VIEWPOINT PIECES, ESSAYS OR 'SPECIAL ARTICLES'

Sustainable veterinary anaesthesia: single centre audit of oxygen and inhaled anaesthetic consumption and comparisons to a hypothetical model

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Objectives: Single centre carbon footprint audit of oxygen and inhaled anaesthetic agent consumption. Study design: Retrospective audit with hypothetical intervention.

Materials and Methods: Records of 100 consecutive anaesthetics were examined. Consumption of oxygen and inhaled anaesthetic agent were estimated from oxygen flowmeter and vaporiser settings. Carbon dioxide equivalents (kg CO_2e) were calculated. Records were reassessed to identify potential reductions in oxygen flow. Animals >5 kg were assigned to use circle systems set at a maintenance flow of 1 L/min following a short transitional period of higher flow. Animals <5 kg were assigned to Mapleson-A breathing systems at a flow of 1 L/min. Potential reductions in oxygen and inhaled anaesthetic agent consumption and CO_2e were calculated.

Results: A total of 14,370 minutes of anaesthesia were audited. Median bodyweight of the animals was 12.1 (interquartile range 5 to 25.8) kg. Median anaesthetic time was 110 (interquartile range 73.8 to 205) minutes. It was estimated 43,132 L of oxygen were used to vaporise 2605 mL of liquid sevoflurane and 1654 mL of liquid isoflurane. Potential oxygen consumption was 16,798 L, lowering sevoflurane consumption to 1123 mL and isoflurane to 589 mL. Using the suggested technique, oxygen and inhaled anaesthetic agent could have been reduced in 97% of anaesthetics with a median inhaled anaesthetic agent reduction of 59% (interquartile range 43 to 71%). Carbon footprint of the inhaled anaesthetic agent used was calculated as 1.82 metric tonnes of CO_2e. This could have been lowered to 0.67 metric tonnes (63% reduction).

Clinical Significance: Large reductions in oxygen and inhaled anaesthetic agent consumption and therefore greenhouse gas emission and financial expenditure can be made if we audit and adapt our practices.

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INTRODUCTION

It has never been more important for the veterinary sector to practice a more sustainable approach to anaesthesia. Climate change is a recognised global emergency; human activities and their effects on the climate and environment are already causing unprecedented animal and plant extinctions and consequent loss of biodiversity, as well as impacting and endangering human life (Ripple *et al.* 2017). We must therefore limit our carbon and greenhouse gas emissions as a matter of urgency (Ripple *et al.* 2017).

Inhaled anaesthetic agents (IAAs) including isoflurane, sevoflurane, desflurane and nitrous oxide are well-established green-

house gases with effects 2 to 3 orders of magnitude greater than carbon dioxide (Jones & West 2019). Desflurane and nitrous are the IAAs with the greatest greenhouse potential, followed by isoflurane and then sevoflurane. Although the overall contribution of anaesthesia in human health care to global emissions is small compared to coal power stations, agriculture, aviation and car travel, (Sulbaek Andersen *et al.* 2010) IAAs do have a disproportionate effect. Therefore, it should be considered as our duty to do as much as possible to limit them where it is safe to do so (Jones & West 2019).

Beyond climate change, other practical issues can also be mitigated if we learn how to conserve resources and limit waste. Issues with the manufacture of isoflurane have caused alarm in recent years and led to anaesthetists looking for methods to reduce their consumption (Veterinary Record News 2018). Since December 2019, the COVID-19 pandemic has overwhelmed many of the world's human health care systems, which led to shortages of anaesthetic equipment (including ventilators, syringe drivers and infusion pumps) as well as affecting pharmaceutical availability in the veterinary sector (American Veterinary Medical Association 2020, Bong *et al.* 2020, European Medicines Agency 2020). There were even significant risks at certain points during the pandemic that the demand for oxygen might outstrip supply in human health care which might have reduced the availability of even this most elementary of products for veterinary practices (British Medical Journal News 2020). These factors demonstrate that even in the developed world we cannot take for granted an unlimited, uninterrupted supply of pharmaceuticals and medical resources.

