be achieved using either direct or indirect methods. A direct method quantifies the total volume or flow of gas against a known volume or calibrated scale. Indirect methods use other properties, such as changes in pressure, to calculate flow and volume (Gilbey and Wilson, 2021).

An example of a direct measuring device is a Benedict Roth spirometer (Tissot, 1904, West and Photiou, 2018) or Tissot apparatus (Tissot, 1904). Such equipment is bulky and is not convenient to incorporate into existing anaesthesia apparatus. This difficulty is encountered with other direct measuring devices, such as the wedge bellows design of spirometers (West and Photiou, 2018).

Indirect methods allow for the reduction in size of the apparatus. This allows for greater utility in the clinical setting and incorporation into the breathing apparatus. This requires a measuring device which does not impart excessive resistance into the system. In-system measurement must be able to deal with a wide range of flows of an intermittent nature. Respiratory gases are also mixed compositions of individual constituents and vapours. One of these vapours is water, which gives the respiratory gases a high humidity (Gilbey and Wilson, 2021). Several different indirect monitors have been developed. The main ones which will be discussed are the Wright respirometer, pneumotachographs and pitot tube flowmeters.

The Wright respirometer, an inferential mechanical flow meter, uses the gas pressure to generate movement of a lightweight turbine. Each rotation of the turbine is equated to a set volume of gas. This allows calculation of a tidal volume. The frequency of rotation is proportional to the flow (Beatty, 2012). The limitations of this system lie in the fact that the turbine (plus the gearing and dial in an analogue version) all have mass. This leads to a high inertia, so the initial and final components of flow are understated and overstated respectively (Hatch and Williams, 1988).

Pneumotachographs are fixed orifice variable pressure drop flowmeters which rely on the Hagen-Poiseuille relationship for laminar flow. They are composed of a tube which has a known resistance placed as an obstruction to the flow. For resistance to remain a known quantity, the resistance element must maintain laminar flow. Thus, their design allows for laminar flow in the flow ranges they are intended to measure. The pressure difference which occurs across the resistive element is measured. This allows flow to be calculated based on the principle of Ohm's law (Mandal, 2006). There are two types of resistance element. The first is a Fleisch screen, which is a series of narrow parallel tubes (Fleisch, 1925). The second resistor type is a Lilly, which uses a membrane as the resistive element (Lilly, 1950, Silverman and Whittenberger, 1950). Both are subject to condensation build up which can cause obstruction of the resistor, changing the overall resistance. This can be overcome by heating the resistor, so many include a thermal element (Mandal, 2006).

A pitot tube flow meter uses the Bernoulli principle (Bernoulli, 1738) to allow calculation of flow based on the measured difference in static and total pressure. Static pressure is the force exerted by a fluid or gas at rest. The difference between total pressure and static pressure is the dynamic pressure. Dynamic pressure is the kinetic energy of a gas per unit volume (Gilbey and Wilson, 2021). Once the kinetic energy is known, this allows calculation of velocity based on the following equation, as described by Merilainen et al. (1993):

$$q = \frac{1}{2}\rho v^2$$

q = dynamic pressure

ρ = *fluid density*

v = velocity

The configuration of a pitot tube for use in a breathing system is detailed in Figure 1-6. There is also a sampling port for anaesthetic agent and gas composition. Measurement of gas composition allows accurate estimation of gas density for calculating velocity (Filmyer et al., 1999).

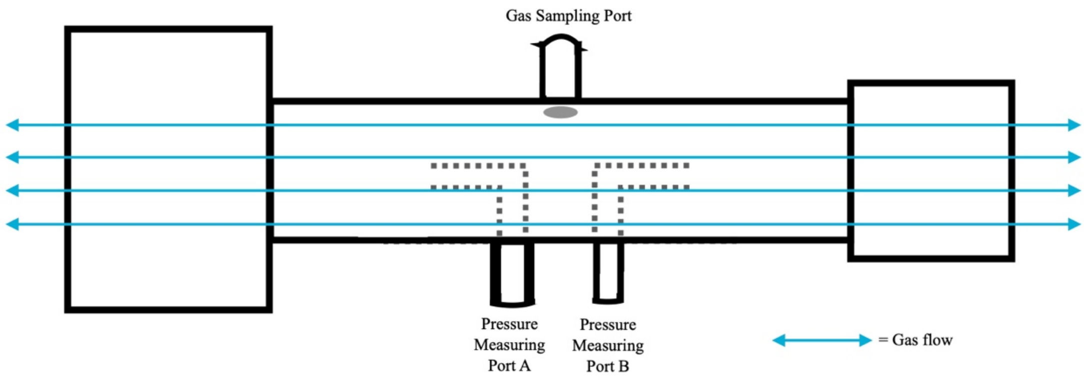


Figure 1-6 Diagram of a pitot tube style flow meter (based on the Datex pedilite (Datex, Helsinki)). Here there are two pressure measuring ports facing in opposite directions, the openings of which sit in the lumen of the tube. The gas sampling port allows for side-stream sampling for gas and agent analysis.

1.9.2 Measurement of carbon dioxide?

The most accurate measure of carbon dioxide as a marker of ventilation is arterial blood gas analysis (Davis et al., 2013). To perform this, a blood sample must be taken and it is therefore an invasive test (Flenley, 1980). Between arterial and venous samples there is expected to be a difference in carbon dioxide concentrations due to the excretion through the lungs (Dubin and Pozo, 2023). Reference arterial and jugular venous measurements are 5.36 ± 0.45 and 5.88 ± 0.51 kPa respectively (Haskins et al., 2005). Blood carbon dioxide analysis is performed using a Severinghaus electrode, which is a modified glass electrode. This electrode utilises the solubility and dissociation of carbon dioxide into a weak acid. As it dissociates releasing a hydrogen ion, the concentration of carbon dioxide is proportional to the potential difference between the electrodes. The potential difference can be measured, and the concentration of carbon dioxide can be calculated from this. This theory relies on a constant temperature and environmental pressure (Severinghaus and Bradley, 1958). The invasive nature of blood gas analysis limits its clinical usefulness. It is also not routinely performed as a continuous measurement, providing only a snapshot of information from when the sample was taken (Venkatesh, 1999).

Expiratory gas analysis provides a suitable non-invasive alternative to blood gas analysis. For the analysis of carbon dioxide, this is termed capnometry. If it is recorded and displayed in a graphical form, this becomes capnography (Dorsch and Dorsch, 2008c). As the concentration of carbon dioxide in exhaled gas must be lower than that in the blood to have a diffusion gradient, there is an expected discrepancy between capnometry and arterial blood gas analysis (Hendricks and King, 2007). In the healthy dog this is reported to be between 0.75 ± 0.74 kPa with side-stream capnography (Teixeira Neto et al., 2002).

Clinically the measurement of carbon dioxide in respiratory gas can be performed using infrared light absorption. Other methods are available such as mass spectroscopy and Raman spectroscopy, however, these require bulkier equipment not suited to the clinical setting (Briley et al., 2024). A diagram of the components of an infrared capnograph are shown in Figure 1-7. This analyser works by directing an infrared light through a filter and then across a chamber filled with sample gas. The filter is used to ensure only a narrow wavelength of light is directed through the sample which improves accuracy as it limits interference from other gases. The carbon dioxide in the sample chamber absorbs the infra-red light: the reference chamber has no absorption qualities. At the other side of the chamber is a photodiode which converts the light energy it receives into a potential difference which can be measured and compared between the two chambers (Dorsch and Dorsch, 2008c). The absorption of light can then be used to calculate the carbon dioxide concentration according to the Beer Lambert law. The Beer Lambert law states that the absorption of light is directly proportional to the concentration of a substance (Briley et al., 2024). Infrared spectroscopy is subject to interference from nitrous oxide. In monitors which will have exposure to nitrous oxide, this can be corrected for by measuring the concentration of nitrous oxide by other means.

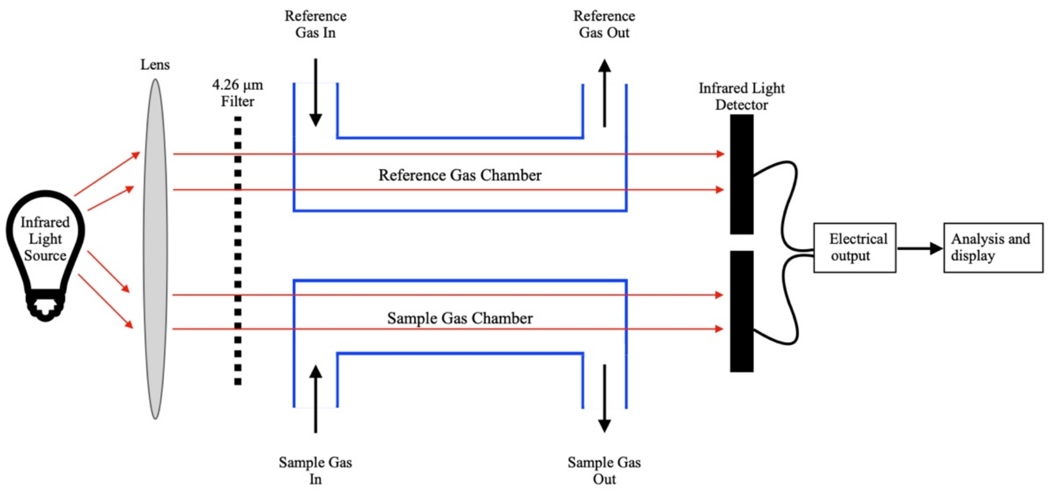


Figure 1-7 Diagram of a side-stream capnograph with an infrared light source and two chambers, one for the sample gas and the other for reference gas based on Dorsch and Dorsch (2008c). The 4.26µm filter is specific to the wavelength carbon dioxide absorbs.

Modern anaesthesia monitors may use mainstream or side-stream techniques. Both are used to measure inspired and expired gases. In mainstream, the analyser unit sits within the respiratory apparatus, whereas in side-stream a small volume of gas is continuously sampled from the respiratory apparatus and analysed in a separate unit (Dorsch and Dorsch, 2008c). During expiration, the first portion of gas to leave the airways is from anatomical dead space, thus should contain no carbon dioxide. The final portion of gas should be predominantly alveolar gas and should equate most closely with the blood. Thus, end-tidal carbon dioxide is the most closely equated to arterial blood gas values (Schauvliege, 2016).

Mainstream capnography does not remove any volume from the breathing apparatus. The measurement is made without any delay, and it therefore displays a reflection of the immediate airway conditions (Schauvliege, 2016). As the sample is measured immediately there is less diffusion of carbon dioxide making it more accurate (Teixeira Neto et al., 2002). It does, however, add a volume of dead space at the end of the airway device. In animals with a small tidal volume, this can be significant and cause rebreathing of carbon dioxide (Schauvliege, 2016).

Side-stream capnography continuously removes a small volume of around 50–200 ml minute^{-1} from the breathing apparatus. This is conveyed via a sample line to the monitor (Briley et al., 2024). The advantages of this are that the monitor itself does not add considerable bulk between the airway device and the breathing system. It should be noted, however, that the connector may contribute its own dead space and bulk. There is a delay in the measurement as the sample takes time to travel up the sample line. This also allows for diffusion of the sample within the line between areas of high gas concentration to areas of lower concentration, reducing the accuracy. The sample tubing can also become obstructed resulting in inaccurate readings (Dorsch and Dorsch, 2008c).

Both capnography techniques have the potential to be affected by dilution due to incoming fresh gas from the breathing system should it enter the sampling chamber. Dilution can be minimised in side-stream capnography by sampling from as close as possible to the airway device (Gravenstein et al., 1985).

Capnography and blood gas analysis are sensitive, but not specific, markers of respiratory function as results can be altered due to metabolic and circulatory changes. Carbon dioxide production is proportional to metabolic rate. A such, changes in metabolic rate will result in changes to the concentration of carbon dioxide in the blood and therefore excreted in expired gas (Willner and Weissman, 2011). Although change to the metabolic rate does not usually happen abruptly under anaesthesia, a general decrease in metabolic rate will be seen with hypothermia. Certain processes will increase metabolic rate such as sepsis and hyperthermia (Schauvliege, 2016). Malignant hyperthermia is a condition which may result in a rapid increase in metabolic rate, increasing carbon dioxide production and excretion into alveolar gas by a concentration detectable on capnography (Moens and Verstraeten, 1982).

Capnography and, to a lesser extent, blood gas analysis measurements will also be subject to fluctuation with the cardiovascular status of the animal. When there are changes in perfusion of the peripheral vascular bed, this will alter the uptake of carbon dioxide from its site of production into the blood. For example, a reduction in perfusion may be seen after an acute haemorrhage. The pulmonary perfusion may also be affected, resulting in a change to the ventilation/perfusion status of the alveoli. In the case of a decrease in perfusion, this would lead to a reduction in carbon dioxide excretion into the alveolar gas and a reduction in the end tidal carbon dioxide (Moens and Verstraeten, 1982).

Capnography may highlight and prompt investigation of several breathing system problems. These include excessive dead space, exhaustion of the soda lime or faulty one-way valves in a rebreathing system and insufficient fresh gas flow in a non-rebreathing system. All of these would result in rebreathing of carbon dioxide. This rebreathing would be detected by a carbon dioxide reading during the inspiratory phase (Moens and Verstraeten, 1982).

1.10 How does anaesthesia alter respiratory function?

When using an anaesthetic breathing system, dogs are usually anaesthetised or sedated. Anaesthesia can interfere with respiratory function through various mechanisms. This can alter a dog's ability to regulate its own respiratory function, thus resulting in respiratory compromise.

Firstly, anaesthetic drugs decrease sensitivity of the peripheral and central chemoreceptors to changes of blood carbon dioxide and pH (Lumb, 2017a). With opioids, this results in a suppression of minute volume mainly by reducing the respiratory rate through an increase in expiratory time (Quickfall et al., 2024). With propofol, a reduction in tidal volume (Quickfall et al., 2024) and dose dependent reduction in respiratory rate are observed (Muir and Gadawski, 1998). The respiratory suppressive effects of these drugs can be potentiated when used concurrently. The respiratory drive can be abolished completely resulting in a period of apnoea (Muir and McGuirk, 1984). Post induction apnoea is described following both propofol and alfaxalone induction in the dog (Bigby et al., 2017). Isoflurane also supresses central respiratory drive, resulting in a decreased minute volume. This has been recorded due to a decrease in respiratory rate (Jones and Snowdon, 1986) or both respiratory rate and tidal volume (Steffey and Howland, 1977).

During medium, stage 3 anaesthetic depth (as classified by Guedel (1966)) there is progressive paralysis of the intercostal muscles and diaphragmatic movement becomes the sole driver of ventilation. At a deeper plane of anaesthesia, stage 4, diaphragmatic paralysis will develop (Norkus, 2024). This altered muscle function can result in a decreased minute volume. There is also a decrease in the FRC due to the relaxation of the musculature, which predisposes to atelectasis formation. Atelectasis occurs readily in both sedated and anaesthetised dogs, being reported to have developed in as little as 15 minutes (Barletta et al., 2014). Animals with a reduction in muscle tone due to disease or sarcopenic change will be at greater risk of atelectasis developing. Furthermore, animals which have an increased pressure on the thorax due to accumulations of body fat or increased intra-abdominal pressure (which can occur during pregnancy for example) will also have a reduction of FRC. The formation of atelectasis results in a ventilation/perfusion mismatch due to shunting. It is more likely in the dependant areas of the lung. Atelectasis also reduces compliance and increases the elastance of the lung.

In the healthy conscious dog, the effects of atelectasis are partially compensated for by hypoxic pulmonary vasoconstriction. Hypoxic pulmonary vasoconstriction is a mechanism of autoregulation within the lung. This reflex results in afferent vasoconstriction to any acini which develop relatively hypoxic efferent blood flow, thus diverting blood to better ventilated areas (Lumb, 2017c). Where deoxygenated blood does not receive oxygenation (as it has passed by atelectatic alveoli before returning to the left atrium), this can be termed shunting. In the anaesthetised dog, the hypoxic pulmonary vasoconstriction reflex is supressed resulting in more significant shunting of blood and a reduced efficiency of gas exchange (Lennon and Murray, 1996).

The use of a fraction of inspired oxygen greater than that of room air is common during general anaesthesia. Most small animal inhalant anaesthesia in the UK is expected to be delivered in close to 100 percent oxygen (Raillard et al., 2024). As oxygen is continuously being taken up by the blood when it is in the alveoli, this can lead to absorption of the entire contents of the alveolus resulting in absorption atelectasis (Joyce and Baker, 1995).

Suppression of reflexes and postural changes associated with anaesthesia impact on lung ventilation and perfusion. Anaesthesia prevents the sigh reflex which is a protective mechanism against atelectasis (Saraswat, 2015). The sigh reflex is the response to decreasing lung compliance, as is seen in atelectasis. A sigh breath is one of a tidal volume greater than the eupnoeic volume. The larger tidal volume of a sigh breath permits reinflation of areas of collapsed or atalectic lung (Severs et al., 2022). Positioning in lateral or dorsal recumbency has also been associated with development of atelectasis (Ambrisko et al., 2017).

The bronchodilation induced by inhalant anaesthetics (Yamakage, 2002) may be seen as an advantage to respiratory function as it will reduce airway and physiological resistance. The disadvantage of bronchodilation is an increase in anatomical dead space.

Inadvertent hypothermia is a common complication of anaesthesia in dogs (Clark-Price, 2015). Severe hypothermia reduces central chemoreceptor sensitivity, thus leading to hypoventilation. There is also a progressive decrease in cellular metabolism resulting in a reduced oxygen consumption and carbon dioxide production (Mallet, 2002).

1.11 Conclusions

There is a large selection of breathing systems available for use in veterinary anaesthesia but little evidence for their selection. Due to the lack of evidence most references are based on author opinion. Different sources prioritise different factors when selecting a breathing system which adds to the complexity of the decision process. Animal weight appears the major determinant for most, however, different cut off weights are reported depending on the author with no evidence to substantiate these figures in dogs. The greatest area of overlap exists between around 5-10 kg. Little recent evidence exists documenting the impact of resistance imposed by each breathing system on the ventilatory function of dogs to help guide this choice. This is of increasing importance as attituded towards the selection of breathing systems may be changing to allow the increased use of more economical systems with environmental and financial benefits. Whilst acknowledging that anaesthesia itself can impact ventilation in the dog the quantification of the ventilatory function between two breathing systems may be achieved using monitoring equipment found in a referral level hospital.

1.12 Aims of Thesis

The main aims of this work were to examine if higher resistance breathing systems (e.g. the circle) were being selected in 5-10 kg dogs and if so, what was driving this selection. Additionally, this thesis aimed to determine the impact of reportedly higher resistance breathing systems on spontaneous ventilation in dogs and if the clinical use of these higher resistance systems was safe in this group of dogs.

Based on the literature examined and the aim of this work, two potential avenues for research were revealed. The first looking at current availability of breathing systems and the attitude and process behind their selection. The second, to compare what were considered to be the most prevalent systems (Bain, Circle and T-piece) performance in dogs of 5-10 kg body weight to allow comparison of ventilation between the groups. The specific weight was chosen due to the overlapping guidance which existed for this group. The referral hospital setting available during this research project provided access to both the animals and the necessary equipment to compare ventilation.

The following research questions summarise the aims of this work:

1. Which anaesthetic breathing systems are available and in use in small animal veterinary practice?
2. Which weight limits of dog are used when choosing a breathing system?
3. Which factors are considered most important when choosing a breathing system?
4. In the weight range of 5–10 kg dogs, is there variation in the breathing system anaesthetists select at extremes of age, weight, chest conformation and body condition score?
5. What are the effects of breathing systems of differing resistance on the spontaneous ventilation of anaesthetised 5–10 kg dogs? More specifically, how do measured end expired CO_2 ($P_{E'}CO_2$), tidal volume (V_T) and respiratory rates compare in anaesthetised dogs breathing spontaneously through either a circle or a Bain with a T-piece control?

The first 4 questions are asked in a survey study of veterinary anaesthetists. The last question is examined in a clinical study which took place at the University of Glasgow Small Animal Hospital.

Chapter 2 A survey study on the availability of anaesthetic breathing systems and their use in 5–10 kg dogs.

2.1 Preface to Survey Study

The survey study was designed and to examine individual accessibility to different breathing systems and the decision making behind their selection. Common anaesthesia reference texts describe several different breathing systems and their use(Mosley, 2024, Hughes, 2016, Dugdale et al., 2020), however, it was considered unlikely that every system would be available to every anaesthetist. Previous survey studies had documented that the circle breathing system was the most commonly available to Australian veterinarians(Nicholson and Watson, 2001). The survey presented in this thesis was designed to examine availability amongst the veterinary anaesthesia specialty in a wider geographical pool.

The survey also looked to examine what factors veterinary anaesthetists consider most important when selecting or recommending a breathing system. Different considerations are given when choosing a system, however, the importance of each aspect as part of the decision process is poorly defined. There is often more than one system which may be deemed appropriate and as such during day-to-day clinical work there can be debate over which system to select. Surveys in the human paediatric anaesthesia field have seen a shift in practice where circle systems have increased in use(Marsh and Mackie, 2009, Fesseau et al., 2014). Breathing system resistance has been considered a key factor in the past (Clutton, 1999) but this has been questioned more recently by those who consider the endotracheal tube the main additional source of apparatus resistance in the anaesthetised animal (Mosley, 2024) based on similar evidence in human anaesthesia(Shandro, 1982).

Animal weight is the key factor used by many texts to determine the suitability of a system for and animal under anaesthesia. The weight limit provided for each system is inconsistent between sources, this is especially true around the weights of 5-10 kg(Sawyer, 2008, Hughes, 2016, Mosley, 2024, Dugdale et al., 2020). The evidence for the safe use of a circle system in animals of around 5kg was only available for cats (Hartsfield and Sawyer, 1976) at the time of conducting the survey study. No such evidence was available for dogs. Despite the lack of evidence in dogs the circle had been recommended down to a weight of 7 kg based on the increasing availability of more modern circle systems (Dugdale et al., 2020) or less then 5 kg by others(Mosley, 2024). The survey was designed to gauge what weight limits individual anaesthetists recommended and used given the wide array of recommendations available.

