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Reducing the oxygen concentration of gases delivered from anaesthetic machines unadapted for medical air

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Abstract

High fractional concentrations of inspired oxygen (FiO₂) delivered over prolonged periods produce characteristic histological changes in the lungs and airway of exposed animals. Modern medical anaesthetic machines are adapted to deliver medical air (FiO₂=0.21) for the purpose of reducing FiO₂; anaesthetic machines designed for the veterinary market have not been so adapted. Two inexpensive modifications that allow medical air to be added to the gas flow from veterinary anaesthetic machines are described. The advantages and disadvantages of each modification are discussed.

HIGH oxygen (O₂) concentrations are toxic to dogs (Cimons and others 1966, Clarke and others 1973), cats (Lambertsen and others 1953) and laboratory animal species (Frank and others 1978), including pigs (Yam and Roberts 1980), when delivered over prolonged periods (Smith 1899) or under hyperbaric conditions. They also increase the risk of combustion or explosion during surgery involving high-energy devices (Wolf and others 2004). Oxygen toxicity, which may be fatal, is characterised by adverse neurological signs, for example, seizures and pulmonary signs (atalectasis, pulmonary capillary congestion, interstitial oedema, haemorrhage) that appears to be dependent on age and species. Younger animals have a variable response to high inspired fractional O₂ concentrations (FiO₂): precocial neonates such as guinea pigs respond in a similar fashion to adults, but rat, mouse and rabbit neonates appear to be resistant (Frank and others 1978); the same is true for piglets (Yam and Roberts 1980). However, although they survive hyperoxic environments, altricial neonates show abnormal alveolarisation and pulmonary vascular development (Frank 1991). These factors may be important in prolonged administration of high O₂ concentrations to companion animals in the intensive care setting; laboratory animal studies of lung structure or function; prolonged surgical or experimental procedures involving anaesthesia, where O₂-induced lung damage may increase morbidity, and extended

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pharmacological studies involving aerosolised medications (Sood and others 2008). Protective strategies for hyperoxic situations at least in rats include pre-exposure to high FiO_2 , treatment with bacterial endotoxin or antioxidant enzymes or rest periods in lower oxygen environments (Frank 1991).

Concentrated O_2 gas mixtures should also be avoided when high-energy surgical tools, for example, lasers, are used because they increase the risk of combustion and operating room fires. The ignition time of endotracheal tubes, surgical drapes and towels shortens with increased ambient oxygen concentrations (Wolf and Simpson 1987, Wolf and others 2004).

Many modern medical anaesthetic machines have the capacity to deliver medical air ($\text{FiO}_2=0.21$) for the purpose of reducing the FiO_2 of the delivered gas mixture. Most also have the facility to deliver nitrous oxide (N_2O). Many devices produced for the veterinary market are unable to deliver medical air but are adapted to supply O_2 and N_2O . The O_2 concentration delivered from such devices may be reduced by incorporating 50 to 80 per cent N_2O in the fresh gas stream. However, N_2O is not without effect. It inactivates vitamin B12, a coenzyme of methionine synthetase, and so is central in DNA, RNA, catecholamine and myelin synthesis (Deacon and others 1980, Xue and others 1986). Consequently, N_2O can lead to neurotoxicity, dyshaemopoiesis and an increased incidence of myocardial infarction in susceptible individuals (O'Sullivan and others 1981, Weir and others 1988, Suzuki and others 1990, Badner and others 2000). During anaesthesia, N_2O increases cerebral blood flow and volume (Field and others 1993), enhances myocardial sensitivity to epinephrine-induced arrhythmias after prolonged administration (Leslie and others 2011) and increases pressure and/or volume in air-filled spaces (Akca and others 2004). It may also modify the inflammatory response (Lehmberg and others 2008). In human beings, the use of N_2O increases the incidence of postoperative nausea and vomiting (Fernández-Guisasola and others 2010). In the operating room, waste N_2O is associated with a poorly characterised health risk while atmospheric N_2O is a greenhouse gas (Ryan and Nielsen 2010). When these effects are undesirable, inert gases, for example, nitrogen (N_2), may be used to lower FiO_2 . However, the least expensive source of N_2 is medical air. Faced with the challenge of anaesthetizing and ventilating the lungs of Gottingen minipigs (PPL 60-3757) for periods of up to 72 hours using an anaesthetic machine (Burton's Medical Equipment; Marden) that delivered O_2 and N_2O , but not air, the authors devised two inexpensive modifications that allowed the inclusion of medical air into the anaesthetic gas stream so that an FiO_2 of 0.5 could be delivered. The advantages and disadvantages of both modifications are described. These modifications may prove suitable in other circumstances in which the N_2O -free control of FiO_2 is desired.

Modification 1

A medical air regulator-pressure gauge-flowmeter assembly (Model GASSO4; MEC Medical) with bullnose connector and barbed tapered outlet (A; Fig 1) was attached to a G-sized medical air cylinder (B; Fig 1). Air leaving the outlet passed down a 2.5 m length of Portex translucent PVC thick-walled tubing (Portex 800/012/425/800 7.00 mm ID; 10.5 mm OD) (Smith Medical International) to one limb (L1) of a barbed tapered 'Y' connector (C; Fig 1; Polycarbonate Y connector 60126 [3/8 inch diameter ports]; Qosina). The second

limb (L2; Fig 1) of this connector was attached to the common gas outlet (D; Fig 1) of the anaesthetic machine using 0.3 m of the same hose connected to a 22 mm tapered female catheter mount. The third limb (L3; Fig 1) was connected to a 2.7 m length of hose terminating on the tapered fresh gas inlet of the mechanical ventilator (Blease Medical Manley MP3; Blease Medical Equipment).