As well as avoiding the use of desflurane and nitrous oxide, one simple method of reducing oxygen and IAA consumption, and consequently the release of waste anaesthetic gases into the atmosphere, is to use low-flow inhalational anaesthesia administered via a circle breathing system in preference to higher flow anaesthesia administered via a non-rebreathing system (McGain *et al.* 2020). Although numerous definitions of low-flow anaesthesia exist they all involve the use of rebreathing anaesthetic systems with fresh gas flows below a patient's minute volume (Meakin 1999). For the purposes of simplicity and practicality, throughout this article we use the definition of low-flow as a maintenance flow of 1 L/min as first described by Foldes in 1952 (Nunn 2008). Whatever the definition, literature suggests that most anaesthetists in human medicine fail to use efficient fresh gas flows during most anaesthetics (McGain *et al.* 2020).

In veterinary medicine, we are often presented with animals under 10 kg to anaesthetise and therefore we often favour the use of non-rebreathing systems for the lower resistance and equipment dead-space they offer (Dunlop 1992). Unfortunately, the trade-off we make in doing so is a reliance on high fresh gas flows, often at multiples of minute volume, to prevent rebreathing. This in turn vaporises more IAA which is then most often released into the atmosphere. The reasoning behind the preference for using non-rebreathing systems over circle systems for patients under 10 kg may have been overemphasised (Rasch *et al.* 1988, Dunlop 1992, Meakin 1999). Indeed, circle systems with a reduced capacity reservoir bag and narrow bore breathing hoses are considered as safe and suitable for use in infants of all ages with the caveat that mechanical ventilation is delivered to neonates when these systems are used (Meakin 1999). Therefore, when also considering sustainability, it may be not only safe but more appropriate to employ circle systems even in some of our smaller animals. Where this is not possible lower-flow non-rebreathing systems, such as the miniature parallel Lack or Humphrey ADE, offer a viable alternative (Walsh & Taylor 2004, Gale *et al.* 2015).

Objective

To estimate oxygen and IAA consumption in our hospital and calculate the carbon footprint associated with it. To hypothetically implement a conservative low-flow anaesthesia model in the audited anaesthetics and to eliminate the use of desflurane to identify potential reductions in usage and environmental impact.

MATERIALS AND METHODS

Ethics and data protection

This study was authorised by the local Social Science Research Ethical Review Board as an audit of individuals' behaviour and practice. All data were anonymised and stored in a secure server.

Setting and current local practices

The anaesthesia team at the Queen Mother Hospital for Small Animals, Royal Veterinary College performs around 6000 anaesthetics annually. Anaesthetics are performed by either specialist veterinary anaesthetists in training or veterinary nurses and students under the direct supervision of a residency trained or specialist veterinary anaesthetist.

Anaesthesia is induced in one of three induction areas: in the operating theatre suite, in the magnetic resonance imaging (MRI) suite or the out-of-theatre induction suite serving the remaining imaging department and wider hospital. Following induction of anaesthesia with injectable drugs, most animals undergoing imaging procedures or being prepared for surgical procedures have anaesthesia maintained using IAAs vaporised in oxygen administered via a non-rebreathing, Mapleson-D anaesthetic breathing system (either a Bain or a modified T-piece). The initial fresh gas flows for these breathing systems are typically calculated based upon one and a half to three times the animal's estimated minute volume or 300 to 600 mL/kg/min. Once in the operating theatre or in one of the diagnostic or imaging suites, most animals are changed onto the in-built circle system of an anaesthetic workstation for the duration of their procedure. The consequence of this is that animals tend to begin anaesthesia on relatively high fresh gas flows before being switched onto more economical flows.

Choice of IAA is left to the anaesthetist performing or supervising the case. Isoflurane is considered the standard IAA for healthy animals, but sevoflurane is often preferred if there is a perceived benefit (*e.g.* being able to achieve faster changes in the depth of anaesthesia during the anaesthetic of sick animals which make up a considerable proportion of the hospital's caseload). Desflurane is occasionally used in suitable cases for teaching purposes.

Participants and study size

Starting from a Monday of a typical week, 100 consecutive anaesthetics were selected from hospital databases.

Inclusion and exclusion criteria

Cases were included if the anaesthetic had an accompanying record that contained the animals' bodyweight and all 5-minute recordings of fresh gas flows and vaporiser settings for the duration of the anaesthetic and excluded if they were incomplete.