It was also hypothesised that different animal characteristics including breed, age and body condition would impact the selection process. These factors can impact ventilation due to their impact on chest compliance in for example barrel chested dogs(Asorey et al., 2020), or functional residual capacity in the case of geriatric or obese dogs(Mauderly, 1974, Bach et al., 2007). As well as examining the importance of these factors using a Likert scale case scenarios were constructed to allow comparison of the selection in extremes of each characteristic.

To allow for relatively rapid global distribution, administration and compilation of the results, an internet-based survey was selected as the most useful medium by which to conduct this research. It was hoped the survey would reach a target population of those actively involved in clinical work, dedicated to the advancement of veterinary anaesthesia and responsible for the dissemination of knowledge on the subject of veterinary anaesthesia. To achieve this goal, the distribution of the survey was conducted via associations, colleges and groups dedicated to veterinary anaesthesia.

It is hoped the results obtained from this survey are informative to other veterinary anaesthetists regarding the selection process for breathing systems.

2.2 Title

A survey study on the availability of anaesthetic breathing systems and their use in 5–10 kg dogs.

2.3 Abstract

Objective

To investigate which breathing systems are available and why they are selected in 5–10 kg dogs.

Study Design

Anonymous online voluntary open survey.

Methods

An online survey, designed following CHERRIES guidelines (Eysenbach, 2004), was advertised through the American College of Veterinary Anesthesiologists - List (ACVA-List), Association of Veterinary Anaesthesia (AVA) and European College of Veterinary Anaesthesia and Analgesia (ECVAA) (February-March 2022). A convenience sample was taken.

Results

Of the 256 responses received, 138 were completed. This included (*n* responses received) veterinarians (107) and veterinary nurses or technicians (29) actively involved in the anaesthesia of dogs.

The most prevalent breathing systems available to respondents were circle (99%), coaxial Bain (79%) and modified Ayre's T-piece (with adjustable pressure limiting valve) (72%). When recommending a dog weight range suitable for the use with these systems, respondents advised a median (interquartile range) of 5 (3–10) to 100 (100–100), 3 (0–8) to 20 (10–33) and 0 (0–0) to 10 (7–10) kg, respectively. Respondents agreed or strongly agreed that important factors in selecting a breathing system were the fresh gas flow requirement (92%), dog weight (91%), resistance (83%) and environmental pollution (79%). In clinical scenarios based on 5–10 kg dogs, the circle system was chosen by 58% for a thin and 77% for a keel-chested *versus* 44% for an obese and 66% for a barrel-chested dog, respectively.

Conclusions

The circle system is the most commonly available breathing system. The minimum weight limit used for the circle system is less than previous surveys have reported (Nicholson and Watson, 2001). Several factors influence the choice of breathing system other than dog weight.

Keywords

anaesthesia, dogs, equipment and supplies, inhalation, questionnaire.

2.4 Introduction

Breathing systems are used in veterinary anaesthesia to carry anaesthetic gases and vapours to and from animals in a controlled manner. Breathing systems can be classified as non-rebreathing or rebreathing systems. Non-rebreathing systems are categorised A-E based on the layout of their components (Mapleson, 1954) with an F classification added later (Willis et al., 1975). Only Mapleson classifications A, D, E and F are used in veterinary anaesthesia (Hughes, 2016). Examples of non-rebreathing systems include Lack/mini-Lack (Mapleson A), Bain (Mapleson D), and the Ayre's T-piece (Mapleson E - with no bag; Mapleson F - with open ended bag; Mapleson D with adjustable pressure limiting (APL) valve and closed bag). These systems require fresh gas flows (FGF) near or above minute volume ($\dot{V}E$) to prevent rebreathing of carbon dioxide (CO_2).

Rebreathing systems contain soda lime which removes CO_2 from the gas mixture allowing recycling of exhaled gas and a FGF significantly less than $\dot{V}E$. The most commonly used type of rebreathing system available in small animal practice is a circle system (Mosley, 2015). Hybrid systems exist, such as the Humphrey ADE, which allows the user to change between Mapleson classifications depending on the need to ventilate the animal (Humphrey et al., 1986). A soda lime canister and one-way valves can be added to the Humphrey ADE for use as a circle in larger animals (Hughes, 2016).

The guidance available for selecting an anaesthetic breathing system is mainly based around the weight of the animal and varies across publications. Authors and text editions often provide differing information as to which body weights are appropriate for each system (Hughes, 2016, Clutton, 1999, Mosley, 2015). In the veterinary clinic, the choice ultimately comes down to anaesthetist preference and the availability of the systems in the workplace. Prior surveys have examined the availability of breathing systems in veterinary clinics as part of a wider review of anaesthetic practice (Clarke and Hall, 1990, Nicholson and Watson, 2001). No research has been undertaken to examine how veterinarians select a breathing system.

We conducted this study to improve our understanding of which breathing systems are available for use in dogs and how they are chosen. This survey was designed to investigate the following research questions: 1) Which anaesthetic breathing systems are available and in use in veterinary practice? 2) What are the weight limits used when choosing a breathing system? 3) What factors are considered most important when choosing a breathing system? 4) In the weight range of 5–10 kg, is there variation in the breathing system anaesthetists select at extremes of age, weight, chest conformation and body condition score? We hypothesised that the circle would be the most commonly breathing system and dog weight would be agreed as the most influential factor when selecting a breathing system.

2.5 Material and methods

Research was approved by the University of Glasgow College of Medical, Veterinary & Life Sciences Ethics committee (Ref. 200220025). The survey was conducted using the Checklist for Reporting Results of Internet E-Surveys (CHERRIES) guidance (Eysenbach, 2004). The online survey platform Qualtrics was used to conduct the survey.

Informed consent was obtained via a consent form with an accompanying information sheet and privacy notice detailing the storage and use of any data provided by the participant. No personal data, including respondents' internet protocol (IP) addresses, were collected as part of this research. Duplicate entries were avoided using the survey platform to assign a unique user identifier to each client computer through cookies. The survey was voluntary with no incentive offered for participants to complete the survey.

The questionnaire underwent a two-stage testing process prior to distribution. Initially, the questions were distributed internally to colleagues in the anaesthesia department to ensure technical accuracy and clarity of wording. Following construction of the questionnaire on the online platform, it underwent a second round of testing with a group of 10 colleagues, some based internationally, to ensure functionality of the user platform.

The anonymous link to the open online questionnaire was distributed through multiple channels. The survey was open for a period of two months 1st February 2023-31st March 2023. Distribution was conducted via email to the American College of Veterinary Anesthesiologists - List (ACVA-List), European College of Veterinary Anaesthesia and Analgesia (ECVAA) residents and diplomates, a website link on the Association of Veterinary Anaesthetists (AVA) webpage, and via Facebook to the AVA and ECVAA residents' groups. A reminder was sent to the ACVA-list on the 20th of March. All survey announcements with distribution dates are contained in Appendix A.

The online questionnaire was comprised of three sections: 1) consent, 2) survey - research questions and 3) survey - demographic questions. Each section was designated one page. Participants could navigate both forward and backwards through the sections. A copy of the online questionnaire is available in Appendix B. The first section was to ensure informed consent; this comprised of 10 questions in total. All questions in this section were compulsory. The final consent question required a mandatory 'yes' response, without which the survey ended for the participant. The second section assessed the main research questions of the study. This was comprised of a variety of question modalities including tick box, Likert scale and sliding scale. Additionally, a drop-down list, scenario-based question was used. This introduced a selection of 5–10 kg dogs presented for anaesthesia at extremes of weight, body condition, age and chest conformation, and requested participants to allocate their preferred breathing system. The third section asked questions concerning the type of practice participants worked in and their level of experience and training in anaesthesia. In the second and third section an "other" answer in the form of free text was submittable for each question. It was expected all the questions should be applicable to all the participants; therefore, no provision was made through a "not applicable" option.

Responses were excluded from the study if it was incomplete at the time of closing the survey, consent was not given, the second section was left entirely blank, or the respondent's occupation was given as something other than employed in clinical practice.

2.5.1 Statistics

Analysis was conducted using Jamovi (the Jamovi project, NSW, Australia). Data were analysed using descriptive statistics. Categorical variables were summarised as percentages whereas continuous variables were summarised as medians and interquartile ranges.

2.6 Results

It is estimated that between 900–1200 people received the survey link. This includes approximately 1000 ACVA-list subscribers, 220 ECVAA diplomates and 84 residents, 100 members of the ECVAA residents Facebook group and 450 AVA members. There was probably significant overlap between some of these groups.

The calculated participation rate was 21–28%. This rate was calculated as the number of individuals who agreed to take part in the survey (256) expressed as percentage of the estimated population who received the study (900–1200). After exclusion criteria were applied, 138 responses were available for analysis. The completion rate was 54%. The margin of error, based on the responses obtained, was 7.7–7.9% (range due to population estimate).

The respondents comprised 107 (79%) veterinary surgeons and 29 (21%) veterinary nurses/technicians. Of the 107 respondents, two withheld demographic information and were not included in the percentages. Of these, 106 (99%) of the veterinary surgeons and 7 (24%) of the veterinary nurses/technicians worked exclusively in the discipline of anaesthesia.

Most respondents worked exclusively in small animal practice (n = 77/136, 57%) with the remainder working in practices with mixed species (n = 59/136, 43%). The types of practice were recorded as academic by 64/136 (47%) and private practice by 66/136 (49%) respondents. A further five respondents (4%) worked across a range of practice types and one (0.7%) respondent worked in a charitable organisation.

Regarding the number of years in clinical practice, this was greater than 20 for 50/136 (37%) followed by 11–20 years for 44/136 (32%) and 5–10 years for 36/136 (27%) of respondents. The lowest representation was from those with fewer than 5 years' experience which comprised of 6/136 (4%) respondents.

Most respondents, 77/136 (57%), were diplomates of the ECVAA or ACVAA with a further 23 (17%) current or former residents of the colleges.

The availability of the breathing systems is detailed in Table 2-1. Other breathing systems respondents stated having access to include a universal F system (*n* = 7, 5%).

Breathing System	**Respondents to which this breathing system was available *n* (%)**
Lack	40 (29)
Mini-Lack	40 (29)
Magill	9 (7)
Coaxial Bain	109 (79)
Circle	136 (99)
Ayre's T-piece (with APL valve)	99 (72)
Ayre's T-piece (without APL valve)	13 (9)
Humphrey ADE (without soda lime)	20 (14)
Humphrey ADE (with soda lime)	21 (15)

Table 2-1 Availability of different anaesthetic breathing systems to respondents (n = 138) of a survey on the selection and use of anaesthetic breathing systems in 5–10 kg dogs. APL – adjustable pressure limiting.

The minimum and maximum weights of dog which respondents would recommend for each breathing system are shown as medians (interquartile range) in Fig. 2-1. This figure also demonstrates the weight range of dog in which respondents would use each system as the range between the median minimum and median maximum weights.

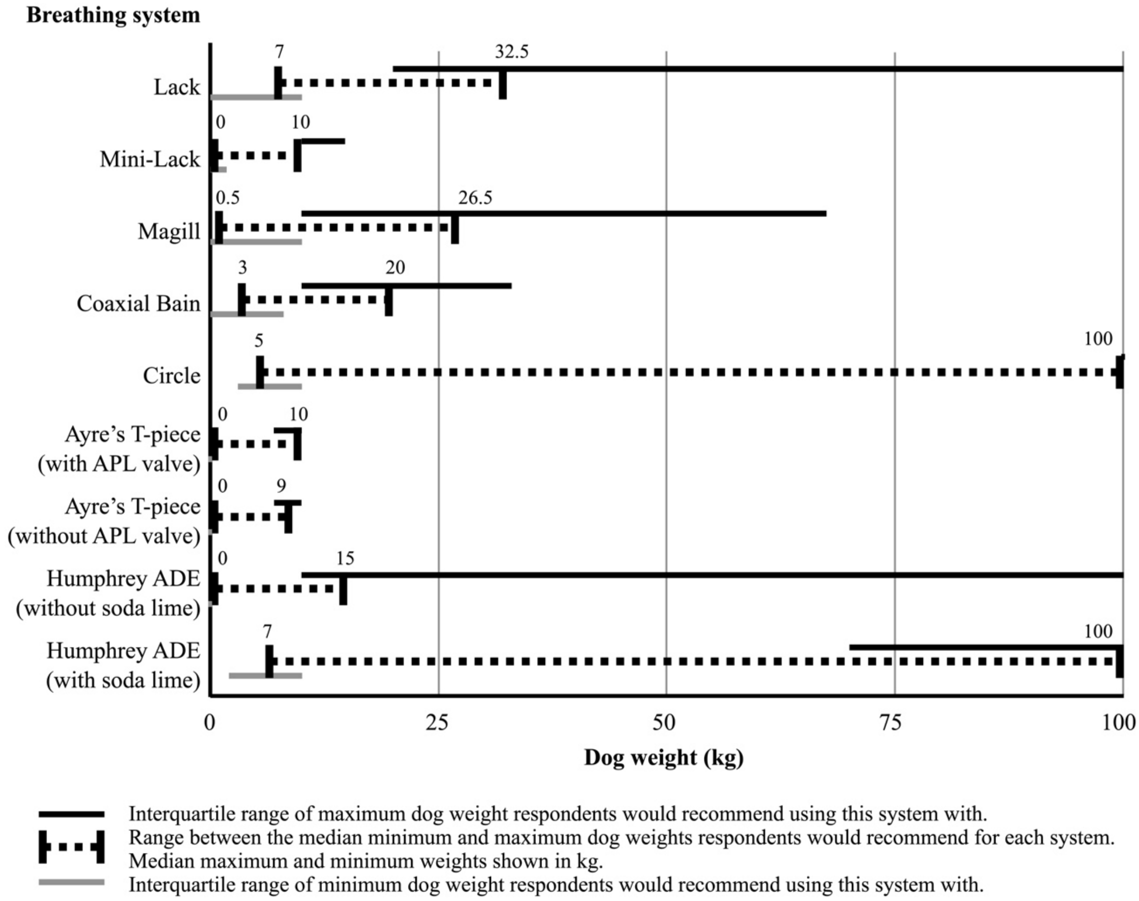


Figure 2-1 Bar chart showing the median and interquartile range of maximum (dark grey bars) and minimum (light grey bars) weight of dog the 138 respondents of the survey would recommend when selecting common breathing systems. The range between the median values

The agreement or disagreement of respondents as to whether a selection of factors affected their choice of breathing system is displayed in Fig. 2-2. Common additional factors respondents considered when choosing a breathing system included suitability of the system for provision of mechanical ventilation and the dog's requirement for mechanical ventilation during a procedure (*n* = 13/138, 9%), development of hypothermia in the dog (*n* = 5/138, 4%) and availability of capnography (*n* = 3/138, 2%).

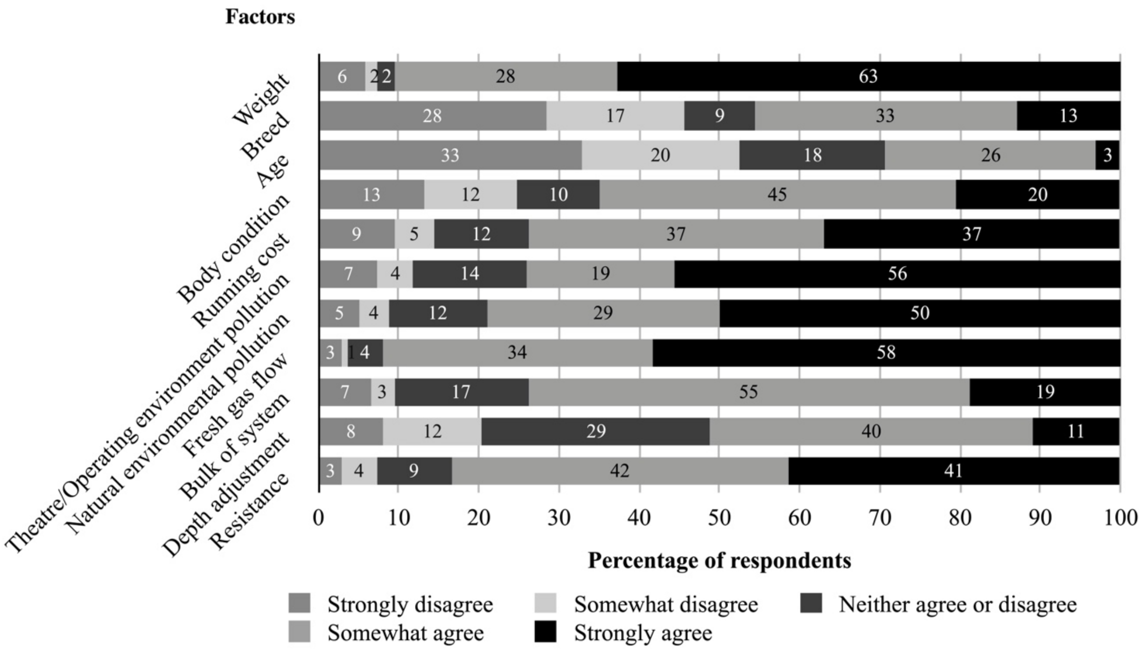


Figure 2-2 Chart showing distribution of the 138 survey respondents' agreement on a 5-point Likert scale (from strongly disagree on left to strongly agree on right) as to the importance of different factors used when selecting breathing systems in 5–10 kg dogs.

The three most frequent breathing systems selected by respondents for each of the clinical scenarios are shown in Table 2-2. Several respondents used the 'other' category to advise they would use a paediatric circle - these have been incorporated into the totals for the circle system during analysis.

Scenario Description	**Responses *n***	**First most frequently selected breathing system *n* (%)**	**Second most frequently selected breathing system *n* (%)**	**Third most frequently selected breathing system *n* (%)**
7.5 kg, adult dog, normal conformation and body condition	136	Circle 73 (54)	Mini-Lack 20 (15)	Coaxial Bain 19 (14)
Juvenile dog	135	Circle 75 (55)	Coaxial Bain 18 (13)	Ayres T-piece (with APL valve) 17 (12)
Geriatric dog	136	Circle 80 (58)	Coaxial Bain 18 (13)	Mini-Lack 15 (11)
Thin dog	136	Circle 80 (58)	Coaxial Bain 18 (13)	Mini-Lack 14 (10)
Obese dog	136	Circle 60 (44)	Ayre's T-piece (with APL valve) 32 (23)	Coaxial Bain 23 (17)
Keel-chested dog	136	Circle 105 (77)	Mini Lack 8 (6)	Coaxial Bain and Humphrey ADE (with soda lime) 7 (5)
Barrel-chested dog	135	Circle 90 (66)	Coaxial Bain 17 (12)	Humphrey ADE (with soda lime) 10 (7)
5 kg dog	137	Circle 55 (40)	Ayre's T-piece (with APL valve) 31 (23)	Coaxial Bain 21 (15)
10 kg dog	136	Circle 117 (85)	Humphrey ADE (with soda lime) 9 (7)	Coaxial Bain 7 (5)

Table 2-2 The three most commonly selected breathing systems in response to different case-based scenarios posed to respondents (n = 138) in a survey of anaesthetic breathing system selection in 5–10 kg dogs. APL – adjustable pressure limiting.

2.7 Discussion

The survey was open to anyone actively involved in the selection of breathing systems for anaesthetised dogs. This was the first survey designed specifically to determine the availability and selection process of breathing systems in dogs weighing between 5 and 10 kg. The respondents included a high proportion of personnel working exclusively in the discipline of anaesthesia as diplomates of the subject. It is likely the results of this survey are indicative of the views of the veterinary anaesthesia community rather than the whole veterinary community. This was expected given that the distribution channels used are subscribed to by veterinarians and nurses who have a particular interest or further training in anaesthesia. As the anaesthesia community is responsible for the wider education of the veterinary profession (as undergraduates, veterinary nurses in training or in continuing professional development) with regards to anaesthetic practice, this information is still highly relevant. Furthermore, there was a much higher percentage of veterinarians than nurses who responded to the survey. This can probably be explained by the larger proportion of veterinarians than nurses contactable through the distribution channels.

The three most commonly available breathing systems for use in veterinary practice are the circle, T-piece and Bain. The circle being almost ubiquitously available for use when anaesthetising dogs is unsurprising given the economic and environmental advantages this system offers when used with low FGFs (Nunn, 2008). This finding is consistent with broader surveys of anaesthetic practice in small animals (Nicholson and Watson, 2001). A circle system is also incorporated into many commercially available anaesthetic machines which has likely increased its availability. The three most common systems (circle, Bain and T-piece with APL valve) are all suitable for use with mechanical ventilation which was noted as an important consideration by 13 of the respondents. The Lack and mini-Lack systems, which are relatively economical, are less commonly used; however, these are less suitable for mechanical ventilation. From the responses of the participants, it appears that the option for mechanical ventilate if required, as provided by the Bain and T-piece, is preferred over the economy of the Lack systems. The percentage of respondents who had access to a breathing system without an APL valve (9%) was surprising given the difficulty of scavenging effectively with these systems. The utility of systems without an APL valve is limited to very small animals, perhaps less than 1-1.5 kg, where the resistance of an APL valve might be considered excessive to allow spontaneous ventilation. If these systems are used with volatile anaesthetic agents there is an increased risk of operator exposure and the possibility of detrimental health consequences, if not scavenged effectively (Varughese and Ahmed, 2021).

The range of weight limits given by the respondents for each system were highly variable. This was expected given the variability present in the literature which advises on the selection process (Dugdale, 2010, Hughes, 2016, Mosley, 2015, Sawyer, 2008). Notably, respondents recommended all the systems surveyed for use in dogs between 7 and 9 kg.

The lowest body weight of 5 kg (median) recommended by the respondents for use of a circle is less than that recommended in some current texts (Dugdale et al., 2020, Hughes, 2016). This value is also less than previously reported as a 2001 survey of Australian veterinary anaesthetists found most respondents used 10 kg as the lower limit for the use with a circle system (Nicholson and Watson, 2001). Older texts suggest 15 kg (Clutton, 1999) as a lower limit for the use of a circle systems due to use of predominantly adult human systems. However, research existed earlier than this for the use of a circle system in domestic cats (Hartsfield and Sawyer, 1976). More recent textbooks cite a reduced minimum weight for a circle of 7–10 kg (Hughes, 2016) or < 5 kg in some texts (Mosley, 2015, Sawyer, 2008). Dogs with a low body weight have a smaller lung volume (Donati et al., 2018) and muscle mass. These dogs can hypoventilate or become apnoeic with excessive breathing system resistance (Clutton, 1999). Resistance within the breathing system is the opposition created by the apparatus to respiratory gas flow, increasing the work of spontaneous breathing (Shandro, 1982). The simplest breathing system (e.g. an original Ayre's T piece), comprised of only corrugated tubing, creates resistance due to the frictional force it imposes on the free movement of the gas inside (Martin et al., 1989). More complex breathing systems made with additional components, such as connectors, one-way valves or a soda lime canister, have higher resistance to breathing (Parthasarathy, 2013). As well as adding to the frictional force, additional components create turbulence which unpredictably alters the resistance (Martin et al., 1989). Some adaptations, for example the smooth internal bore of the tubing of the mini-Lack, are present to reduce resistance (Walsh and Taylor, 2004). The apparatus resistance can be overcome using mechanical ventilation, but the survey questions asked specifically about spontaneous ventilation. Due to the economic and environmental advantages they possess, newer circle breathing systems have been developed for paediatric human use with lower resistance APL, one-way valves and soda lime canisters (Marsh and Mackie, 2009). These modifications have transferred into veterinary products (Dugdale, 2010). Due to the risk of rebreathing, in extremely small dogs, apparatus dead space can impact the selection of breathing system if the dead space is significant in relation to the tidal volume. More widespread use of capnography (Richardson and McMillan, 2019) has enabled the early detection of hypoventilation and rebreathing in anaesthetised dogs. This increase in monitoring will have facilitated the use of higher resistance but more economical breathing systems such as the circle by allowing anaesthetists to detect changes in ventilation if they arise. This is reflected in the survey results, as several of the respondents mentioned a requirement of capnography in the free text portion of the questions as an additional consideration if they selected the circle system.

Over 60% of respondents strongly agreed that body weight was an important factor when selecting a breathing system. Other important factors included the resistance of the system and the body condition score of the dog. The ability of a dog to overcome the inherent resistance of a breathing system is impacted by these characteristics. Excessive resistance is challenging to particularly small, obese or old dogs (Clutton, 1999) especially because obese or barrel-chested dogs have reduced chest wall compliance (Asorey et al., 2020). In the cases of obesity and old age, functional residual capacity (FRC) is reduced (Bach et al., 2007, Mauderly, 1974). External resistance, reduced chest wall compliance and reduced FRC all serve to increase the work of breathing. It is noticeable that respondents disagreed that age was important. However, in geriatric dogs, the ability to do this work is hindered by age-related reduction to functional muscle mass (Pagano et al., 2015).

There was strong agreement by respondents that the FGF requirement, running cost and environmental pollution (all of which are interconnected) impact breathing system choice. Rebreathing systems use less medical gas and volatile agent, so are financially and environmentally more advantageous to the user (Mosley, 2015). The environmental benefits of rebreathing systems (Baum and Aitkenhead, 1995) have driven uptake across the human medical profession. The increased use of circle systems is demonstrated in sequential human medical surveys such as Marsh and Mackie (2009) and Fesseau et al. (2014). By requiring a FGF which is less than $\dot{V}_E$ circle systems offer advantages to the dog by retaining the heat and humidity of the expired gas which is then transferred to the dry and cold inspired gas. The concern regarding temperature is reflected in the strong agreement as to the importance of FGF as well as in the responses of the five individuals who specifically raised this concern. A lower FGF slows changes in concentration of anaesthetic agent inspired by the dog should the vaporiser be adjusted (Hughes, 1998). The speed of depth adjustment was not agreed to be an important consideration by those respondents.

When presented with clinical scenarios of 5–10 kg dogs, the respondents' most frequently chosen system of a circle varied by over 10% based on chest conformation and body condition score. This was expected given the additional resistance inherent in a circle system and the concerns of overcoming this in obese and barrel-chested dogs. Barrel-chested dog breeds are commonly brachycephalic in their conformation. The number of brachycephalic dogs in the UK (the country the survey was distributed from) has increased significantly over recent years. In 2019 the French Bulldog was the most common purebred dog under 1 year old (O'Neill et al., 2023) representing 7% of the population. If the demand for these dogs continues, it may influence the breathing system selection process across the profession.

A major limitation of this survey was the use of convenience sampling. Due to the open nature of the survey on the websites and sharing of the link by respondents on other platforms, it was not possible to accurately calculate the view or participation rates. The low response rate and relatively high margin of error of this survey limits the ability to generalise the results beyond the confines of the surveyed population (Bennett, 2020). This is a common feature of internet-based surveys. Respondents also commented that the survey was difficult to complete due to a lack of familiarity with the terminology used, especially across continents. This likely arose due to the multiple ways of categorising breathing systems. The Mapleson classification was avoided as multiple systems exist which could be placed within each category (e.g. Bain and Mapleson D T-piece in D) which would have made analysis difficult. The wide range of breathing systems available across the world advertised by different manufacturers may have influenced respondents. The survey was unable to collect IP address data since this was outside the ethical approval granted for this study. The inability to collect IP address data has prevented examination of differences between continents where different breathing system manufacturers exist.

2.8 Conclusions

The circle is the most commonly available breathing system in veterinary practice. When the weight of a dog allows a wide range of breathing systems to be selected, other aspects of the dog's conformation (breed and body condition score) impact this selection process. There is strong agreement that environmental and cost factors also affect the choice of breathing system. The circle is being recommended for use in dogs which weigh less than some reference materials would recommend.

Chapter 3 Comparing respiratory variables with circle, Bain and T-piece breathing systems in 5–10 kg dogs: randomised crossover trial.

3.1 Preface to Clinical Study

Textbooks and guidelines have contradictory or unclear guidance on which breathing systems are best suited to animals of the 5–10 kg weight range. With increasing concern for wasted volatile agents affecting the environment, there is a distinct interest in using breathing systems which need a lower fresh gas flow. These environmental and economic concerns were highlighted in the survey results.

There is also a change in the use of the circle breathing system, which would traditionally be considered a higher resistance but more economical. The 5 kg median minimum weight recommended by the surveyed group for the use of a circle system was lower than previously reported by others, where this value was 10 kg (Nicholson and Watson, 2001). This reduction in recommended weight for the circle has limited published evidence for safety. This lack of evidence generated concern that the circle breathing system may be being used for animals which were unable to tolerate the resistance it imposes. The most likely impact of excessive breathing resistance is reduction to minute ventilation or apnoea.

Hypercapnia is difficult to detect without the monitoring equipment to measure expired carbon dioxide. The use of capnography during anaesthetic monitoring appears to be increasing, with 21% of centres having it available in a survey conducted between 2002 and 2004 (Brodbelt et al., 2008) compared to 47% of respondents reporting using it in a survey conducted in 2017 (Richardson and McMillan, 2019). It is unlikely, however, that the profession has reached a stage where capnography is used in every anaesthetic in dogs. The availability of spirometry is suspected to be limited to a smaller still number of practices, however, there are no data on this.

Performing this study in a hospital environment was intended to allow us to establish how well 5–10 dogs tolerate these breathing systems whilst still always ensuring a high degree of safety. The monitoring equipment available in the hospital provided the capabilities by which to obtain spirometry and capnograph values. To improve data collection and increase accuracy, this was performed digitally by extracting values directly from the monitors to the computer.

This clinical study aimed to evaluate the tidal volume, respiratory rate and end tidal CO_2 in spontaneously breathing, anaesthetised, 5–10 kg dogs using a Bain or circle compared to a T-piece breathing system. The Bain, circle and T-piece were chosen as these were expected to be the most common breathing systems available in practice. This availability was confirmed by the survey study. The purpose of comparing respiratory rate, tidal volume and capnograph measurements was to compare the dogs' minute volume and ability to expel carbon dioxide and thus overall ability to ventilate on each system. It was considered likely that breathing systems of excessive or differing resistance would have a clinically significant effect on these measurements. The T-piece was chosen as a control as this was considered the lowest resistance system. Having been developed for paediatric anaesthesia, the T-piece has always been recommended for what would be considered small dogs. Due to a concern over the degree of variation between individual animals, the study was designed to allow for paired analysis. A sample size calculation performed during the design stage demonstrated that paired analysis allowed for a reduction in the number of animals which needed to be recruited to provide a statistically significant result.

The period during which clipping and surgical site preparation occurred was considered an ideal time during which to take the measurements. During this time, there is no surgical stimulus, and the plane of anaesthesia does not need to be changed. It also allowed for collection of measurements without any impact on the surgical procedure. Overall, this study was intended to allow the production of more rigorous guidance for the selection of breathing systems.

3.2 Title

Comparing respiratory variables with circle, Bain and T-piece breathing systems in 5–10 kg dogs: randomised control trial.

3.3 Abstract

Objective

This study aimed to compare different breathing systems during spontaneous ventilation in anaesthetised 5–10 kg dogs.

Study design

Randomised, non-blinded, crossover, clinical trial

Animals or animal population

Thirty, 5–10 kg dogs anaesthetised for a range of procedures.

Methods

A Mapleson D T-piece system was used as a control in all dogs. The dogs were equally randomised to the test breathing systems: circle or Bain. All dogs received a standard anaesthetic protocol. Respiratory rate (f_R), end expired carbon dioxide ($P_{E'}CO_2$), tidal (V_T) and minute ($\dot{V}_E$) volume were compared using a paired student’s t test or Wilcoxon rank test.

Results

The circle $P_{E'}CO_2$ (6.04 ± 0.64 kPa), V_T (12.1 ± 3.9 ml kg^{-1}) and $\dot{V}_E$ (116.7 (97.5–166.0) ml kg^{-1}) were significantly higher (p = <0.001, 0.035 and 0.002 respectively) than the T-piece $P_{E'}CO_2$ (5.31 ± 0.78 kPa), V_T (10.6 (7.7–13.3) ml kg^{-1}) and $\dot{V}_E$ (107.8 (77.3–131.9) ml kg^{-1}). The Bain $P_{E'}CO_2$ (5.22 ± 0.98 kPa) was significantly lower (p = 0.032) and the VT (7.1 ± 2.7 ml kg^{-1}) significantly higher (p = 0.041) than the T-piece $P_{E'}CO_2$ (5.61 ±

0.90 kPa) and V_T (6.6 (4.8–7.0) ml kg^{-1}). Between the Bain and T-piece there was no significant difference in $\dot{V}_E$. Respiratory rate was similar in both systems compared with the control.

Conclusions and clinical relevance

Whilst differences were found between both test systems and the control, the clinical consequences appear minimal. Both circle and Bain, appear suitable for use in healthy 5–10 kg dogs as overall ventilatory function was adequate.

3.4 Introduction

Breathing systems are used when anaesthetising dogs to deliver volatile anaesthetic agents and oxygen to the dog and remove waste gases. The most common breathing systems available for use in dogs are the circle, Bain and T-piece (with adjustable pressure limiting (APL) valve) (Murray et al., 2023). The circle system is a rebreathing system and can therefore be used at a fresh gas flow (FGF) below the minute volume ($\dot{V}E$) (Hughes, 2016). The Bain and the T-piece are non-rebreathing systems of the Mapleson D classification (Mapleson, 1954) which require a FGF between one to three times the $\dot{V}E$ to prevent rebreathing of exhaled carbon dioxide (CO_2) (Hughes, 2016).

A recent survey reported that anaesthetists commonly use circle breathing systems in dogs weighing 5 kg and above (Murray et al. 2023) This finding is consistent with the recommendations of Sawyer (2008) and Mosley (2015) but a lower weight than recommended by others (Hughes 2016; Dugdale et al. 2020). In summary, current guidance for the use of breathing systems in 5–10 kg dogs has little consensus. Advantages to the use of a circle breathing system is the reduced FGF required, providing both financial and environmental benefits (McMillan 2021) and conserving moisture and heat within the system (Hughes 2016). Disadvantages are the additional components (one-way valves and absorbent canister) present in the circle breathing system that increase the resistance the dog must overcome to spontaneously ventilate (Dugdale et al. 2020). The additional resistance increases the work of breathing and may result in hypoventilation or apnoea if the animal is unable to do this work (Clutton 1999). Those who advocate for the use of the circle in dogs less than 10 kg argue that the resistance imposed by a circle system is minimal compared to that of the endotracheal tube (Mosley 2024). The T-piece was designed for use in paediatric anaesthesia and is of a low resistance design (Ayre 1937). Due to the low resistance, the T-piece is recommended (Dugdale et al. 2020) and used (Murray et al. 2023) in dogs weighing less than 10 kg.

Detecting the clinical implications of breathing system incompatibility might be challenging without using capnography, spirometry, or blood gas analysis until substantial impairment occurs. As these monitoring techniques are not commonly used in anaesthetic practice (Richardson & McMillan 2019), it is important to study the use of higher resistance breathing systems, such as the circle breathing system, in 5-10 kg dogs to ensure their safety in everyday practice.

The aim of this study was to compare the effects of different breathing systems on the spontaneous ventilation of anaesthetised 5–10 kg dogs. The study was designed to measure end expired CO_2 ($P_{E'}CO_2$), tidal volume (V_T) and respiratory rates of anaesthetised dogs breathing spontaneously through either a circle or a Bain with a T-piece control.

3.5 Material and methods

This was a single centre randomised clinical study, with each animal acting as its own control. Ethical approval was obtained from the University of Glasgow School of Biodiversity One Health and Veterinary Medicine Ethics Committee (Ref EA34/21). Informed owner consent was required for inclusion in this study. Consolidated standard of reporting trial (CONSORT) reporting guidelines were used (Schulz et al., 2010).

Dogs greater than one-year-old that presented to the University of Glasgow Small Animal Hospital, weighed 5–10 kg and were scheduled for anaesthesia, were eligible to participate. All dogs underwent physical examination, and their medical history was reviewed. Dogs were excluded for the following reasons: evidence of a disease process impairing ventilation, need of intermittent positive pressure ventilation (IPPV) due to type of anaesthesia provision and surgical procedure planned, use of any drugs (such neuromuscular blocking agents) that would require IPPV), or their body condition was greater than 7/9 or less than 3/9 based on the World Small Animal Veterinary Association body condition score chart (Members 2011).

Using Microsoft Excel (Microsoft, USA) to generate random numbers, dogs were randomly assigned to one of two test breathing system groups: Bain (BT) or Circle (CT). A second random number generation was used to determine whether the test system should be used first, followed by control, or vice versa. Alongside the assigned breathing system group (BT or CT) each dog underwent testing using a T-piece breathing system which functioned as a control group for the values monitored. The exact specifications of the breathing systems used in this study are described in Appendix C. Measurements were all conducted by the same researcher.

The anaesthetic protocol was the same for all dogs. Premedication consisted of methadone (Methadyne 10 mg ml^{-1}, Zoetis, UK) 0.3 mg kg^{-1} and acepromazine (ACP 2 mg ml^{-1}, Elanco, UK) 0.02 mg kg^{-1} injected intramuscularly in the lumbar epaxial musculature between 30 and 60 minutes prior to induction. Intravenous access was established if not already present and dogs were preoxygenated via face mask for 5 minutes if tolerated. Propofol was intravenously titrated to effect to allow endotracheal (ET) intubation with a cuffed tube (Portex tracheal tube clear PVC high-volume low-pressure cuff, ICU medical, USA) of the largest diameter which comfortably fitted as determined by the supervising anaesthetist. The length of insertion of the ET tube was approximated to the point of the shoulder and was sized so as not to protrude beyond the incisor teeth. The ET tube cuff was inflated using a manometer syringe to a pressure of 25 cmH_2O, initial spirometry curves were assessed for evidence of a leak. General anaesthesia was maintained with the volatile agent, isoflurane (Isofane 100% w/v, Piramal Critical Care, UK) with 100% oxygen as a carrier gas via a T-piece in all dogs at the start of their anaesthetic for stabilisation prior to commencing the study. A FGF of 500 ml kg^{-1} min^{-1} was used and remained constant regardless of the breathing system. Dog weight, breed, age, sex, body condition and surgical procedure were recorded, as was the American Society of Anesthesiologists (ASA) score, total dose of propofol administered, size of the ET tube and recumbency. The dogs were placed in either left or right lateral recumbency; this position was not changed during the study period. Hartmann's fluids (AquaPharm 11, Animalcare, UK) were given intravenously at a rate of 5 ml kg^{-1} hr^{-1}.

A Datex S/5 compact anaesthetic monitor was used (GE Healthcare, USA). The capnograph and anaesthetic agent module of the monitor was calibrated prior to every case with a reference gas (Quick Calibration Gas, GE Healthcare, USA). The spirometry was assessed 10 times with 60 ml of air in a syringe to ensure the measurement was within the ± 6% or 4 ml accuracy as quoted by the manufacturer. A machine warm-up time of 30 minutes occurred prior to any calibration and measurement.

Measurements obtained from this monitor were heart rate (HR), non-invasive blood pressure (NIBP), saturation of peripheral haemoglobin with oxygen (SpO_2), oesophageal temperature (T), capnography, end expired isoflurane ($F_{E'}ISO$) and spirometry. Spirometry measurements included pressure, volume and flow, and were taken from a pitot tube (Pedi-lite Spirometry Sensor, GE Healthcare, USA) placed between the ET tube and the breathing system. This spirometry technique uses the measurement of differential pressures to calculate flow and volume. Side-stream capnography was sampled from the pitot tube. The interface, including monitoring apparatus, between each of the breathing systems and ET tube is shown in Figure 3-1. All measurements were exported continuously from the anaesthetic monitor using VSCapture (Karippacheril & Ho 2013) for further analysis. A recording frequency of 0.2 Hz was used for ECG heart rate, NIBP mean, SpO_2, T and

FE′ISO. A higher recording frequency of 25 Hz was used for capnography and spirometry data. Where the NIBP was not obtainable using the Datex machine, an alternative monitor (Cardell insight (Midmark, USA) or Petmap (Ramsey Medical, USA)) was used and the values manually recorded. During the measurement windows all clipping, cleaning or other preparation was stopped to prevent interference with ventilation. All measurements were conducted in the preparation area prior to the start of any surgical procedure.

Five minutes after intubation the breathing system was changed from a T-piece (if required) to the system they had been randomised to use first – test or control. Five minutes was then allowed to adapt to the first system they were allocated (a total period of 10 minutes to allow redistribution of the propofol and the attachment of monitoring equipment). Following this, the measurements for the first breathing systems were taken over five minutes. The breathing systems were then exchanged, and a period of five minutes given to allow the dog to adapt to the new system. Data for the second system were then collected over a five-minute period. After this point the dogs were released from the study protocol.

Dogs were removed from the study if: apnoea occurred for longer than two minutes, hypoventilation with an PE′CO_2 greater than 8 kPa; the arterial oxygen saturation (SpO_2) was less than 95%; a bolus of induction agent or increase in vaporiser setting was required to maintain anaesthetic depth; the HR was greater than 140 or less than 40 beats minute-1; NIBP mean of less than 60 mmHg mean (repeated over three measurements within three minutes) or body temperature was out with the range 36.5–39.5 °C. Dogs could also be excluded if the anaesthetist in charge of the case deemed it necessary for other reasons.

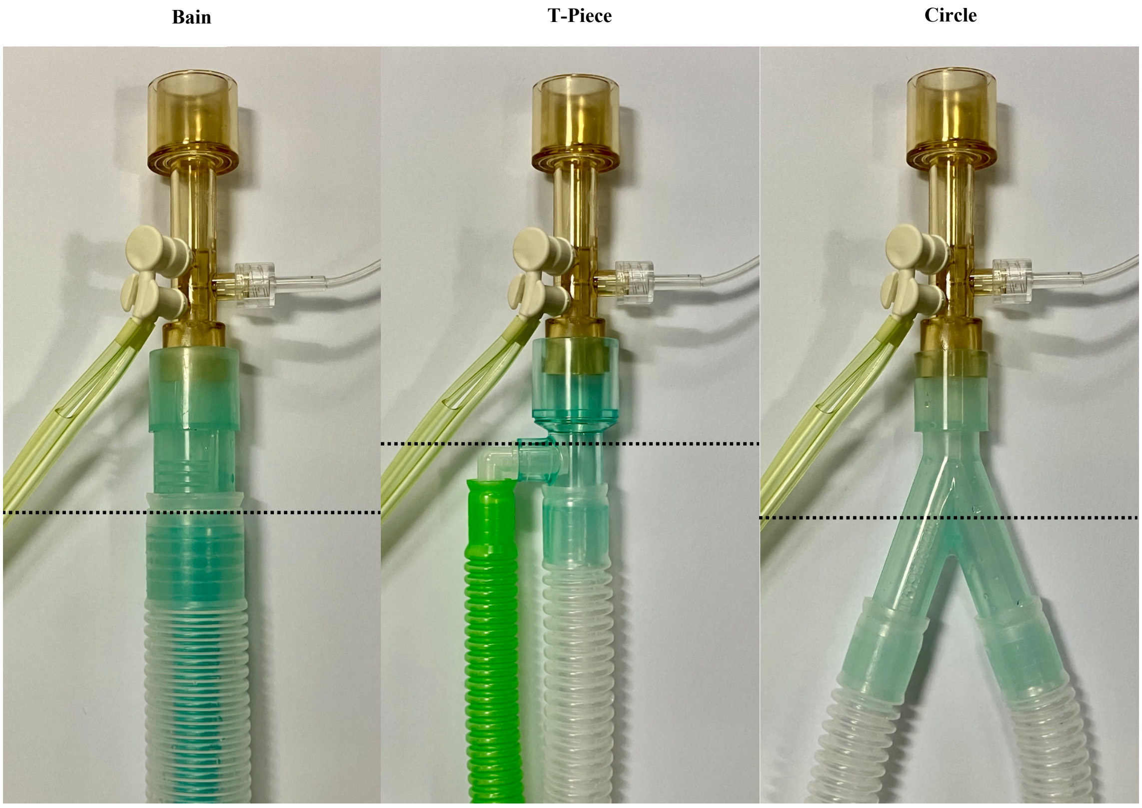


Figure 3-1 Triptych displaying the breathing systems used in 5–10 kg dogs and the arrangement of the spirometry and capnograph monitoring equipment. The endotracheal tube was attached at the 15 mm internal diameter female connection at the top of each image. The point at which dead space was measured in the systems is shown as the black dashed line.