Data sources, variables and calculations

Scanned paper records were downloaded from the animal's electronic medical record. Consumption of oxygen and IAAs were estimated based on the fresh gas flow (O_2 L/min) and vaporiser setting (Vol %) as recorded every 5 minutes on the anaesthetic records. Flowmeter and vaporiser outputs were transcribed from the anaesthetic record into an electronic spreadsheet (Excel, Microsoft) along with the IAA used, the anaesthetised animal's weight, species and the type of procedure(s).

The volume of oxygen used per 5-minute period was calculated using the following equation (Biro 2014):

$$Oxygen[l\ per\ 5\text{-}minute\ period] = flowmeter\ setting[l/minute] \times 5[minute]$$

Subsequently, the volume of inhaled agent used per 5-minute period was calculated using the equation (Biro 2014):

$$IAA\ used[ml\ per\ 5\text{-}minute\ period] = \frac{(Volume\ O_2[ml] \times vaporiser\ setting[\%])}{Saturated\ gas\ volume[ml/ml] \times 100}$$

Where the saturated gas volume refers to the volume of gas produced when 1 mL of liquid anaesthetic agent is fully vaporised. For isoflurane, sevoflurane and desflurane these values are 195, 184 and 210 ml/ml respectively. The sum of all 5-minute periods was used to estimate the total oxygen and IAA consumption of the entire anaesthetic.

Two main assumptions were made for these calculations: (1) vaporisers had precise, accurate outputs at all fresh gas flows and (2) all IAAs escaped into the atmosphere unchanged without undergoing any metabolism before exhalation. For ease of comparison, oxygen consumption was additionally converted to "J" sized oxygen cylinder (BOC, Linde Group UK) consumption. These cylinders have a 6800 l oxygen capacity.

Each anaesthetic was then reassessed to establish whether any reductions in oxygen flows could be made by utilising a conservative low-flow technique. In addition, desflurane was swapped out for an equipotent dose of sevoflurane where there was not a clear benefit to its use. This exchange is in line with what is suggested in sustainable anaesthesia guidelines in human medicine (Sherman *et al*. 2012, Association of Anaesthetists 2020).

A standardised "one-flow-fits-all" model for establishing fresh gas flow was chosen for simplicity purposes and based on author experience. This model was considered to allow acceptable times for both de-nitrogenation and for the concentration of IAA within the breathing system to approach the vaporiser setting (further explanation can be found in the discussion).

For animals with bodyweights over 15 kg, a disposable paediatric circle, or the inbuilt circle system of an anaesthetic workstation with 22 mm internal diameter corrugated breathing hoses was considered appropriate. For animals weighing between 5 and 15 kg the same breathing system with 15 mm internal diameter smooth bore breathing hoses and low dead-space Y-piece was considered appropriate.

The hypothetical fresh gas flows modelled for these animals was 4 l/min for the first 5 minutes of anaesthesia, 2 L/min for the next 5 minutes and flow 1 l/min for the remaining anaesthetic unless the animal required a significant change in vaporiser setting or was attached to a new circle breathing system, such as during transfer between rooms. In these circumstances, oxygen flow was modelled as before with the period of higher fresh gas flow before returning to 1 L/min. A significant change in vaporiser setting was considered as a change of greater than 0.2% inhaled IAA within a 5-minute period (*e.g.* from 1.8 to 2%).

All spontaneously breathing animals under 5 kg were deemed suitable to use either a miniature parallel Lack (Mini-Lack™, Burtons, UK) or Humphrey ADE™ (functioning in "Mapleson A" mode) breathing system. A fresh gas flow of 1 L/min (≥200 ml/kg/min) was allocated for these animals, as this flow rate would likely be sufficient to avoid rebreathing even if minute ventilation increased during the anaesthetic (Walsh & Taylor 2004, Gale *et al*. 2015). For animals under 5 kg requiring mechanical ventilation, they were assigned to the integrated circle system of an anaesthetic workstation with 15 mm internal diameter smooth bore tubing in line with normal hospital practice. In this case, the flows used were as already outlined for the circle system.

To replace desflurane with sevoflurane it was assumed vaporiser setting would need to be four times lower for sevoflurane. These rough potencies were based on the minimum alveolar concentrations of approximately 10.3% for desflurane and 2.4% for sevoflurane (Kazama & Ikeda 1988, Hammond *et al*. 1994).

Hypothetical oxygen and IAA consumption were recalculated using the modelled fresh gas flow settings, using the same equations and assumptions as before. A final assumption, that vaporiser setting would not have been altered because of the lower fresh gas flow used, was also made.