3.5.1 Statistics

Sample size calculations were carried out for the different variables. Using a PE′CO2 mean ± standard deviation of 6.18 (±0.76) kPa reported by Çeçen et al. (2009), VT of 12.8 (±2.9) ml kg^{-1} and respiratory rate of 17 (±5) breaths $minute^{-1}$ reported by indicated that the minimum group size needed was 15 to detect a difference of 1 kPa, 3 ml kg^{-1}, or 4 breaths $minute^{-1}$ respectively with an 80% power and an alpha error of 0.05. Fifteen was the sample size for each group, so 30 dogs were required in total.

Microsoft Excel (Microsoft, USA) was used to process the data prior to statistical analysis. The mean values over each five-minute period for heart rate, NIBP mean, T and FE′ISO were calculated for the test and control system in each dog. The same five minutes of capnograph and spirometry data was used for analysis. Individual breaths were identified by detecting changes from negative (inspiration) to positive (expiration) in the airway pressure. The sensitivity of this detection was altered as necessary on an individual basis to match the computer-generated respiratory rate with a manually calculated rate from a plot of the pressure wave. A 30 second capnogram was subjectively examined for the presence of an expiratory plateau. For each individual breath, the peak airway pressures (maximum and minimum), $PE'CO_2$ and VT were identified. The mean of the individual breath values for the five-minute periods were calculated for the test and control system in each dog, and these were carried forward for further analysis. The respiratory rate was calculated by dividing the total number of breaths over the five-minute window by five. Minute volume per kg was also calculated based on this information.

Statistical analysis was performed using Jamovi (The Jamovi Project, Australia). This was used to report frequencies for categorical data, mean ± standard deviation for normally distributed data and median (interquartile range (IQR)) values for not normally distributed data. Normality of data was tested via a Shapiro-wilk test. A violation of the assumption of normality was taken as a p value <0.05. Normally distributed data were compared using a paired student's t-test; non-normally distributed data were compared with a Wilcoxon signed rank test. Differences were considered significant with a p value <0.05.

3.6 Results

A total of 35 dogs were recruited for this study (see Figure 3-2 – Consort Diagram (Schulz et al., 2010)). Two were removed as sedation was insufficient to be able to place an intravenous catheter for induction. One was removed as the owner withdrew consent after premedication. A further two were excluded due to hypotension during the measurement phase (unrelated to the study but intervention was instigated). Thirty dogs completed the study, 15 per group. Petmap or Cardell monitors were used to measure NIBP in 18 of the 30 dogs. In subjective analysis of the capnogram (contained in Appendix D), a clear expiratory plateau was present in 13 (87%) dogs with the circle system, 0 (0%) dogs with the Bain system and 5 (17%) dogs with the T-piece.

A summary of the animal and anaesthetic variables is presented in Table 3-1 for both the Bain and T-piece group and the circle and T-piece group.

The mean ± standard deviation or median (IQR) values of the measurements obtained during the measurement windows are shown alongside the results of paired testing for the Bain and the T-piece and for the circle and T-piece in Table 3-2 and Table 3-3 respectively.

CONSORT Diagram

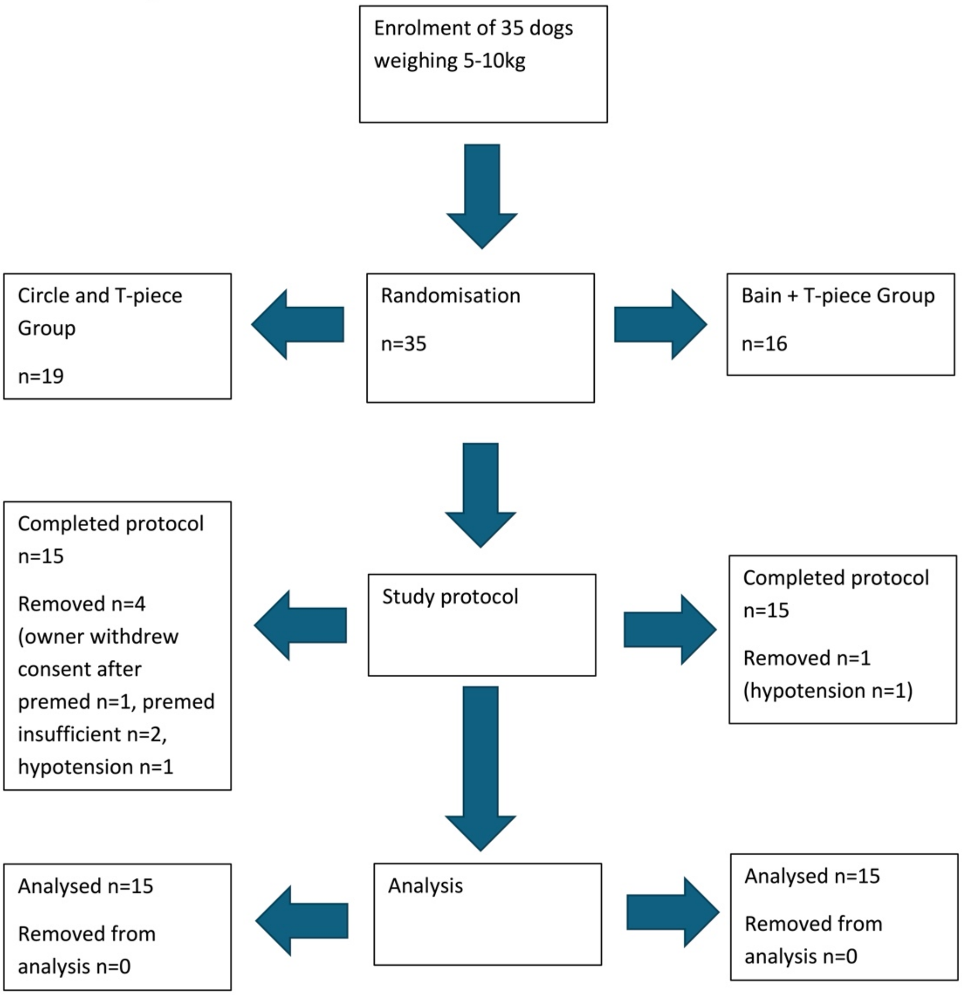


Figure 3-2 Consort Diagram (Schulz et al., 2010) for a study comparing respiratory variables with circle, Bain and T-piece breathing systems in 5–10 kg dogs: randomised control trial.

	Bain vs T-piece		Circle vs T-piece	
Breed	Crossbreed	4	Maltese	2
	Border terrier	3	West Highland White terrier	2
	Lhasa Apso	3	Yorkshire terrier	2
	Bichon Frise	1	Lhasa Apso	2
	Cairn terrier	1	Crossbreed	2
	Jack Russel terrier	1	Border terrier	1
	Pomeranian	1	Dachshund	1
	West Highland White terrier	1	Jack Russel terrier	1
			Shih Tzu	1
			Toy poodle	1
Sex	Female entire	2	Female neutered	9
	Female neutered	6	Male entire	3
	Male entire	2	Male neutered	3
	Male neutered	5		
Weight (kg)	8.3 ± 1.1		6.8 ± 1.5	
BCS (out of 9)	5 (5–6)		4 (4–5)	
Age (years)	7 (4–8.5)		8 (3.5–8.5)	
ASA Score	I/V	11	I/V	10
	II/V	4	II/V	5
Induction Propofol dose (mg kg^{-1})	3.8 ± 1.6		4.2 ± 1.3	
ET Tube internal diameter (mm)	7 (6.5–7)		6.5 (6–7)	
Recumbency	Left lateral	11	Left lateral	6
	Right lateral	4	Right lateral	9

Table 3-1 Summary of the animal and anaesthetic variables for 30 dogs randomized equally into a Bain vs T-Piece and Circle vs T-piece groups and spontaneously ventilating with these breathing systems. Values are reported as number, mean ± standard deviation or median (interquartile range). Body condition score (BCS), American Society of Anesthesiologists (ASA), Endotracheal (ET).

Measurement	T-Piece	Bain	p value
f_R (breaths minute^{-1})	16 (11–25)	16 (12–25)	0.861 b
V_T (ml) kg^{-1}	6.6 (4.8–7.0)	7.1 ± 2.7	**0.041 b**
$\dot{V}_E$ (ml) kg^{-1}	121.3 (77.4–132.5)	103.7 (88.9–146.5)	0.303 b
$P_{E'}CO_2$ (kPa)	5.61 ± 0.90	5.22 ± 0.98	**0.032 a**
Pmax (cmH_2O)	2.1 ± 0.7	1.7 ± 1.0	**0.004 a**
Pmin (cmH_2O)	-1.3 ± 0.7	-0.9 ± 0.6	**<0.001 a**
HR (beats minute^{-1})	82 ± 22	79 ± 23	0.253 a
T (°C)	37.2 ± 0.4	37.3 ± 0.3	0.161 a
Mean NIBP (mmHg)	69 (66–71)	68 (65–70)	0.201 b
$F_{E'}$Iso (%)	1.09 (1-1.29)	1.15 ± 0.14	0.599 b

Table 3-2 Mean ± standard deviation or median (interquartile range) respiratory rate (f_R), tidal (V_T) and minute $\dot{V}_E$ volumes, end tidal carbon dioxide ($P_{E'}CO_2$), maximum (Pmax) and minimum (Pmin) airway pressures, heart rate (HR), temperature (T), mean non-invasive blood pressure (NIBP) and fraction expired isoflurane ($F_{E'}$Iso) in 15 anaesthetised dogs spontaneously ventilating through a Bain or T-piece breathing system. Paired samples testing was performed using a student's t (a) or Wilcoxon rank test (b). Values in bold were considered statistically significant ($p<0.05$).

Measurement	T-Piece	Circle	p value
f_R (breaths minute^{-1})	10 (6–14)	9 (7–16)	0.176 a
V_T (ml kg^{-1})	10.6 (7.7–13.0)	12.1 ± 3.9	**0.035 b**
$\dot{V}_E$ (ml kg^{-1})	107.8 (77.3–131.9)	116.7 (97.5–166.0)	**0.002 a**
$P_{E'}CO_2$ (kPa)	5.31 ± 0.78	6.04 ± 0.64	**<0.001 a**
Pmax (cmH_2O)	2.3 ± 0.6	2.8 ± 0.8	**<0.001 a**
Pmin (cmH_2O)	-0.9 (-1.7–-0.7)	-1.6 ± 0.8	**0.022 a**
HR (beats minute^{-1})	78 ± 24	77 ± 20	0.714 a
T (°C)	37.2 ± 0.4	37.0 (36.7–37.2)	0.351 a
Mean NIBP (mmHg)	66 (63–75)	68 ± 6	0.373 a
$F_{E'}$Iso (%)	1.12 ± 0.25	1.09 ± 0.17	0.418 a

Table 3-3 Mean ± standard deviation or median (interquartile range) respiratory rate (f_R), tidal (V_T) and minute $\dot{V}_E$ volumes, end tidal carbon dioxide ($P_{E'}CO_2$), maximum (Pmax) and minimum (Pmin) airway pressures, heart rate (HR), temperature (T),mean non-invasive blood pressure (NIBP), and fraction expired isoflurane ($F_{E'}$Iso) in 15 anaesthetised dogs spontaneously ventilating through a circle or T-piece breathing system. Paired samples testing was performed using a student's t (a) or Wilcoxon rank test (b). Values in bold were considered statistically significant ($p<0.05$).

3.7 Discussion

In the circle system there was a significantly higher $P_{E'}CO_2$, V_T per kg and $\dot{V}_E$ with a greater difference between highest and lowest airway pressures recorded compared to the control. Dogs using the Bain system had a significantly lower $P_{E'}CO_2$ and a smaller difference between the highest and lowest airway pressures recorded compared to the control. Additionally, whilst using a Bain the dogs had a higher V_T per kg, however, there was no significant difference in $\dot{V}_E$ compared to the T-piece. In neither the circle nor the Bain was there a significant difference in respiratory rate compared with the T-piece. Both Bain and circle breathing systems functioned adequately compared to the control and allowed spontaneous ventilation.

The purpose of breathing systems is to allow the safe and effective delivery of inhalant anaesthetic agents to dogs without compromising ventilatory function. Should the animal not be able to overcome the resistance of the breathing system, there is a risk of hypoventilation (Clutton, 1999) and, at the start of anaesthesia, failure of sufficient volatile agent uptake to maintain anaesthesia (Lockwood and White, 1991).

The lower $P_{E'}CO_2$ in the Bain compared to the T-piece is not caused by a significant change in $\dot{V}_E$, although there is a significantly greater V_T. As this was a crossover study, significant changes in CO_2 production and transport are unlikely. This is confirmed by no significant difference in the physiological variables to support alterations in perfusion or metabolism. Under anaesthesia, the metabolic rate decreases (Brunner et al., 1975) and can be further reduced by a drop in body temperature (Fairley, 1961), which is expected to rapidly fall in the first 15 minutes (Sage et al., 2023). The use of a standard anaesthetic protocol and randomisation of the order of the first breathing system, test or control, should have reduced the impact of the drop in body temperature on results. Inaccurate $P_{E'}CO_2$ has been reported due to dilution of the sample in side-stream capnography by incoming FGF resulting in a low measured value (Gravenstein et al., 1985). It is possible dilution was present for both the Bain and T-piece control. This is suspected in this study based on the frequent lack of a clear plateau in the examined capnogram for each case. The greater effects on the Bain breathing system potentially occurred due to the the proximity of the fresh gas inlet in relation to the capnography port (Gravenstein et al., 1985). It is also hypothesised that the angle of the incoming fresh gas jet may have contributed to this observed difference.

The $P_{E'}CO_2$ measurement for the circle is higher than the normal range of 4.5–6.0 kPa (Schauvliege, 2016), despite a higher $\dot{V}_E$ and V_T than with the T-piece control which had a normal $P_{E'}CO_2$ measurement. As was the case in the BT group, dilution is suspected with the T-piece in the CT group. Given the greater V_T and $\dot{V}_E$ when attached to the circle, all the animals appeared to be able to spontaneously ventilate better on this system. The greater $P_{E'}CO_2$ in the circle breathing system, despite a greater V_T and $\dot{V}_E$, is unlikely to be due to an increase in physiological dead space due to bronchodilation caused by the isoflurane (Dikmen et al., 2003). As the dogs were used as their own controls and the order of breathing system was randomised, this would be expected to impact both groups equally. The elevated $P_{E'}CO_2$ with the circle system is not unexpected in the anaesthetised animal given the potential for methadone and isoflurane contributing to respiratory depression (Galloway et al., 2004, Schlitt et al., 1978).

The lower extremes of airway pressure when attached to the Bain breathing system are significant and unexpected given the Bain is described as a higher resistance system than the T-piece (Shandro, 1982). The Mapleson D T-piece also had a paediatric APL valve which should be of a lesser resistance. The main aspect which could explain the pressure difference is the larger cross-sectional area of the Bain system expiratory tubing (Bain = 267 mm^2; T-piece = 113 mm^2).

A previous study has demonstrated the safe use of an adult human circle system in cats of a lower body weight than the dogs examined in this study (Hartsfield and Sawyer, 1976). It should be noted that there is wide variety in the design, and therefore the inherent resistance of, the circle breathing systems (Shandro, 1982). The style of tubing, soda lime canister and the composition and orientation of the one-way valves all alter the resistance to ventilation (Hatch, 1985). The circle system chosen for this study had a manufacturer recommended weight range of 10–40 kg. If 22 mm Y-piece tubing had been used instead of 15 mm, resistance would have been lower according to Poiseuille's law (Hatch, 1985). The narrower bore Y-piece was used due to the clinical desire to reduce system volume and for a more rapid change in anaesthetic gas composition in response to changes to the vaporiser (Conway, 1986). The FGF used (500 ml kg^{-1} min^{-1}) when the dogs were attached to the circle system were identical to the FGF used with the T-piece control. A FGF above $\dot{V}_E$ is required when a dog is first attached to a circle to denitrogenate and to achieve the desired inspired fraction of anaesthetic agent (Mapleson, 1998, Herbert and Magee, 2017). The high FGF used initially in the circle can be reduced after a defined period (Hughes, 2016), or based on gas and agent monitoring (Warne et al., 2018). In practice it is common to use the circle system at a lower FGF than the 500 ml kg^{-1} min^{-1} used in this study. A lower FGF may result in a system of lower resistance (Hartsfield, 1994). This lower resistance may prevent or reduce fatigue especially in this weight of dog. There was a greater difference between peak inspiratory and expiratory pressures when the dogs were breathing through the circle system compared to the T-piece. The requirement to generate such pressures to move gas through the system suggests higher a breathing system resistance (Shandro, 1982) compared to the T-piece.

For consistency, the measurement of V_T was taken between the ET tube and the breathing system in all systems to reduce the influence of breathing system compliance. Measurements taken here have been shown to be accurate in the human paediatric setting (Morgenroth et al., 2018). Tidal volume may also be influenced by changes in pulmonary structure. Should atelectasis develop, there will be a reduction in V_T and reduced area of alveolar ventilation resulting in ventilation/perfusion mismatch due to shunting (Schauvliege, 2016). Atelectasis can begin to form within 15 minutes in sedated and anaesthetised dogs (Barletta et al., 2014, le Roux et al., 2016). Diffusion atelectasis occurs more readily when using 100% oxygen (Staffieri et al., 2007), as was used in this study. Development of atelectasis may be accelerated in geriatric or obese animals as the functional residual capacity is closer to or below closing capacity (Barletta et al., 2014, Hornby and Lamb, 2017. The impact of atelectasis development in this study was mitigated by the exclusion of extremely obese dogs, randomisation of the order of system which was tested and the measurement windows being close to the start of anaesthesia.

The design of this study, using dogs as their own control, reduced the required number of dogs. This minimised the impact individual variations, for example required propofol dose (4.2 ± 1.3 mg kg^{-1} in the CT group *versus* 3.8 ± 1.6 mg kg^{-1} in the BT group), had on the results. The ability of an animal to overcome the resistance imposed by a breathing system will be hindered by other factors which increase the dog's work of breathing (WOB) (Clutton, 1999). Dogs with an increased WOB include those at the extremes of age (Mauderly, 1974) and with severe obesity (Bach et al., 2007) where chest wall compliance is altered in relation to pulmonary compliance. Dogs less than one your old or at extremes of body condition were excluded from this study.

Limitations of this study include the apparently significant effect of dilution on the $P_{E'}CO_2$ sample. This could be minimised in future studies by sampling from the ET tube or using mainstream capnography. Alternatively, blood gas measurement of partial pressure of carbon dioxide would quantify the impact of this effect. Blood gas analysis was not performed in this study as these dogs were clinical cases with no other clinical indication for arterial sampling.

The selection criteria for this study aimed to ensure the animals enrolled were systemically healthy and without compromised ventilatory function. However, as this was only based on physical examination and history, other subclinical thoracic or systemic pathologies may have been missed. The results of this study may not, therefore, be applicable to the entire canine population of 5–10 kg dogs, particularly since dogs at extremes of obesity and and dogs less than one year of age were also excluded. The short window of anaesthesia this study examined does not evaluate the suitability of each breathing system for prolonged procedures. It is possible for fatigue to reduce ventilation over time, especially on breathing systems which have a higher resistance (Nunn and Ezi-Ashi, 1961). Other connections, for example additional connectors or humidity and moisture exchange filters, are commonly used when anaesthetising dogs (Dugdale et al., 2020). These may add to the overall resistance the dog must overcome to spontaneously ventilate (Parthasarathy, 2013). This study does not evaluate the breathing systems when used in conjunction with such other components.

3.8 Conclusions

A difference was found between both test systems and the control (T-piece). The use of a circle system resulted in a significantly higher $P_{E'}CO_2$ along with a statistically significantly higher V_T per kg and $\dot{V}_E$. In the Bain group a statistically significantly lower $P_{E'}CO_2$ alongside a higher V_T per kg were observed. The clinical significance of these differences appears minimal. Both tested systems, circle and Bain, appear suitable for use in healthy 5–10 kg dogs for short anaesthetic procedures.

Chapter 4 General Discussion

4.1 Association between manuscripts

The foci of this research were to understand what anaesthetic breathing systems were available and how they were selected in practice and to recommend, safely, breathing systems which are appropriate in the 5–10kg weight of dogs. The survey was distributed and targeted towards the anaesthesia community. This group was targeted as the respondents were expected to be those actively involved in the selection process of breathing systems. The analysis of the survey data confirmed the three most prevalent systems in the community surveyed were the circle, Bain and T-Piece. This was the expected finding and gave justification for the analysis of these breathing systems in the clinical study.

The 5 kg median minimum weight recommended by the surveyed group for the use of a circle system was lower than previously reported by others, where this value was 10 kg (Nicholson and Watson, 2001). The reduction in recommended weight for the circle has no or limited published evidence for safety. There is only some support of this by manufacturer weight recommendations. This gave justification for the further clinical analysis of the use of this system in the 5–10 kg weight of dog.

4.2 Integration of findings

The results of the clinical study may justify the lower median minimum weight used by the survey respondents for the circle system. In the clinical study, there was no statistical difference in minute volume between the T-piece and the Bain, and in the circle the minute volume was greater than that of the T-piece. It should be noted that there was a significant difference in $P_{E'}CO_2$ between the circle and the T-piece, however, the significance of this difference may be limited by the impact of dilution on the sample. Over 80% of respondents in the survey study agreed that system resistance is an important factor in the selection process of breathing systems. Pressure measurements at the breathing system to airway device interface, recorded as part of the collection of data for the clinical study and reported in Table 3-3, did show a greater pressure difference between inspiration and expiration in the circle system compared to the T-piece. This finding may suggest the circle used was indeed a higher resistance breathing system than the T-piece, as expected. The impact of this resistance on the respiratory function of the dogs in the clinical study appeared minimal.

Results of the survey study show the numerous factors which come into the selection process of choosing a system. A number of these decision factors were animal based, including the animal weight and breed. However, there were other factors independent of the animal, such as environmental concerns, which were also agreed to be important by the respondents. The environmental impact of anaesthetic agents and the economic advantages of lower flow anaesthesia have potentially put pressure on the anaesthesia community to utilise rebreathing systems where possible. Prior to the work undertaken in the clinical study, there was a lack of clinical evidence for the use of such breathing systems in dogs of this weight. The use of the circle had been evaluated in cats (Hartsfield and Sawyer, 1976).

The survey results support the use of the T-piece as the control system for the clinical study. The results show the respondents used a median minimum and maximum weight of dog of 0 and 10 kg respectively for this system. This made the system an ideal control as it is normally used in dogs 5–10 kg or less. This provided opportunity for comparison with the circle and Bain, which were reported to be used in animals weighing as little as 5 and 3 kg respectively. The maximum weights for the Bain and the circle are, however, higher, being 20 and 100 kg respectively. For the circle, the survey results support the comparison of the T-piece, which is used for 10 kg and below, with the circle, which is used for 5 kg and up. This justified the weight range of 5–10 kg dogs which was selected for evaluation.

The fresh gas flow required for each system was strongly agreed to be important for selecting a breathing system in the survey study. The fresh gas flow was constant during the clinical study as a standard rate of 500 ml/kg/minute was used across all the systems. This is a higher rate than would routinely be used when operating a circle with a dog, especially during semi-closed use. The higher the fresh gas flow in a breathing system, the greater the expiratory resistance is likely to be (Hartsfield, 1994). The resistance encountered in the circle system during the clinical study is therefore more likely to be equivalent to the use of the circle during the initial stages of anaesthesia when denitrogenating. Use of lower flows after denitrogenating would therefore likely result in a lower breathing system resistance, improving the system. Resistance was not considered to be a problem in the clinical study, however, this only studied the first 30 minutes of anaesthesia. Any reduction in breathing system resistance is considered beneficial for the dog and reduces the likelihood of fatigue.

In the survey study, 45% and 25% of the respondents indicate that they disagree (strongly disagree or disagree) that breed and body condition respectively significantly impact their decision making. However, in the case scenarios based on 5–10 kg dogs, the circle system was chosen by 57% for a thin and 76% for a keel chested vs 43% for an obese and 64% for a round chested dog, suggesting these aspects are indeed part of the decision process. The clinical study excluded extremes of body condition and young age, but did not control for conformation. The exclusion was based on the potential for changes in the underlying work of breathing in such dogs. Although not excluded, by chance, data was not collected from dogs with extremes of conformation in the clinical study. There was therefore no attempt of any analysis with respect to differences seen in dogs of differing conformation.

4.3 Limitations

The studies share the limitation that anaesthetic breathing systems are numerous in their individual designs, even within different types of system. This creates the limitation that the breathing systems studied may not be the specific types used by all the survey respondents. Thus, the results of the clinical study may not be applicable to each respondent's clinical decision making in the survey study. The global nature of the survey distribution may contribute to this as, across large geographical distances, it is considered more common for breathing systems to vary significantly in design due to different manufacturers. No geographical location data was collected for any of the respondents despite being a globally distributed survey. However, it is considered likely this geographical effect and individual system variation had some influence on the selection process.

Another shared limitation is the lack of investigation of any accessory apparatus which is commonly used with breathing systems. This includes humidity moisture exchange filers, catheter mounts and elbow connectors. The use of such equipment alongside the breathing systems was not enquired about during the survey study. The presence of accessory equipment was controlled in the clinical study. The use of such apparatus concurrently with a breathing system is likely to alter gas flow and affect apparatus resistance.

The survey study was limited in the sample size, and it is difficult to extrapolate the findings across the wider veterinary community. The sample size is likely reflective of the fact that the channels used to distribute the survey were mainly used by those with a prior interest in veterinary anaesthesia. This bias towards the anaesthesia community is also a limitation as the results cannot be extrapolated into the wider veterinary community. It is considered likely that those with an interest in anaesthesia have access to a wider range of anaesthetic monitoring equipment, such as capnography. The use of capnography was advocated for by some respondents when selecting a circle breathing system in the case scenarios in the study. The access to capnography may have given respondents greater confidence selecting the circle system.

The survey study also did not ask individuals to rank the importance of different factors for the selection of breathing systems. This limits the ability to understand whether respondents have a sequential approach to the decision process.

The clinical study may have suffered from significant dilution of the side-stream capnography sample. This is a reported complication of this monitoring technique. Respiratory fatigue was also not examined for in the clinical study. The recording of all data in the clinical study was performed in the first 30 minutes of anaesthesia. This was done to minimise the effects of surgical stimulation and formation of atelectasis on results. However, it is not uncommon for anaesthetics in dogs to be significantly longer than 30 minutes. It is therefore considered possible that the results of the clinical study may not account for the effects of higher breathing system resistance over a longer period.

The clinical study also followed a specific protocol for the induction and maintenance of anaesthesia. This was specifically chosen to be suitable for the cases presented and allow for case inclusion but have a minimal impact on ventilation. It is possible that with an alternative anaesthetic protocol the findings would have been different.

4.4 Clinical recommendations

The clinical study provided evidence that the circle and Bain breathing systems can be used in 5–10 kg dogs without any clinically significant effects on ventilation in the short term. However, close monitoring of respiratory function is still recommended. It is hoped the results of the clinical study will provide practitioners evidence for the selection and use of rebreathing systems in dogs in the 5–10 kg weight range.

4.5 Areas for further work

Both studies create opportunities for further work to improve and expand on design. Multiple avenues of further research would be beneficial to further expand the knowledge base in this area.

Subsequent surveys could be targeted to examine a wider population of general practitioners. This may provide a better understanding of the availability of breathing systems across the small animal veterinary profession, rather than specifically the more anaesthesia focussed community. This could be added to by examining the level of anaesthetic monitoring available to the respondents when using the breathing systems to determine if this affects their comfort using different systems. It would also be useful to survey the availability of ventilators alongside the use of breathing systems. The ability to mechanically ventilate an animal's lungs easily may significantly reduce any concern that the animal may not be able to overcome the resistance of a system.

A natural addition to the clinical study would be to examine dogs of a lower weight than 5 kg. This has already been done with the circle in cats and the circle was deemed clinically safe to use. The clinical study could also be advanced by altering the capnography to avoid dilution. This could be achieved by sampling respiratory gases from inside the trachea.

The use of continuous sampling of data over the 5-minute test period in the clinical study would allow for retrospective graphical plotting and further analysis of volume flow and pressure to better understand the resistance of each system.

Both the survey study and clinical study could be added to by delving into greater detail regarding specific breathing systems. Whilst the broad categories of breathing system design were examined, individual variation between manufacturers and systems was not investigated. As there is such a wide variety in circle system design especially, this would be the ideal candidate of system for such further work. This aspect was picked up on by some of the survey respondents, as they asked specifically for a paediatric circle to be used in some of the case scenarios. In further expanding information regarding individual variation, it may be beneficial to investigate the geographical differences in the selection of breathing systems.

The clinical study design could be used to examine the differences between other types of breathing system, e.g. the Lack and circle. Adaptation of the anaesthetic protocol would also allow for assessment of the same breathing systems when using different agents.

Further work could also look at the detection of reduced respiratory function in dogs under anaesthesia. Not all practices have access to the monitoring used in the clinical study. This may make for difficult detection of any complications associated with the breathing system imposing too much resistance and causing an increased work of breathing. The development of a work of breathing scale in human ICU patients has been performed. This scale uses visual and palpable elements to assess work of breathing. Analysis of dogs using breathing systems of differing resistance may allow for the development of more detailed guidance to detect excessive resistance.

Chapter 5 Conclusions

The two studies presented in this thesis aimed to better the understanding of the availability and selection of breathing systems in 5–10 kg dogs. It is hoped that the studies serve to expand on the knowledge and evidence surrounding this clinical decision-making process.

The circle is the most commonly available breathing system in veterinary practice. When the weight of a dog allows a wide range of breathing systems to be selected, other aspects of the dog's conformation (breed and body condition score) impact this selection process. There is strong agreement that environmental and cost factors also affect the choice of breathing system. The circle is being recommended for use in dogs which weigh less than some reference materials would recommend.

A difference was found between both test systems and the control (T-piece). In the circle system, there was a significantly higher $P_{E'}CO_2$ along with a significantly higher V_T per kg and $\dot{V}_E$. The Bain system had a significantly lower $P_{E'}CO_2$ alongside a higher V_T per kg. The clinical significance of these differences appears minimal. Both tested systems, circle and Bain, appear suitable for use in healthy 5–10 kg dogs for short anaesthetic procedures.

Ultimately it is hoped that the results of this work improve anaesthetic safety. The results may also give confidence in the uptake of lower fresh gas flow systems, reducing the financial and economic impact of veterinary anaesthesia.

Chapter 6 Appendices

6.1 Appendix A – Survey distribution dates and notifications

- ACVA-List – email list – on the 1st of February 2023.
- Association of Veterinary Anaesthetists (AVA) – website – 12th of February 2023.
- ECVAA list of diplomates and residents – email – 20th of February 2023.
- Association of Veterinary Anaesthetists (AVA) – Facebook – 13th of February 2023.

Dear Colleague,

The Anaesthesia Department in the Small Animal Hospital of the University of Glasgow School Biodiversity, One Health and Veterinary Medicine is investigating the selection and use of anaesthetic breathing systems in dogs weighing 5-10kg. If you are a vet or vet nurse who works with dogs and are involved in this selection process, we would like to invite you to take part in our survey.

Further information about this research and the survey can be found in the documents below

[Participant Information sheet]

[Privacy notice]

[Downloadable consent form copy]

Here is a link to the survey should you wish to take part in the research.

[Survey Link]

The closing date for participation is the 31st of March 2023

Kind regards,

Andrew Murray

ECVAA Resident in Veterinary Anaesthesia and Analgesia,

University of Glasgow School of Veterinary Medicine

(a.murray.9@research.gla.ac.uk)

- ECVAA residents' group – Facebook – on the 7th of March 2023.

Dear All,

I am a third-year resident at the University of Glasgow investigating the selection and use of anaesthetic breathing systems in dogs weighing 5-10kg. I would be very grateful if any of you would be willing to take part in a survey (if you haven't completed it already). Also feel free to distribute to colleagues in your own institutions as I am keen to get as many nurses, interns etc, involved as well.

Here is the link: https://uofg.qualtrics.com/jfe/form/SV_5APUe5wIKcUzy98

Many thanks,

Andy

- A reminder was sent to the ACVA-list on the 20th of March.

Dear colleagues,

There are less than two weeks left to respond to our survey investigating the selection and use of anaesthetic breathing systems in dogs weighing 5-10kg (original invite below). We would like to invite you to take part in our survey if you have not had the chance to complete it yet. If you are a vet or vet nurse who is actively working with dogs and involved in choosing breathing systems, the link below will take you to the survey.

Survey Link - https://uofg.qualtrics.com/jfe/form/SV_5APUe5wIKcUzy98

The closing date for participation is the 31st of March 2023

We would be extremely grateful for your participation. Your input may help to inform anaesthesia guidelines and contribute to improving patient safety.

Kind regards,

Andrew Murray
ECVAA Resident in Veterinary Anaesthesia and Analgesia, University of Glasgow School of Veterinary Medicine
(a.murray.9@research.gla.ac.uk

6.2 Appendix B – Survey outline

Breathing Systems

Start of Block: Consent Questions

Info The Anaesthesia Department in the Small Animal Hospital of the University of Glasgow School of Biodiversity, One Health and Veterinary Medicine is investigating the selection and use of anaesthetic breathing systems in dogs. If you are a vet or vet nurse who is actively working with dogs and involved in this selection process, we would like to invite you to take part in our survey.

Study Title: Investigating the selection and use of anaesthetic breathing systems in dogs; with a focus on dogs weighing 5-10kg.

The study will ask you questions concerning the type of practice you work in and the availability of different anaesthetic breathing systems in your practice. Furthermore, it will enquire about your selection process for using these in dogs and the level of experience you have in doing so. This study is a survey and will use multi choice, drop down list, Likert scale and sliding scale question formats in addition to an open-ended option for additional information, concerning breathing systems, you may wish to contribute. This research has been approved by the College of Medical, Veterinary & Life Sciences ethics committee panel.

You are being invited to take part in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information contact detail for the principal researcher are below. If you decide to take part in this study, you may download a copy of this Participant Information Sheet, the Consent Form, and the Privacy Notice to keep.

Participant Information Sheet - Participant information

Privacy Notice - Privacy notice

Consent Form - Consent form

Contact information for the principal researcher: Andrew Murray ECVAA Resident in Veterinary Anaesthesia and Analgesia, University of Glasgow School of Veterinary Medicine Email - a.murray.9@research.gla.ac.uk

Q1 I confirm that I have read and understood the Participant Information Sheet version 1.1 dated 08/08/22.

Yes (1)

Q2 I confirm that I have read and understood the Privacy Notice version 1.1 dated 08/08/2022.

Yes (1)

Q3 I consent to the University processing the data I provide for the purposes detailed in the Privacy Notice version 1.1 dated 08/08/2022.

Yes (1)

Q4 I have had the opportunity to think about the information, ask questions, and understand the answers I have been given.

Yes (1)

Q5 I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my legal rights being affected.

Yes (1)

Q6 I confirm that I agree to the way my data will be collected and processed and that data will be stored for up to 10 years in University archiving facilities in accordance with relevant Data Protection policies and regulations.

Yes (1)

Q7 I understand that all data and information I provide will be kept confidential and will be seen only by study researchers and regulators whose job it is to check the work of researchers.

Yes (1)

Q8 I understand that if I withdraw from the study, my data collected up to that point will be retained and used for the remainder of the study

Yes (1)

Q9 I agree to take part in the study.

Yes (1)

No (4)

End of Block: Consent Questions

Start of Block: Breathing System Questions

Q1 Which anaesthetic breathing systems are available for use in dogs in your practice? Please select all that apply.

Lack (1)

Mini-Lack (2)

Magill (3)

Coaxial Bain (4)

Circle (5)

Ayres T-piece (with APL valve) (6)

Ayres T-piece (without APL valve) (7)

Humphrey ADE (Without Soda-lime) (8)

Humphrey ADE (With Soda-lime) (9)

Other (write in text box below) (10)

____

Q2 Dogs come in different sizes, what would you teach as your absolute MINIMUM weight limits (in kg) for each anaesthetic breathing system in dogs?

If you are unfamiliar with a system please leave this system blank.

	Weight kg	No Minimum Limit
	0 5 10 15 20 25 30 35 40 45 50	
Lack ()		
Mini-Lack ()		
Magill ()		
Coaxial Bain ()		
Circle ()		
Ayres T-piece (with APL valve) ()		
Ayres T-piece (without APL valve) ()		
Humphrey ADE (Without Soda-lime) ()		
Humphrey ADE (With Soda-lime) ()		
Other (write in text box below) ()		

Q3 Dogs come in different sizes, what would you teach as your absolute MAXIMUM weight limits (in kg) for each anaesthetic breathing system in dogs?

If you are unfamiliar with a system please leave this system blank.

	Weight kg / Not Applicable 0 10 20 30 40 50 60 70 80 90 100
Lack ()	
Mini-Lack ()	
Magill ()	
Coaxial Bain ()	
Circle ()	
Ayres T-piece (with APL valve) ()	
Ayres T-piece (without APL valve) ()	
Humphrey ADE (Without Soda-lime) ()	
Humphrey ADE (With Soda-lime) ()	
Other (write in text box below) ()	

Q4 “The following factors are important when selecting an anaesthetic breathing system for a dog.”

Please indicate your opinion on the above statement in relation to all of the following:

	Strongly disagree (1)	Somewhat disagree (2)	Neither agree nor disagree (3)	Somewhat agree (4)	Strongly agree (5)
Weight of dog (1)	○	○	○	○	○
Breed of dog (2)	○	○	○	○	○
Age of dog (3)	○	○	○	○	○
Body condition of dog (4)	○	○	○	○	○
Running cost associated with the system (5)	○	○	○	○	○
Theatre/operating environment pollution (6)	○	○	○	○	○
Natural environmental pollution (e.g. greenhouse gases) (7)	○	○	○	○	○
Fresh gas flow required to operate the system (8)	○	○	○	○	○
Bulk of the system (9)	○	○	○	○	○
Ability to rapidly adjust depth (10)	○	○	○	○	○
Breathing system resistance (11)	○	○	○	○	○
Other factor (write in text box below) (12)	○	○	○	○	○

Q5 For the given case examples, please select which anaesthetic breathing system you would advise to be used for each dog.

	Breathing System (select from dropdown)	Other
4-year-old male neutered Jack Russell weighing 7.5kg with a body condition score of 4/9 (ideal). Presented for stitch up of paw laceration. (1)	Lack (1) Mini-Lack (2)	(Please Specify) (1)
16-year-old male neutered Toy Poodle weighing 8.5kg with a body condition score of 4/9 (ideal). Presented for skin mass excision. (2)	Magill (3) Coaxial Bain (4)	
5-year-old female entire Yorkshire Terrier weighing 7.3kg with a body condition score of 8/9 (obese). Presented for pyometra surgery. (3)	Ayres T-piece (without APL valve) (5)	
6-year-old male entire Scottish Terrier weighing 6.5kg with a body condition score of 2/9 (too thin). Presented for cystotomy and bladder stone removal. (4)	Ayres T-piece (with APL valve) (6) Humphrey ADE (Without Soda-lime) (7)	
8-week-old female entire Labrador weighing 7.1kg with a body condition score of 5/9 (ideal) Presented for radiographs due to suspected tibial tuberosity avulsion. (5)	Humphrey ADE (With Soda-lime) (8) Circle (9)	

5-year-old female neutered Whippet weighing 9.1kg with a body condition score of 4/9 (ideal). Presented for toe amputation. (6)		
4-year-old male entire French Bulldog with significant BOAS weighing 8.7kg with a body condition score of 5/9 (ideal). Presented for castrate due to testicular mass. (7)		
3-year-old female neutered Beagle weighing 10kg with a body condition score of 5/9 (ideal). Presented for cherry eye correction. (8)		
5-year-old male neutered Bichon Frise weighing 5kg with a body condition score of 4/9 (ideal). Presented for stitch up of superficial laceration over left thigh. (9)		

End of Block: Breathing System Questions

Start of Block: Veterinary Experience Questions

Q6 How would you describe the veterinary work you are involved in?

Exclusively Small Animal Work (1)

Mixed (2)

Other (Please Specify) (3) ____

Q7 In which type of veterinary practice do you work?

Academic Institution (1)

Private (2)

Charity (3)

Other (Please Specify) (4) ____

Q8 How many years of experience do you have working in veterinary practice?

Less than 5 (1)

5-10 (2)

11-20 (3)

Greater than 20 (4)

Q9 What is your role in the veterinary practice?

Veterinary Surgeon (Anaesthesia Specific) (1)

Veterinary Surgeon (Not specific to anaesthesia) (2)

Veterinary Nurse (Anaesthesia Specific) (3)

Veterinary Nurse (Not specific to anaesthesia) (4)

Other (Please Specify) (5) ____

Q10 What level(s) of anaesthesia education you have? (Select all that apply)

Veterinary/Veterinary Nursing Qualification (1)

Attendance of Conferences/Courses in Anaesthesia Without Formal Qualification (2)

Post Graduate Certificate in Anaesthesia (3)

Anaesthesia Internship (4)

Masters in Veterinary Anaesthesia (5)

PhD in Veterinary Anaesthesia (6)

ECVAA or ACVAA Residency (Current or Past) (7)

ECVAA or ACVAA Diploma Holder (8)

Other (Please Specify) (9) ____

End of Block: Veterinary Experience Questions

6.3 Appendix C – Breathing system specifications

The three breathing systems were only used for study cases for the duration of the data collection and were kept separate from general hospital use.