Carbon footprint through greenhouse gas emissions was calculated in carbon dioxide equivalents (CO_2e) using the following equation (Campbell & Pierce 2015):

$$CO_2e[kg] = (GWP_{100} \times volume\ of\ IAA[mL] \times IAA\ density[g/mL]) / 1000$$

Where GWP_{100} is the IAA's Global Warming Potential over 100 years with Sevoflurane being 130, Isoflurane 510 and Desflurane 2540 (Campbell & Pierce 2015), *Volume of IAA* is Volume of liquid IAA vaporised (mL) as calculated above and *IAA*

density is the density of the specific IAA in g/mL (Sevoflurane 1.52 g/mL, Isoflurane 1.5 g/mL, Desflurane 1.46 g/mL).

Actual consumption of oxygen and IAA and CO_2e emissions was then compared to hypothetical consumption and emissions.

Statistics

No statistical comparisons were made in this study. Analysis of histogram plots showed a skewed data distribution, and therefore data is presented using descriptive statistics for non-normal distributions. Reductions in IAA and oxygen consumption are reported as percentage decreases when comparing actual to hypothetical calculations.

RESULTS

Participants, procedures and anaesthetics

All but three anaesthetic records examined (n=103) were considered as "complete." The species anaesthetised were 76 dogs, 22 cats and two exotic species. A mixture of breeds were represented (data not reported). Bodyweight ranged between 1.3 and 54.5 kg with a median 12.1 kg (interquartile range, IQR 5.0 to 25.8). The procedures performed during the 100 anaesthetics were: 33 soft tissue procedures (12 coeliotomies, six brachycephalic upper airway surgeries, five thoracotomies, three total ear canal ablations, two wound closures, two mass removals, two mass biopsies, one ventral neck explore), 25 MRI procedures, 15 computed axial tomography procedures, 13 orthopaedic procedures (five tibial plateau levelling osteotomies, three fracture repairs, three elbow arthroscopies, two patella luxation corrections), 10 ophthalmological procedures (four phacoemulsification surgeries, two corneal surgeries, two enucleations, one eyelid surgery, one retrobulbar surgery), seven medical procedures (four gastrointestinal endoscopies, three chest drain placements), four neurosurgical procedures (four hemilaminectomies), three dermatological procedures (three skin and ear examinations including biopsies and sampling) and two interventional cardiology procedures. Twelve of the procedures had a second procedure carried out during the same anaesthetic (*e.g.* hemilaminectomy following spinal MRI) and three animals were anaesthetised twice during the audited period for different procedures.

Volumetric consumption of oxygen and IAA were calculated for 14,370 total minutes of anaesthesia over 8 working weekdays. Individual anaesthetic times ranged between 15 and 460 minutes, with a median 110 (IQR 73.8 to 205.0) minutes. Isoflurane was used 42 times, sevoflurane 60 times and desflurane once, with both isoflurane and sevoflurane administered non-concurrently in two anaesthetics and both sevoflurane and desflurane non-concurrently once.

Descriptive data – oxygen and IAA consumption

A total of 43,132 l of oxygen (6.3 J size cylinders) were used to vaporise 2605 ml of liquid sevoflurane (10.4×250 ml bottles), 1596 ml of liquid isoflurane (6.4×250 ml bottles) and 22 ml of liquid desflurane (0.1×240 ml bottles).

Hypothetical oxygen consumption was 16,798 l (2.5 J size cylinders), representing a reduction of 61%. This would have lowered IAA consumption to 1123 ml of liquid sevoflurane (4.5×250 ml bottles; a 57% reduction) and 589 ml of liquid isoflurane (2.4×250 ml bottles; a 63% reduction). It was assumed that the use of desflurane was not clinically necessary and that it was exchanged for an equipotent volume of sevoflurane in the analysis.

Only three anaesthetics recorded met or bettered the IAA and oxygen consumption calculated in the hypothetical model. Oxygen and IAA consumption could have been reduced by up to 86% in the remaining 97 anaesthetics, with a median IAA reduction of 59% (IQR 43 to 71%).

Descriptive data – carbon footprint

The estimate CO_2e calculated for actual IAA consumption was 1.81 metric tonnes of CO_2e. Sevoflurane contributed 0.51 metric tonnes (28%), isoflurane 1.19 metric tonnes (67.2%) and desflurane 0.08 metric tonnes (4.5%) of CO_2e. This could have been lowered to 0.67 metric tonnes using the low flow techniques described in the hypothetical model, representing a reduction of 63%.