T-Piece

- Description
  - Infant T-piece breathing system with 0.5 l closed tail bag, length 1.8 m
- Manufacturer
  - Intersurgical, UK
- Reservoir bag size
  - 0.5 l
- APL valve description
  - Spring loaded disk with 28 cmH_2O pressure limit at a flow of 6 l minute^{-1} and 35 cmH_2O at a flow of 15 l minute^{-1}
- Dead space
  - 4.38 ml
- Tubing diameters
  - Corrugated fresh gas limb
    - Narrowest inner diameter = 9 mm
    - Widest outer diameter = 14 mm
  - Corrugated scavenging limb
    - Narrowest inner diameter = 12 mm
    - Widest outer diameter = 18 mm

Bain

- Description
  - Mapleson D deluxe Bain coaxial breathing, length 1.6 m
- Manufacturer
  - Intersurgical, UK
- Reservoir bag size
  - 1 l
- APL valve description
  - Spring loaded disk with 60 cmH_2O pressure limit
- Dead space
  - 6.35 ml
- Tubing diameters
  - Smooth bore inner fresh gas tube
    - Inner Diameter = 6.5 mm
    - Outer Diameter = 10 mm
  - Corrugated scavenging limb
    - Narrowest inner diameter = 21mm
    - Widest outer diameter = 25 mm

Circle

- Description
  - semi-disposable circle circuit
- Manufacturer
  - Burtons, UK
- APL valve description
  - Lightweight springless screw-down plastic valve (manufacturer specific)
- Reservoir bag used
  - Description
    - 1 l closed tail reservoir bag
  - Manufacturer
    - Intersurgical, UK
  - Reservoir Bag size
    - 1 l
- Tubing used
  - Description
    - Y-piece/1.8m Flextube
  - Manufacturer
    - Intersurgical UK
  - Dead Space
    - 6.18 ml
  - Corrugated tubing diameters
    - Narrowest inner diameter = 12 mm
    - Widest outer diameter = 18 mm
- Absorbent used (absorbent was fully changed on a monthly basis)
  - Description
    - Medical grade soda lime - Spherasorb™
  - Manufacturer
    - Intersurgical, UK
  - Granule Description
    - 3-4mm spheres
  - Dry Constituents
    - Calcium Hydroxide 93.5%; Sodium hydroxide 1.5%; Zeolite 5%; Indicator 0.03%
  - Weight Used
    - 425g

6.4 Appendix D – Capnography Data

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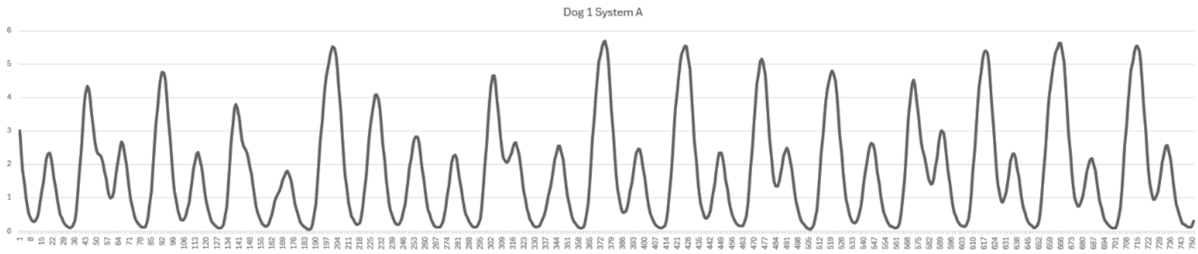

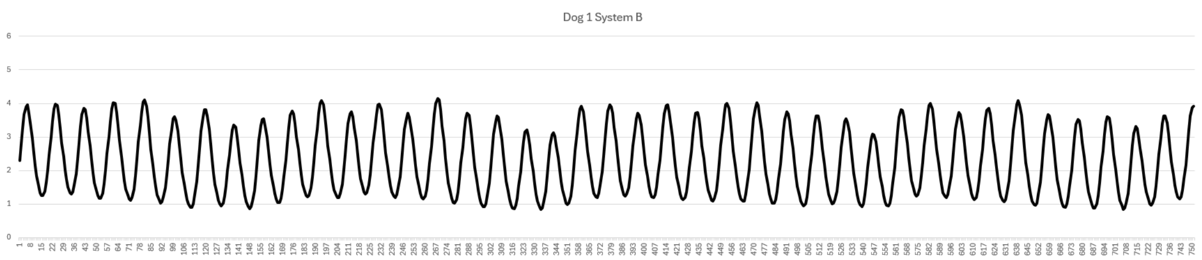

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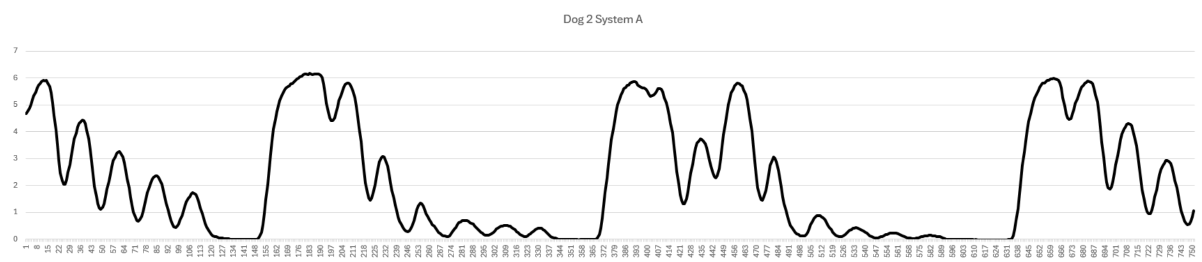

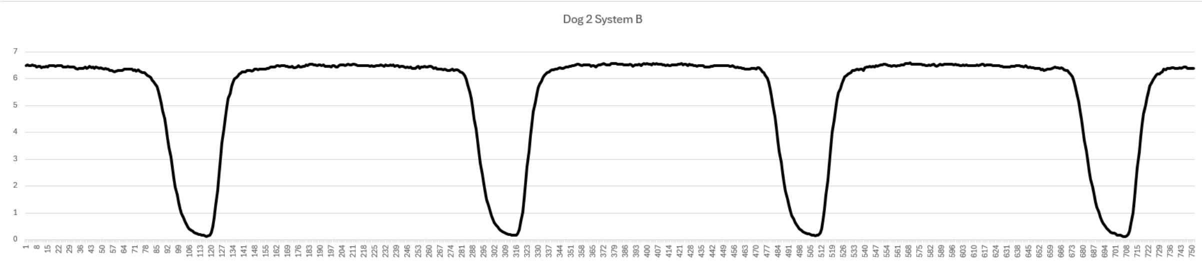

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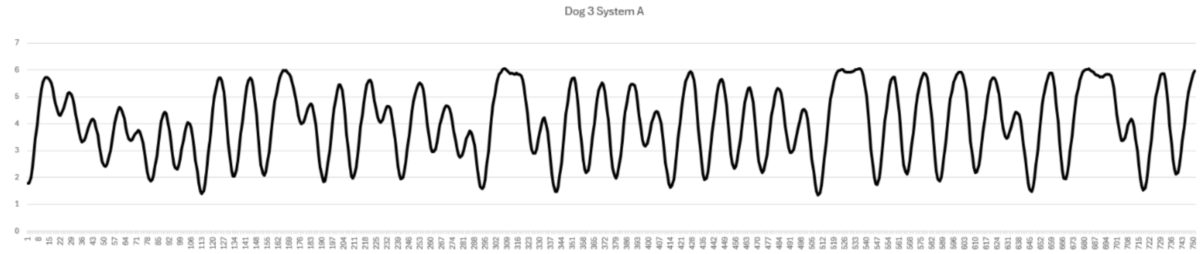

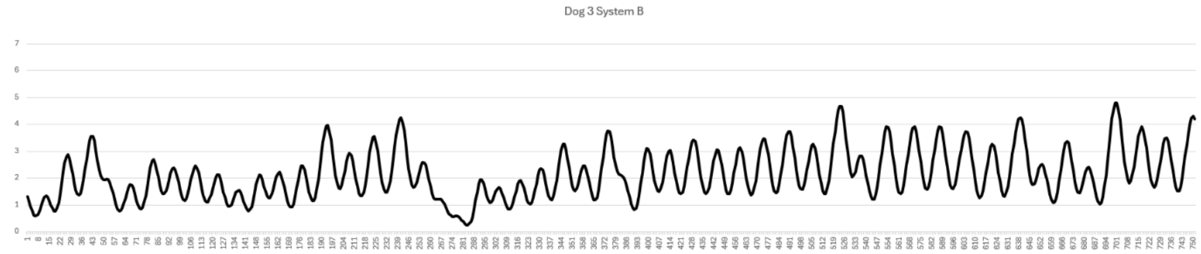

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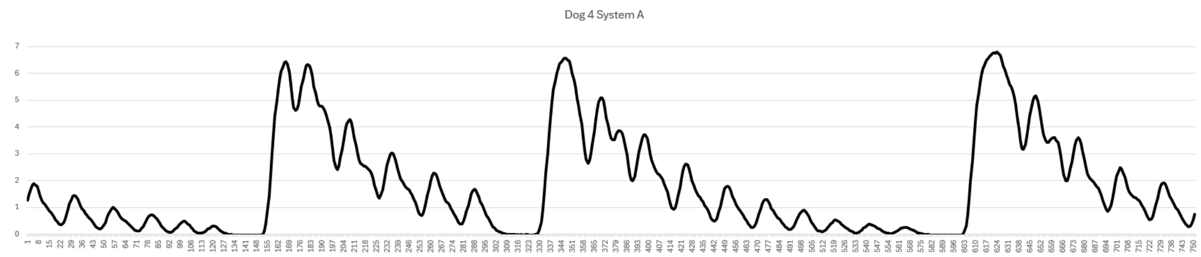

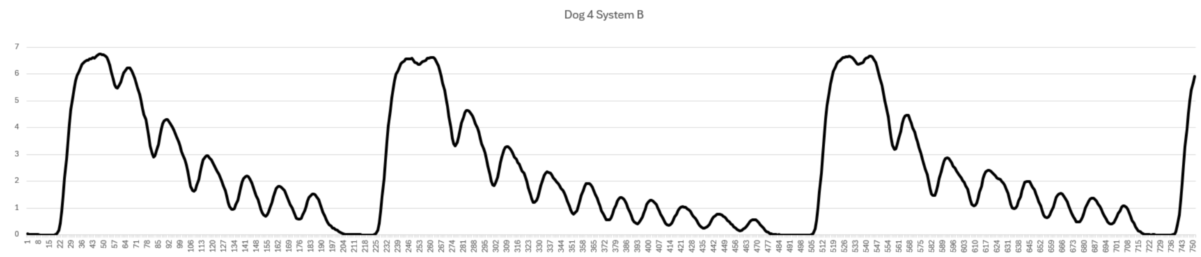

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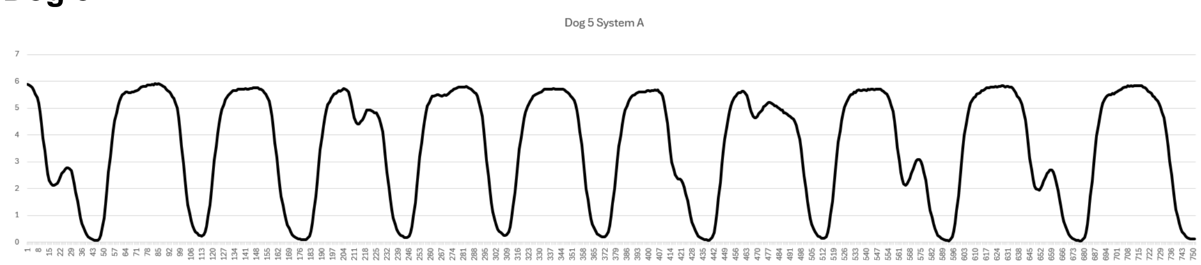

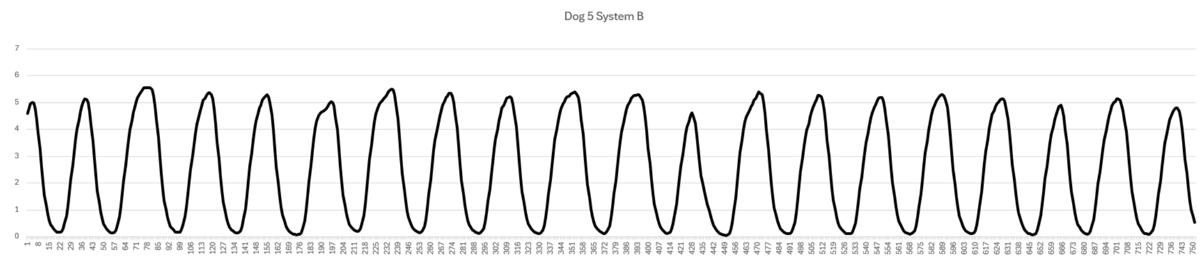

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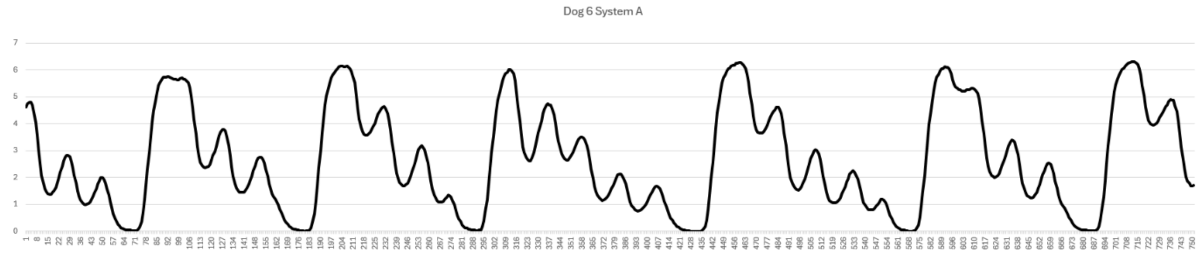

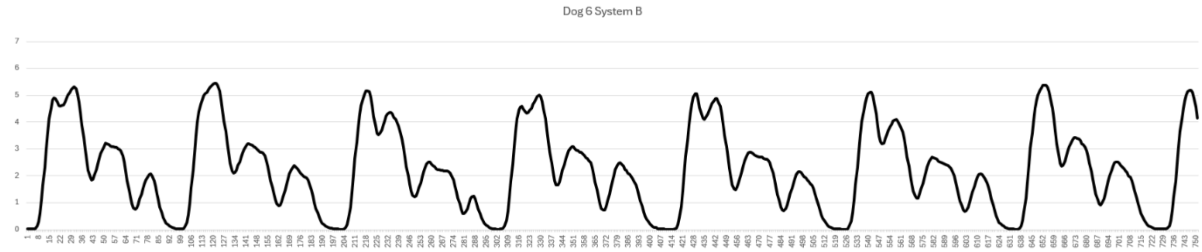

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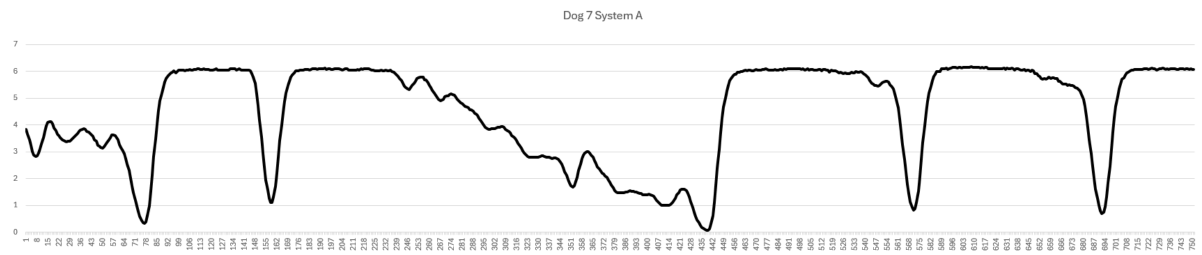

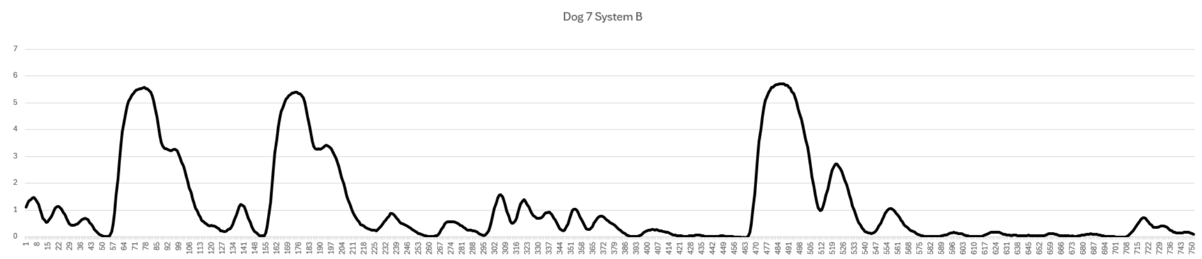

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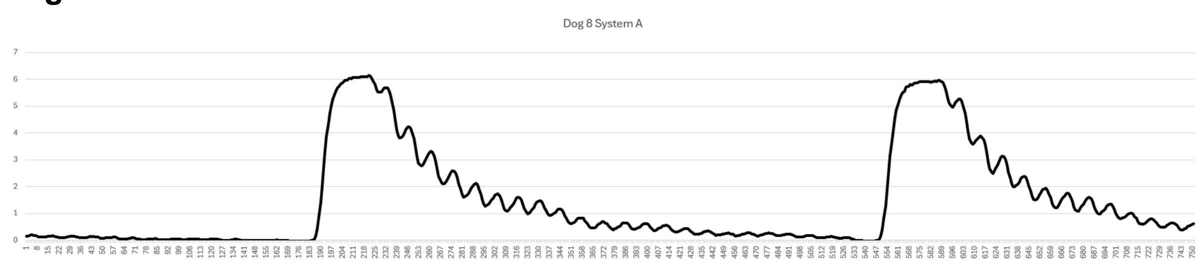

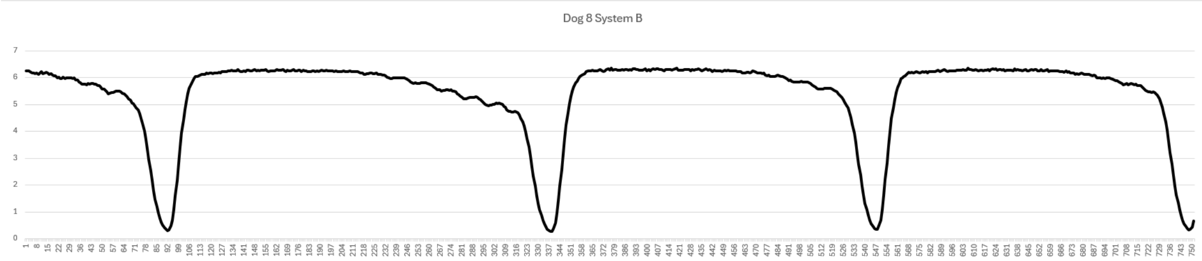

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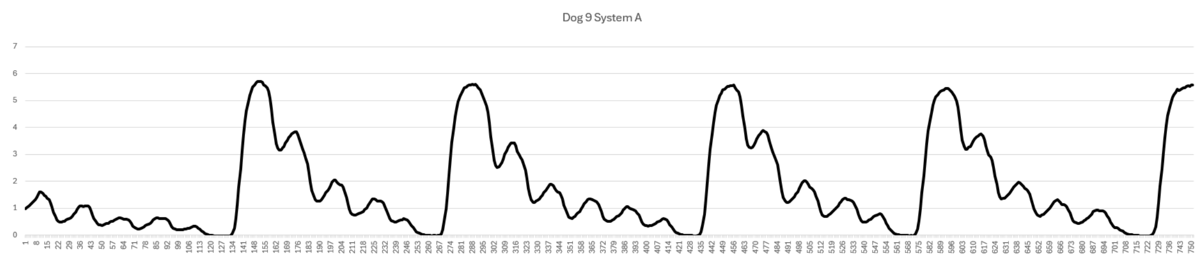

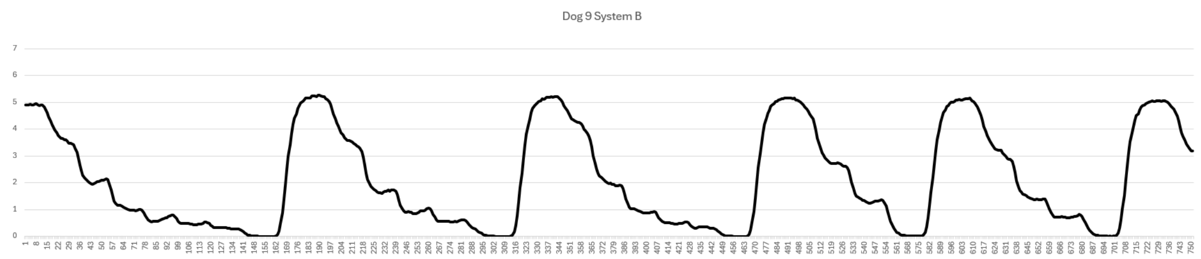

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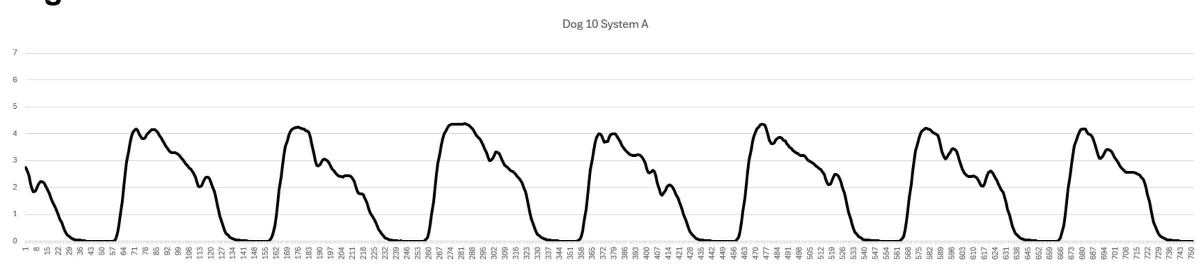

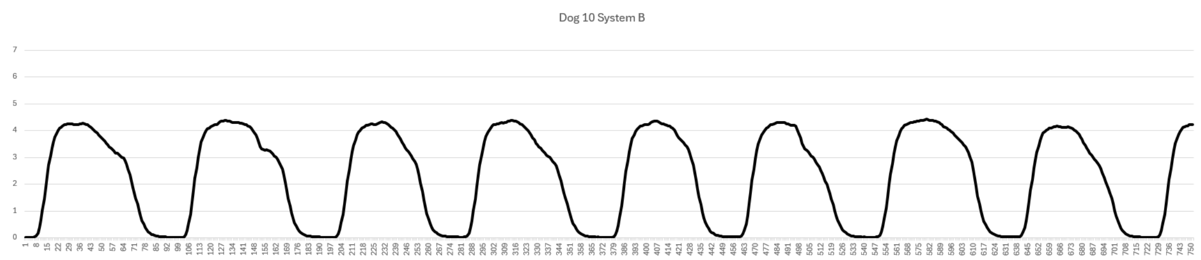

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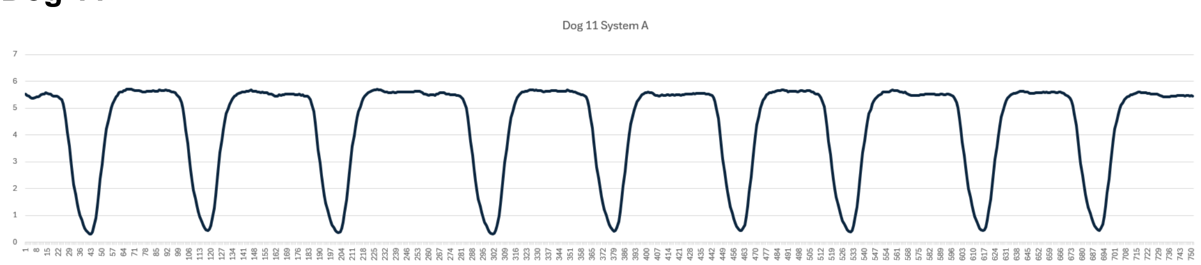

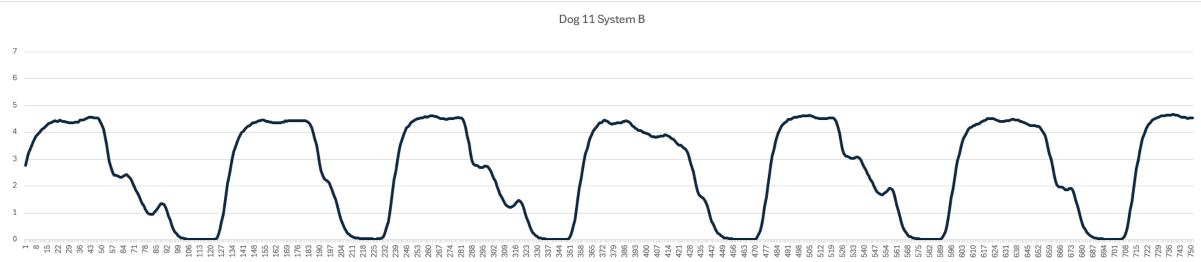

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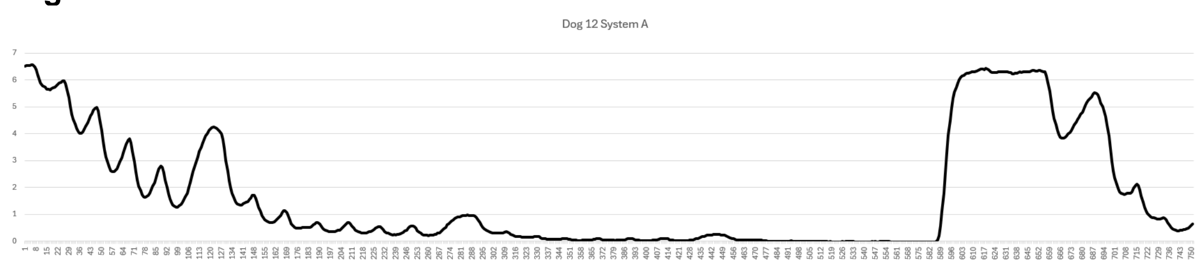

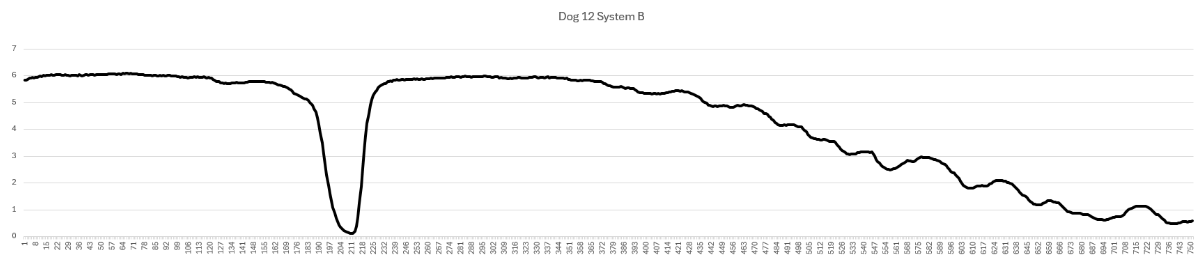

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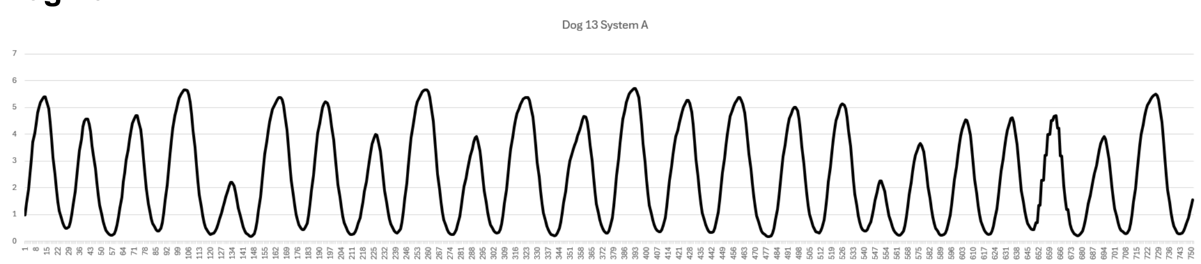

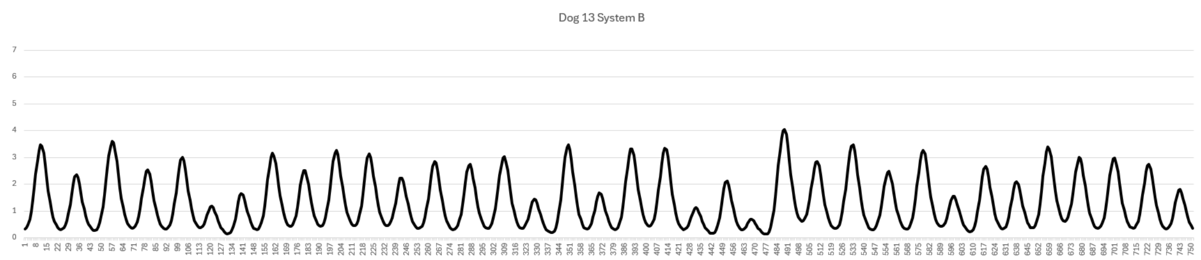

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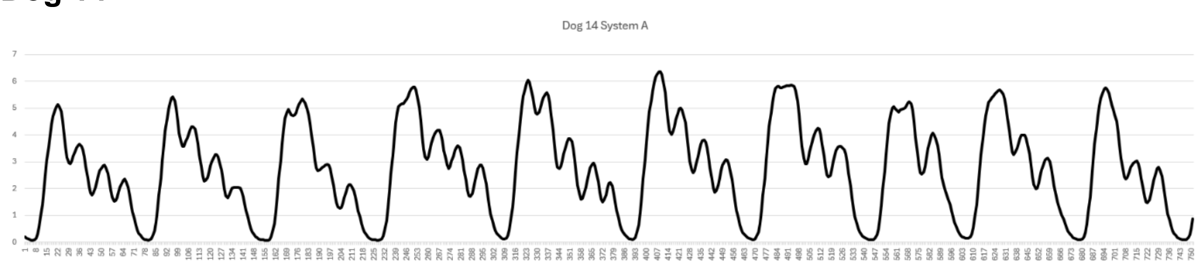

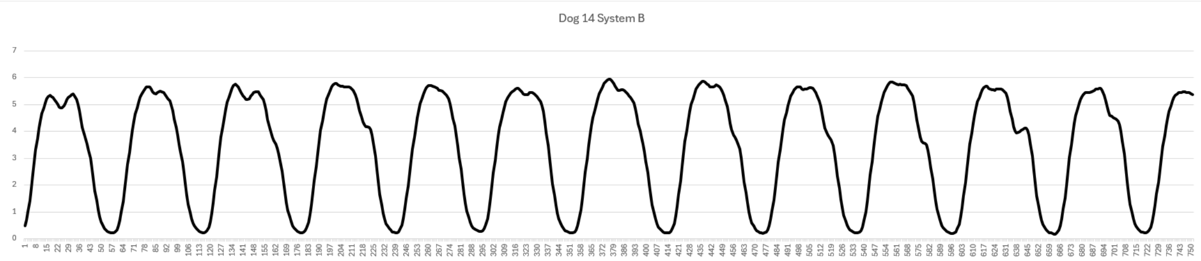

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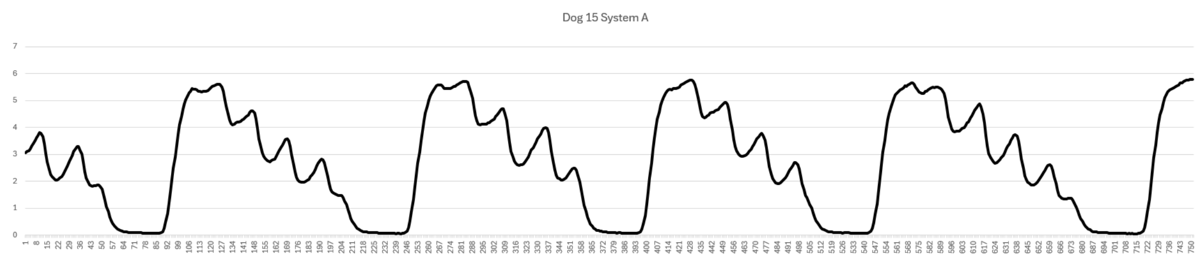

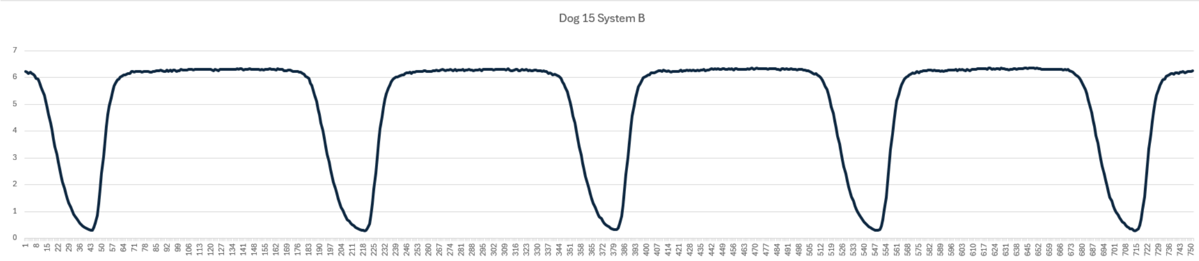

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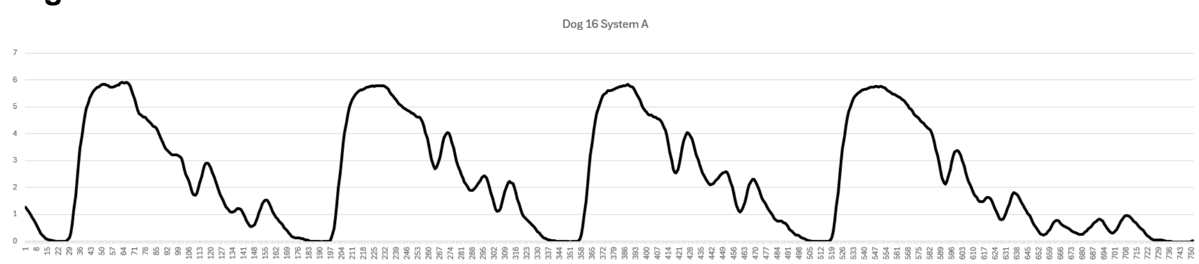

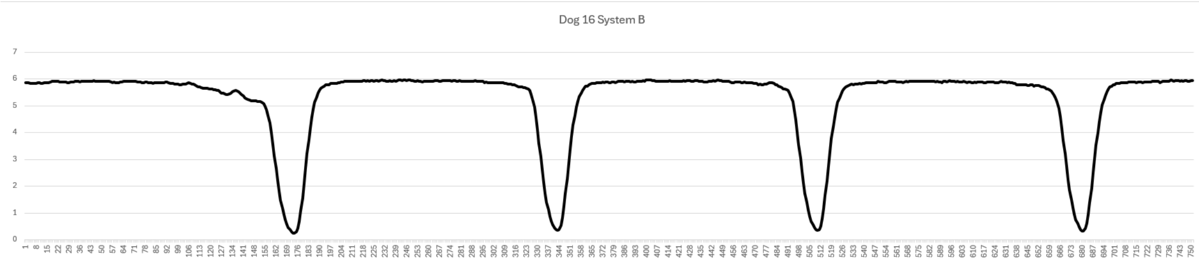

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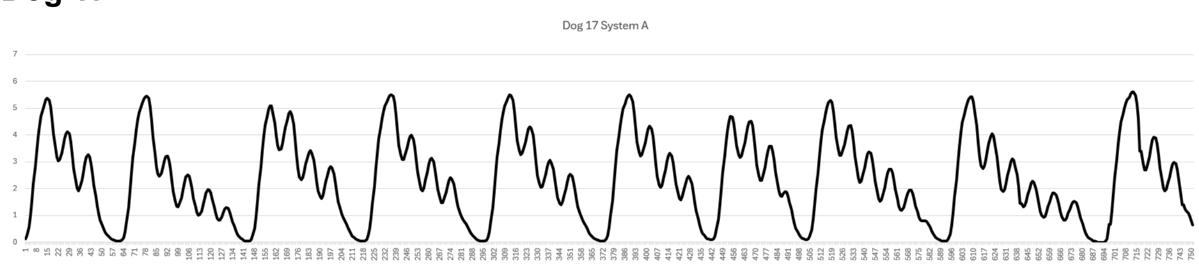

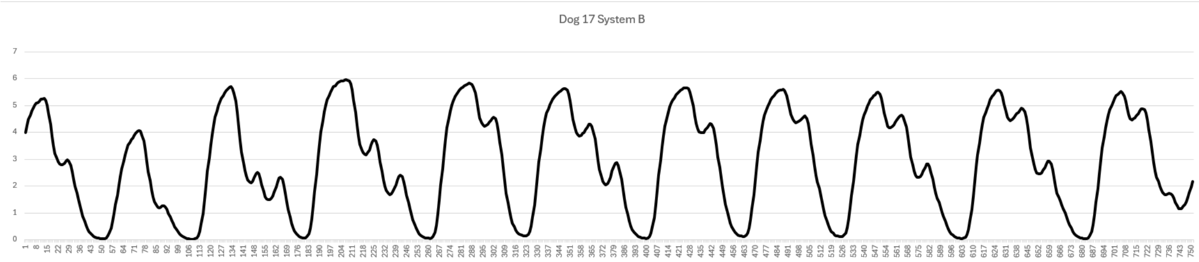

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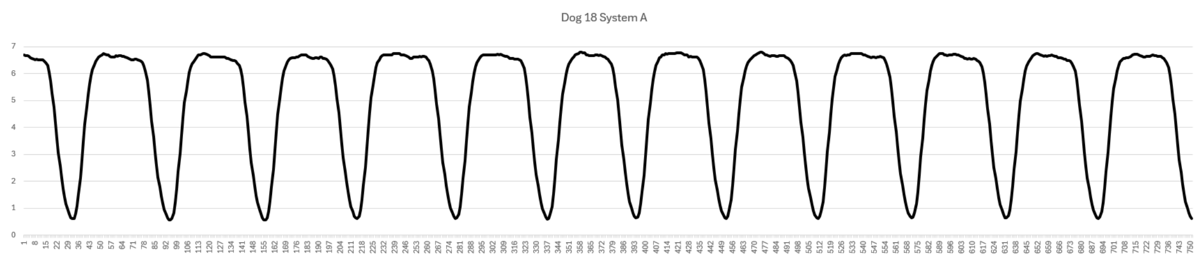

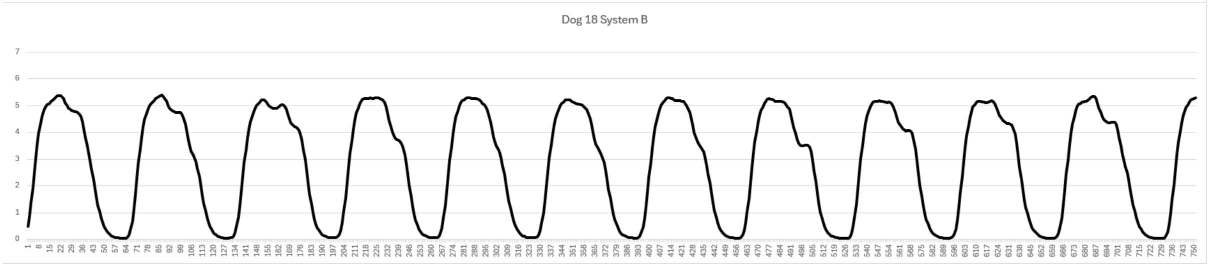

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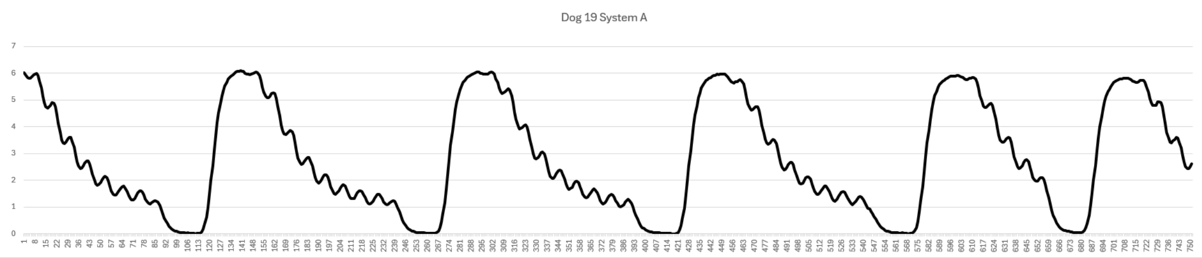

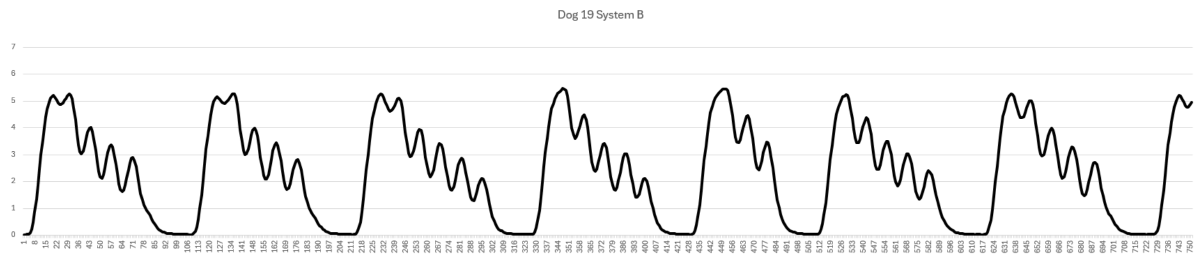

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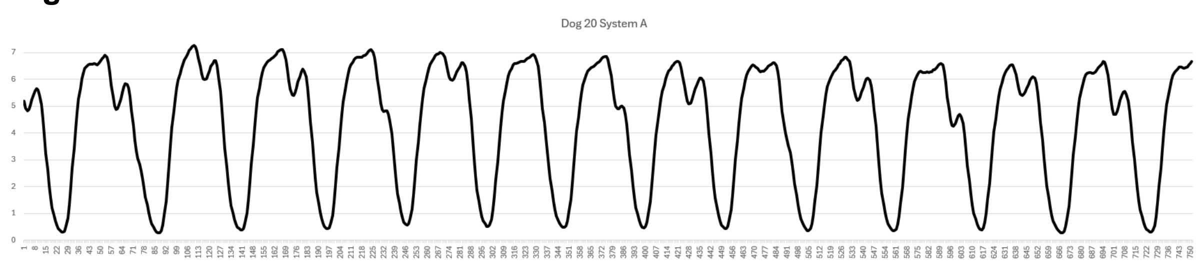

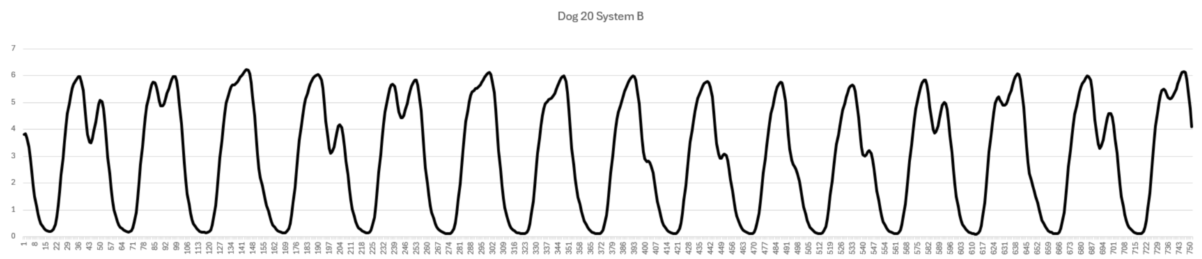

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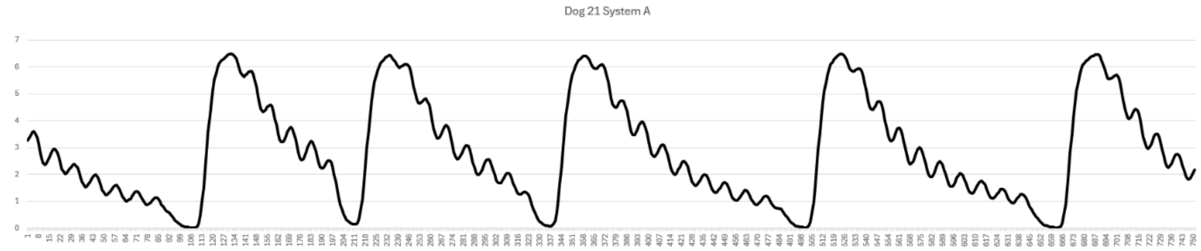