DISCUSSION

Key results

This audit demonstrates the significant reductions in IAA consumption and associated carbon footprint which could be achieved through the adoption of conservative low-flow anaesthetic techniques in practices which routinely use non-rebreathing systems. Assuming the hypothetical intervention described here could be sustained, oxygen and IAA consumption and CO_2e emissions could each be reduced by around 60%. This could have the additional benefit of reducing the financial cost of anaesthesia, although the purchase of new breathing systems and increased use of soda-lime would need to be included in any calculations. These reductions are slightly greater than 25% reduction in sevoflurane usage achieved in human paediatric anaesthesia through a quality improvement initiative (Glenski & Levine 2020) and the 21% reduction in isoflurane using an inhalational anaesthetic computer simulation (Feldman 2012). However, it should be noted both these studies involved reduction of fresh gas flow in circle systems to 1 l/min from a standard of 2 l/min rather than a shift from non-rebreathing systems to low-flow techniques (Feldman 2012, Glenski & Levine 2020).

Limitations

There are numerous limitations to our methods, results and the conclusions that may be drawn from them. The accuracy of these results can be questioned due to the methodology used to calculate them. Calculations based on intermittent recordings on anaesthetic records might be inaccurate as periods where flowmeters and vaporiser dials were temporarily altered may have occurred between recordings. Furthermore, handwritten recordings may be illegible, or the measurement may

be erroneous; precise recording of gas flows using a mechanical flowmeter is difficult. Despite modern Plenum anaesthetic vaporisers being considered as "precision vaporisers," they are still not particularly accurate instruments (Kelly & Kong 2011) and are working to most manufacturer specifications if output is within 15 to 20% of the dial setting (Blease 1999, Datex-Ohmeda 1999, Penlon 2002). This means a vaporiser set to 2% on the dial could be delivering anywhere between 1.6 and 2.4% or 1.7 and 2.3% depending on the make and model of vaporiser and assuming it has been checked and serviced recently. Consequently, any calculation based upon vaporiser setting and not measured vaporiser output will introduce a considerable degree of error. In addition, vaporiser output can also vary with flow, the degree to which this occurs depends on vaporiser type, with older models having more variability. In addition, the swapping out of desflurane for sevoflurane is not an exact science. We decided on an approximate model based on the drugs potencies and this undoubtably added a considerable degree of error. However, there is no doubt that this swap from high-flow desflurane anaesthesia to low-flow sevoflurane anaesthesia would have led to massive reductions in greenhouse emissions as the use of desflurane in this single case contributed 4.5% of the total greenhouse emissions.

It is worth emphasising that the hypothetical model used is just that, hypothetical. There are no guarantees these potential flows could have been achieved in the original anaesthetic. There are several reasons why fresh gas flow may not be reduced during anaesthesia even when circle systems are being used. The anaesthetist may be focussed on other factors of anaesthetic management, particularly during emergency cases, or may simply forget to reduce the flow. In hyperthermic or pyrexic animals, it may not be possible to reduce flows as this will lead to heat retention within the circulating gas mixture whereas higher flows will flush the system out more rapidly with cold fresh gas. In addition, the rate of change of IAA within a circle is much slower than compared to non-rebreathing systems, which means to achieve rapid changes of IAA concentration the fresh gas flow would need to be increased. Finally, in some cases, changing the animal from a non-rebreathing to a rebreathing system to achieve lower fresh gas flows may not be feasible as the increase in resistance could be excessive for smaller spontaneously breathing animals.

The justification for why this methodology was chosen is that it was performed in the face of the COVID-19 pandemic and allowed rapid data collection and analysis which would demonstrate potential benefits in an ultra-short time-period. The simplicity of applying a hypothetical model rather than assessing consumption prospectively meant that easy direct comparisons could be made. Because fresh gas flows for non-rebreathing systems are based on minute volume and are therefore bodyweight dependent, the hypothetical approach gave a simple method of matching for bodyweight, as well as for variables such as anaesthetic length and vaporiser setting. So although the study quality is significantly diminished by the retrospective and imprecise method of data collection, the comparison remains valid to report albeit with the caveat there may be considerable variation in what can be achieved in a real clinical situation.