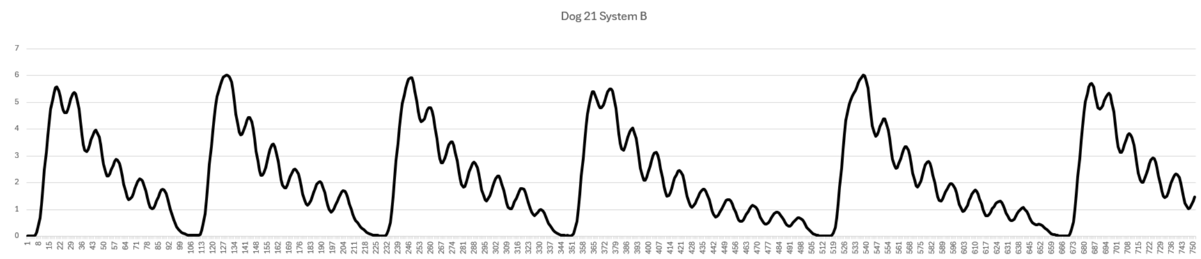

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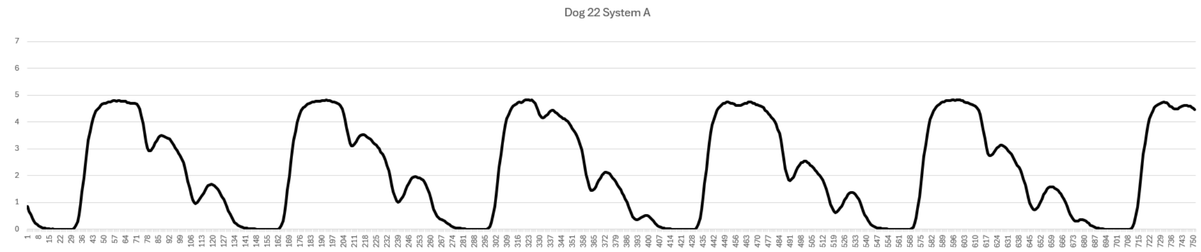

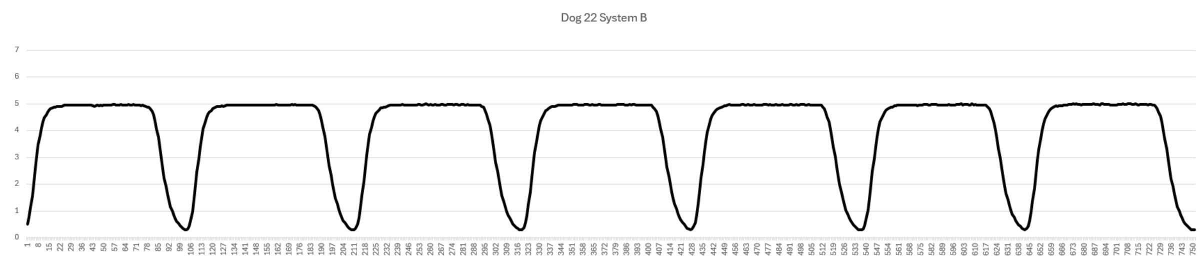

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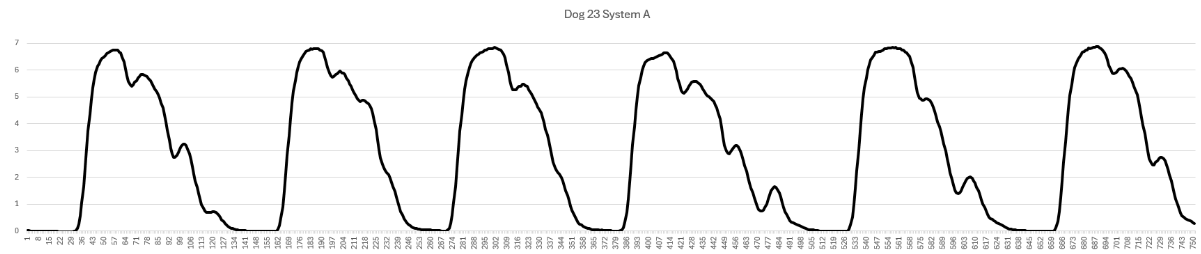

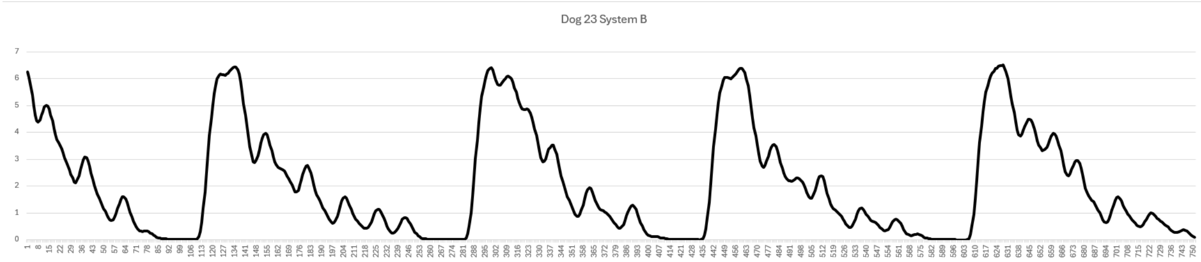

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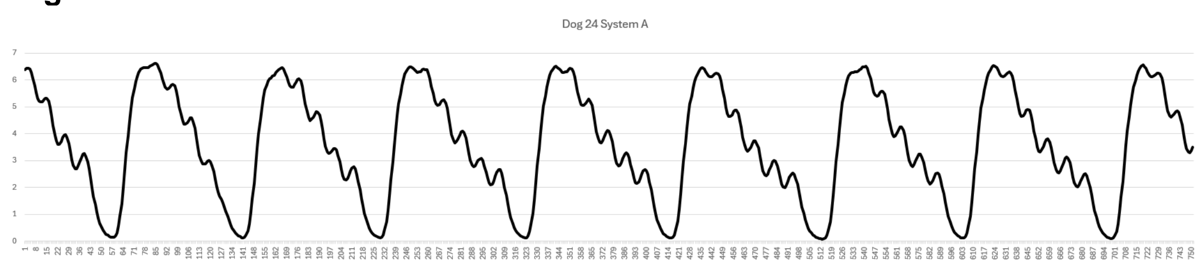
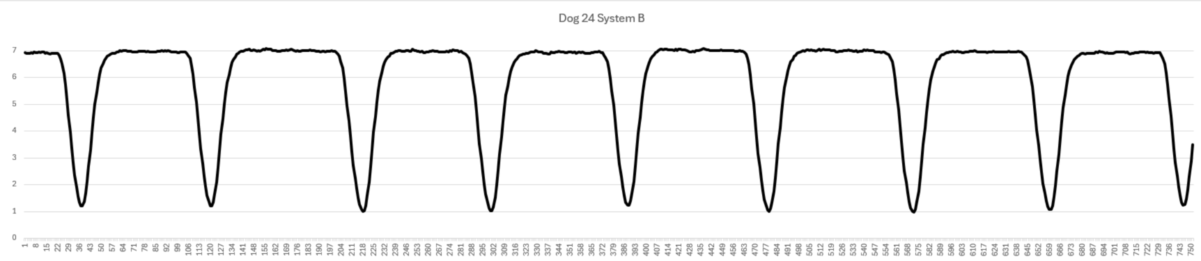
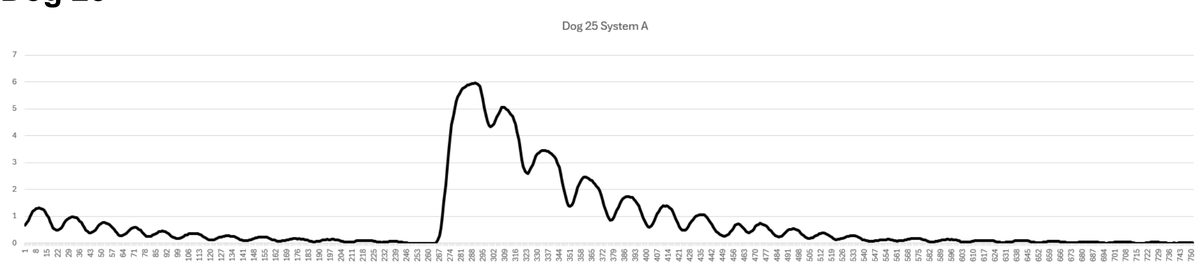
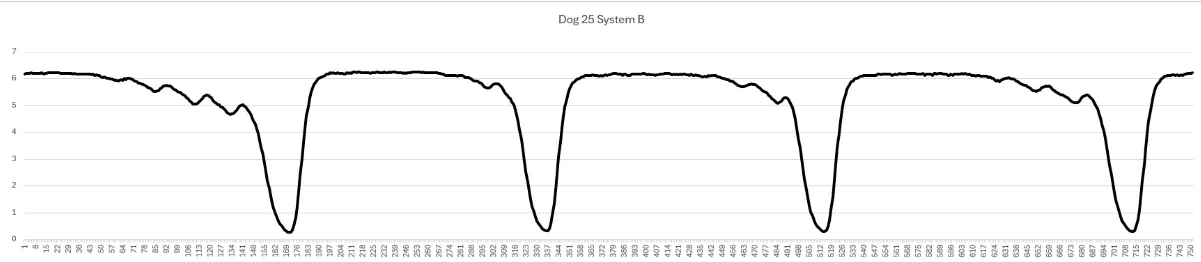




Dog 25





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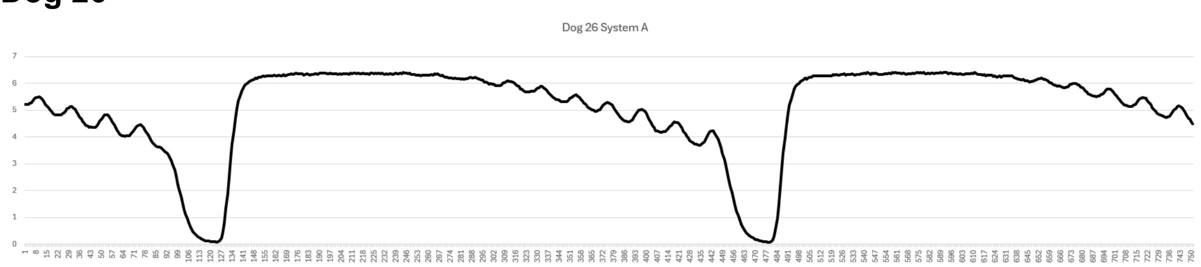

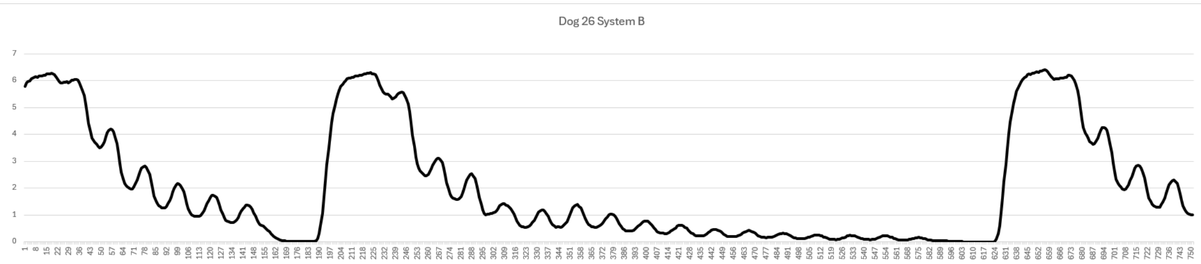

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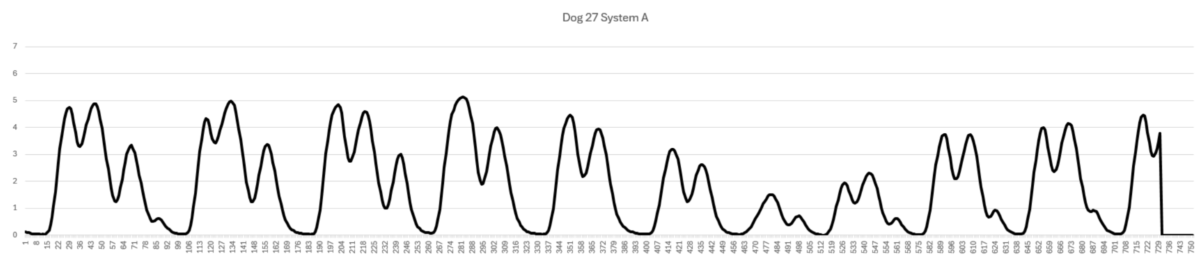

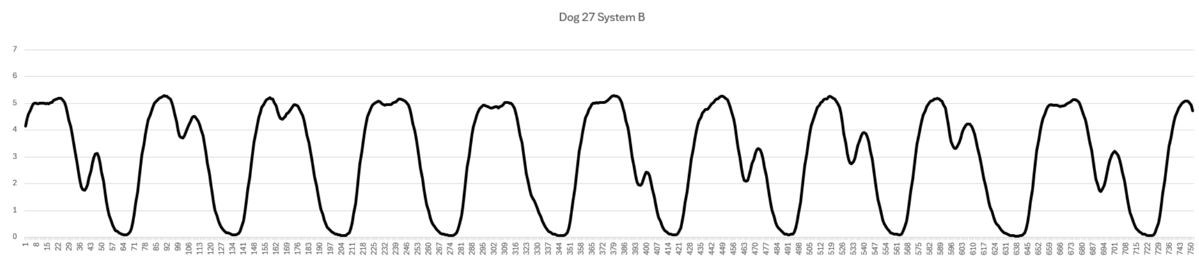

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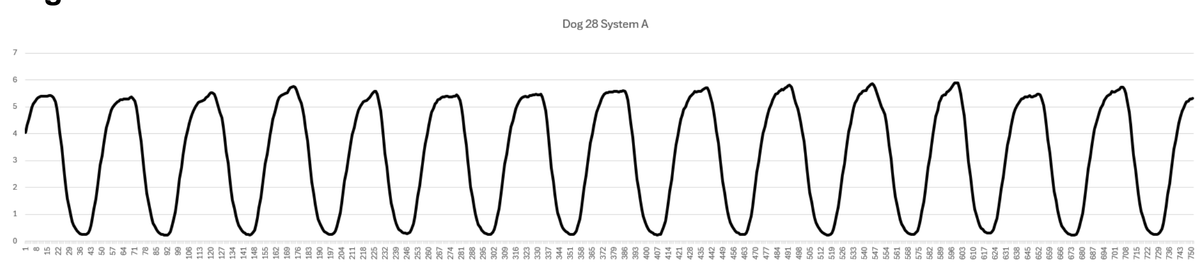

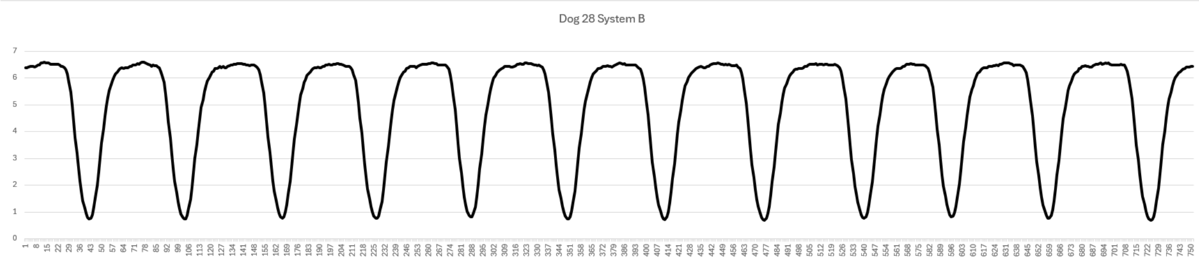

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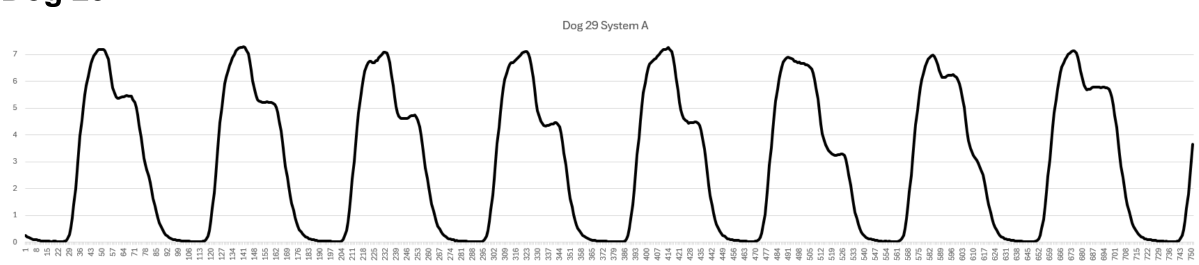

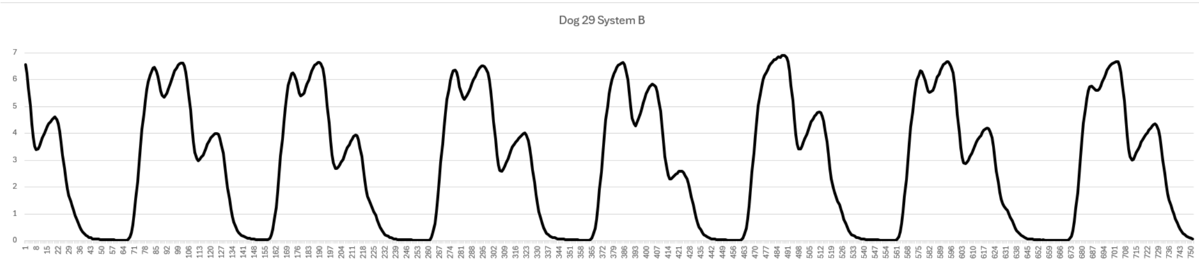

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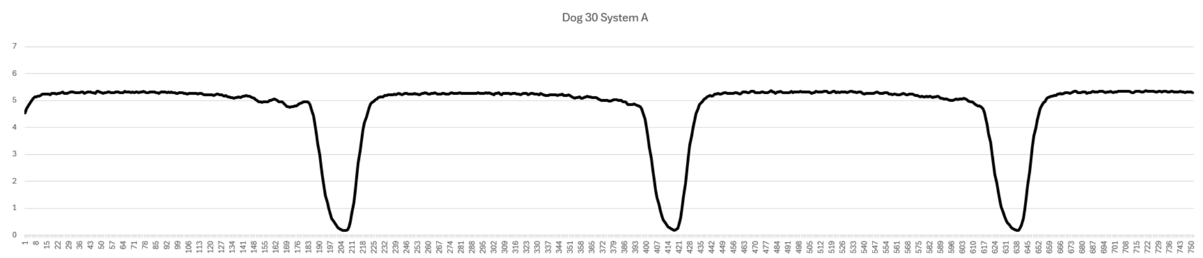

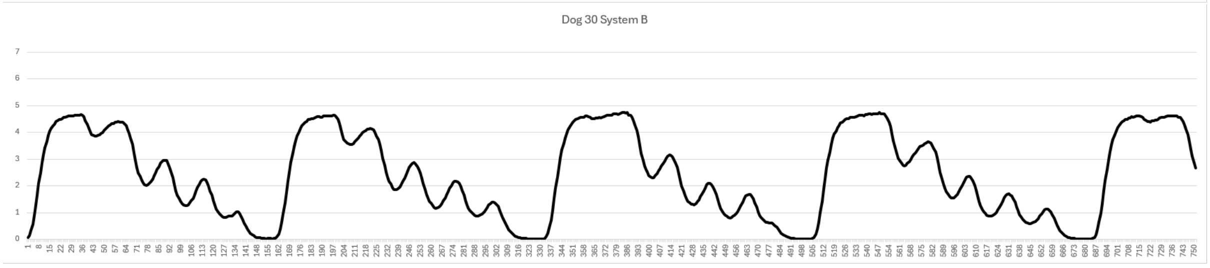

	Subjective presence of plateau		System Key	
Dog	**System A**	**System B**	**System A**	**System B**
1	No	No	Bain	T-piece
2	No	Yes	T-piece	Circle
3	No	No	Circle	T-piece
4	No	No	Bain	T-piece
5	Yes	No	T-piece	Bain
6	No	No	T-piece	Bain
7	Yes	No	Circle	T-piece
8	Yes	Yes	T-piece	Circle
9	No	No	Bain	T-piece
10	No	No	Bain	T-piece
11	Yes	Yes	Circle	T-piece
12	Yes	Yes	T-piece	Circle
13	No	No	T-piece	Bain
14	No	No	Bain	T-piece
15	No	Yes	T-piece	Circle
16	No	Yes	T-piece	Circle
17	No	No	Bain	T-piece
18	Yes	Yes	Circle	T-piece
19	No	No	T-piece	Bain
20	No	No	T-piece	Bain
21	No	No	T-piece	Bain
22	No	Yes	T-piece	Circle
23	No	No	T-piece	Bain
24	No	Yes	T-piece	Circle
25	No	Yes	T-piece	Circle
26	Yes	No	Circle	T-piece
27	No	No	Bain	T-piece
28	No	Yes	T-piece	Circle
29	No	No	T-piece	Bain
30	Yes	No	Circle	T-piece

Breathing System	**Number of plateaus observed**	**Percentage of dogs plateaus observed in**
Bain	0	0%
Circle	13	87%
T-Piece	5	17%

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