Interpretation

This audit indicates that substantial reductions in IAA and oxygen consumption and a consequent reduction in greenhouse gas emissions could be achieved in practices where similar anaesthetic strategies are employed. During the period of the audit, many animals weighing over 10 kg received prolonged periods of high flow anaesthesia utilising Maple-D non-rebreathing systems (a Bain or modified T-piece) for a significant proportion of their anaesthetic. The rationale for this, is the belief that these systems allow for a smoother transition between induction (with injectable anaesthetics) and maintenance (with IAAs) and facilitate rapid changes in anaesthetic depth as compared to circle system. Likewise, Mapleson A non-rebreathing systems like the Lack, mini-Lack or Humphrey ADE tend to be avoided as they tend to lead to rebreathing during the administration of manual ventilation. The assumption that the animal will only be anaesthetised in this manner for a short period is thought to offset the higher oxygen and IAA consumption. However, these factors may have been overemphasised and lower-flow techniques can offer a viable and safe alternative (Rasch *et al*. 1988, Dunlop 1992, Meakin 1999).

Financially, whilst circle systems are more expensive to purchase than non-rebreathing counterparts, the savings brought about through reductions in IAA and oxygen consumption will contribute to offsetting this and are highly likely to have a short return on investment period.

Response times to achieving a particular inspired agent concentration following a change in vaporiser dial setting is much longer in a circle system. Compared to the almost immediate change in IAA concentration achieved within a non-rebreathing system, the change in IAA concentration in a circle breathing system can be considered as a slower exponential "wash-in" process (Meakin 2003). This may lead to concerns over animals not receiving enough IAA especially during transition phases of anaesthesia. IAA concentration change over time in a circle system is governed by a time-constant (τ) with near completion of change occurs after three time-constants have elapsed (1τ=63%, 2τ=86%, 3τ=95%). (Meakin 2003). The time constant for a circle system is calculated based on the total system volume (V_{BS}) divided by fresh gas flow ($Q_{T\text{-}FGF}$) and therefore can be relatively easily estimated (Meakin 2003):

$$\tau = V_{BS} / Q_{T\text{-}FGF}$$

In this audit, the combined volume of the paediatric circle cannister plus 2 l reservoir bag and 1.6 m length, 22 mm diameter tubing was estimated as 4 to 5 L. At the 4 L/min flow used in the hypothetical model, τ for this system is 60 to 75 s and subsequently the circle system would reach 95% the IAA concentration set on the vaporiser dial within 3 to 4 minutes. Although this equation does not consider the animal's lung volume or removal of IAA during passage through the lungs, it demonstrates relatively fast changes in IAA concentration can be achieved in circle systems.

Delays in the changing of IAA concentration do not only occur after induction but might also be of concern later in anaes-

thesia when sudden changes in stimulation occur. Allowances were made for this in the hypothetical model through checking anaesthetic records for sudden changes in vaporiser settings and for times where the animal was moved between locations. Hypothetical fresh gas flows were increased back up to the higher rate for these transitional periods to enable a faster change in inspired IAA concentration. Nonetheless, there is no way to tell whether the rate of change in IAA concentration would have been sufficient in the audited anaesthetics. Considering this information, it is suggested that using circle systems immediately after induction of anaesthesia can permit smooth transition between injectable induction and inhalational maintenance without significant numbers of animals requiring supplemental injectable anaesthetic agents. Indeed, analysis of unplanned administration of supplemental injectable agents suggested most accidental arousal occurred during transport between locations or due to suddenly increased nociceptive input which can occur whatever the breathing system being used (unpublished internal audit based on further analysis of data presented in McMillan & Darcy 2016). A further small-scale audit looking at requirements for supplemental injectable anaesthesia between animals receiving IAA administered via a circle *versus* administered via a non-rebreathing system would help allay these concerns further.

Finally, there have been concerns raised about the use of sevoflurane combined with minimal flow and ultralow-flow techniques due to the production of compound A when sevoflurane is combined with CO_2 absorbers containing a strong alkali, particularly if the soda-lime is desiccated. Compound A has been demonstrated to be nephrotoxic to rats when administered by inhalation or intraperitoneal injection however these effects have not been demonstrated to occur in clinical human anaesthesia and the risk can be eliminated almost entirely using newer CO_2 absorbers (Kennedy *et al*. 2019). No evidence of this risk exists in veterinary anaesthesia but it would seem prudent to maintain fresh gas flows of at least 1 L/min during sevoflurane anaesthesia via a rebreathing system.

If we accept these arguments, practice can easily be changed if enough circle breathing systems and CO_2 absorber are made available and staff having appropriate training in their set-up and use, for example the appropriate flows, when they might need to be altered, when to change absorbers and how to ensure absorbers do not desiccate. Also, the choice of using a conservative low-flow model over the more technically challenging minimal-flow (0.5 l/min) or ultralow-flow (use of flow matching metabolic oxygen consumption) techniques should have made the results applicable to many clinical situations and should reduce any risk associated with the accumulation of degradation products when using sevoflurane.

Although it is true that not all animals will be suitable to receive inhaled anaesthesia delivered via a circle system most, even those under 10 kg, will be. Historically, there has been concern about animals below 10 kg being "too small" to tolerate breathing through a circle system (Rasch *et al*. 1988, Dunlop 1992, Meakin 1999). These concerns originate from the increase in resistance to inspiratory gas flow within a circle system which has been considered enough to cause a significantly increased work of breathing and therefore risks respiratory fatigue (Meakin 1999). In the traditional, large and bulky "adult" circle systems, this increase in resistance was largely attributable to heavy one-way valves and to a lesser degree to the breathing hoses and soda-lime (Meakin 1999). The lightweight, silicon valves, smaller absorbent canisters and narrow, smooth bore hoses in modern paediatric circle systems significantly reduce breathing system resistance and are suggested to be safe to use in cats over 3 kg (Robertson *et al*. 2018). In fact, it is likely the size of endotracheal tube placed in the animal's airway has a far greater effect on resistance to breathing than the choice of breathing system (Rasch *et al*. 1988, Meakin 1999). Low dead space Y-pieces and endotracheal tube connectors can also be utilised where there are additional fears about the amount of equipment dead-space (Hartsfield & Sawyer 1976, Robertson *et al*. 2018). Consequently, using modern equipment it is possible to maintain most small animals on circle systems albeit with the caveat that the smallest patients may require mechanical ventilation (Meakin 1999). Indeed, it is worth appreciating that most animals in the audit, including many cats, were maintained on circle systems once in the operating theatre.

There are significant additional benefits to using low-flow anaesthesia beyond reducing the consumption of anaesthetic gases. Smaller animals are especially prone to hypothermia during anaesthesia due to their high body surface to volume ratio. Non-rebreathing systems constantly supply cold dry gases to be inspired by the animal which may contribute significantly to heat loss. Through the preservation of expired gases and the reaction of carbon dioxide with soda-lime, heat and moisture are added to the inspired gases from circle systems reducing heat loss from the animal. Arousal during transport can also potentially be reduced using portable circle systems, as the adjustable pressure limiting valve can be closed and the fresh gas inlet occluded thus providing a closed reservoir of oxygen and IAA for the animal to breath during transportation. This has the added benefit of reducing staff exposure to expired anaesthetic gases although care must be taken to remember to open the APL valve when it is reconnected to the fresh gas outlet of the new anaesthetic machine. Alternatively, a short hose can be used to connect the scavenging connection to the fresh gas inlet of the circle as this technique closes the system but negates closing the valve.

Clearly using low-flow anaesthesia will also lead to an increased consumption of CO_2 absorbents. The effect of increased use of CO_2 absorbents at low flows on carbon footprint has not been established (Jones & West 2019). Traditional soda-lime can have a pH of 14 and requires disposal as a hazardous waste in some regions as it can cause significant contamination of water courses of sent to landfill. In veterinary practice it is often disposed of as clinical waste and incinerated which will lead to increased emissions downstream in the process. Some more modern CO_2 absorbents on the other hand have a much lower pH and are safer to dispose of as they will break down into organic compounds which are considered as harmless (Armstrong Medical 2004). This offers potential alternative methods of disposal; however, whether these have a greater or lesser environmental impact also remains to be established. There will also be financial cost impli-

cations associated with increased CO_2 absorbent use and disposal which may be significant if a practice is also investing in new circle systems. However, this will at least be partially offset by savings in oxygen and IAAs which will be particularly significant if the more expensive sevoflurane is used.

Other methods to reduce greenhouse emissions, fresh gas and IAA consumption exist beyond low flow anaesthetic techniques. These include the use of sevoflurane instead of isoflurane, total intravenous anaesthetic techniques (TIVA) and the recycling of scavenged IAAs. There is no doubt that further reductions in greenhouse emissions could be made by using sevoflurane in all cases. However, as sevoflurane is currently considerably more expensive than isoflurane, and as isoflurane is licensed and commonly used in general practice it was felt that substituting it might not be as immediately achievable in some practices. Isoflurane use was also considered vital for undergraduate teaching. Therefore, the only agent which was swapped out was desflurane as there is currently no evidence of an advantage to its use in small animals. Finally, regarding sevoflurane use, it may be that moving from high-flow anaesthesia using isoflurane to this conservative low-flow technique may make sevoflurane anaesthesia more economically viable in some situations.

In terms of TIVA, the environmental impact of increasing the use of anaesthetic drugs such as propofol has not been fully investigated. TIVA appears to be several orders of magnitude lower in terms of carbon footprint than inhaled techniques, with its main greenhouse impacts arising from the electricity required to drive a syringe driver (Sherman *et al.* 2012). Carbon footprint is of course not the only environmental impact a pharmaceutical agent can have, as a drug or its metabolites might find its way into watercourses via excretion or through improper disposal. However, despite the potentially high environmental persistence, bio-accumulation and toxicity of propofol metabolites, the overall risk to the environment of propofol is currently considered as low (Stockholm County Council 2010). We did not consider substituting IAA with TIVA techniques as this would require more significant change in anaesthetic practices than would moving to low-flow inhaled anaesthetic techniques and therefore would not be as easily implemented.

As for the recycling of scavenged IAA, although technology exists to allow such a practice, it is not widely available and currently the recycled IAAs have not received regulatory authorisation to be used clinically (Baxter Healthcare 2020).

Generalisability

It is clear that these results may not be possible in all clinical situations, especially in practices where most anaesthetics are already performed using circle systems at low-flow. However, where non-rebreathing systems are routinely used, especially in larger animals, then significant reductions in oxygen and IAA consumption are likely be possible. Even greater reductions in IAA consumption and emissions may be achieved if minimal-flow (0.25 to 0.5l/min) or ultralow-flow (flow equal to metabolic oxygen demand approximately $10\times\text{bodyweight}^{0.75}$) anaesthesia using semi-closed or closed breathing systems is used. However, these techniques are more technically challenging as predicting gas composition within the breathing system becomes harder, changes in gas composition become slower to achieve, older vaporisers may deliver a less accurate concentration of IAA and there needs to be a greater awareness of reservoir bag filling and emptying. Consequently, additional education and training may be required to implement these techniques safely and successfully.

Further research

This audit of clinical anaesthetic practice proposes a practical method to reduce IAA usage. Confirmation that the method is practicable and that these savings are achievable must come from a prospective clinical trial or a full clinical audit. This would entail performing a re-assessment of oxygen and IAA consumption after the implementation of low-flow techniques and comparing the results to the initial audit. Finally, it would be beneficial to monitor IAA and oxygen usage over time to see if the reductions are sustained. This has not yet been performed, as this audit was performed rapidly to highlight the potential for reducing our consumption in a time where there were concerns over the ongoing supply of oxygen. Further studies are planned as part of a larger sustainability drive after the COVID-19 situation has stabilised.

To optimise the success of such an intervention additional training on low-flow anaesthesia for staff involved with anaesthetics could be performed and ongoing support should be offered. In addition to ensure availability, an adequate supply of circle and mini-lack or Humphrey ADE breathing systems would need to be purchased alongside a range of reservoir bag sizes, low dead space adapters and narrow smooth bore tubing for smaller patients (Robertson *et al.* 2018).

CONCLUSIONS

IAA emissions contribute to the environmental impact of veterinary anaesthesia and surgery. Although, staff commutes, product manufacturing and procurement, pharmaceuticals, single use plastics, packaging, lighting, heating and other electrical equipment must also be considered (Sulbaek Andersen *et al.* 2010), reducing our carbon footprint through lowering fresh gas flows is readily achievable using simple, safe and well-established techniques. Adopting low-flow anaesthetic techniques has multiple beneficial effects beyond sustainability, suggesting this is an area we should all invest in if we have not already done so.

Conflict of interest

None of the authors of this article has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of the paper.

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