By delivering medical air downstream from the common gas outlet, this modification diluted the O_2 and the fractional concentration of inhalation anaesthetic agent (FiIAA) delivered from the anaesthetic machine. Consequently, the vaporiser (E; Fig 1) setting had to be considerably greater than that normally used and in proportion to the medical air flow. The FiO_2 resulting from different O_2 and air mixtures can be calculated using the following equation:

$$FiO_2 = \left(\frac{(VO_2 + (0.21 \times V_{air}))}{(VO_2 + V_{air})} \right)$$

where VO_2 and V_{air} are the flows (in litres minute⁻¹) of O_2 and air, respectively.

This equation reveals that producing a gas mixture with an FiO_2 of 0.5 requires air: O_2 flow ratios of 1.7:1.0. When these ratios are maintained, the effect of medical air dilution on delivered anaesthetic concentration can be calculated by multiplying the vaporiser setting (in per cent) by 0.37. For example, the anaesthetic concentration delivered when the vaporiser is set at 4 per cent is (4×0.37) 1.48 per cent. Alternatively, to deliver a specific FiIAA, the vaporiser setting is found by dividing the desired concentration by 0.37, for example, when a 2 per cent anaesthetic concentration is required the vaporiser is set at 5.4 per cent $(2/0.37)$. When FiO_2 values other than 0.5 are required, that is, when the air: O_2 flow ratio is not 1.7:1.0, other calculations are needed. The concentration of inhalant anaesthetic delivered as a function of vaporiser setting (S_v [per cent]) and the flows of O_2 and air is given below:

$$FiIAA = \left(\frac{\left(\frac{S_v}{100} \right) \times VO_2}{(VO_2 + V_{air})} \right) \times 100$$

The vaporiser setting (S_v) required to produce a specific FiIAA is as follows:

$$S_v = \left(\frac{(VO_2 + V_{air})}{VO_2} \times FiIAA \right)$$

The use of end-tidal anaesthetic agent monitors displaying inspired and expired (Fe') concentrations of inhalation anaesthetic agents such as the Datex Engstrom Compact AS/3 (GE Healthcare) obviates the need for these calculations. It also supports the presumption that the subject is anaesthetised. When the end-tidal anaesthetic concentration (Fe'_{IAA}) exceeds the value of the minimum alveolar concentration (MAC) for the anaesthetic used in the target species, then by definition, there is less than a 50 per cent probability that the animal will respond to noxious stimuli. End-tidal concentrations 5 to 40 per cent greater than

MAC approximate the AD_{95} value for the agent, that is, the concentration ensuring that 95 per cent of recipients are unconscious (de Jong and Eger 1973). The assurance provided by end-tidal anaesthetic monitoring is particularly important with modification 1 because differences between calculated and delivered anaesthetic concentrations may also arise from vaporiser and flowmeter inaccuracies.

When modification 1 is used to deliver gases to mechanical ventilators classified as minute volume dividers, such as the Manley MP3, increasing the medical air flow will in addition to reducing FiO_2 , increase the minute ventilation. This, in turn, will reduce the end-tidal carbon dioxide (CO_2) concentration. The ensuing respiratory alkalosis will cause undesirable cardiovascular and electrolyte effects. For example, sustained hypocapnia and alkalaemia cause systemic hypotension without influencing hypoxic pulmonary vasoconstriction in anaesthetised pigs (Jundi and others 2000). Conversely, when $PaCO_2$ falls below 3.3 kPa (25 mmHg), cerebral vasoconstriction and a reduction in cerebral blood flow result, causing cerebral hypoxia, altered mental status and seizures (Muizelaar and others 1991, Unterberg and others 1997, Shangraw and Jahoor 2000). Acute alkalaemia increases the affinity of haemoglobin for oxygen, resulting in decreased tissue oxygen release and a 'left-shift' of the oxygen-haemoglobin dissociation curve. It also promotes hypokalaemia, which occurs as potassium moves into the cell to maintain membrane polarity in the face of falling extracellular H^+ . Hypokalaemia is manifested as neuromuscular weakness, cardiac arrhythmias, polyuria and increased ammonia production. Maintaining constant $Fe'CO_2$, Fe'_{IAA} and FiO_2 values was not straightforward using modification 1 because it was necessary to manipulate both O_2 and air flowmeters, as well as the vaporiser. Furthermore, altering only one of the flowmeters affected all three variables simultaneously.

Modification 2

This modification introduces medical air upstream of the vaporiser and so changing VO_2 relative to V_{air} alters FiO_2 but has no effect upon vaporiser setting and Fi_{IAA} . Using a 2.5 m length of the low-pressure hose described earlier, the medical air leaving the same outlet of the medical air regulator (A; Fig 2) is connected to the 8.5 mm tapered nozzle of a 15 mm Anaesthetic Endotracheal Connector (Portex; Smiths Medical International). The 15 mm end of this connector is then seated firmly into a 15 mm hole pre-drilled into the body of an empty N_2O 'E' cylinder, approximately 10 cm below the shoulder (F; Fig 2). When the modified N_2O cylinder is placed in the hanger yoke of the anaesthetic machine and the N_2O flowmeter (C; Fig 2) opened fully, the flow of air into the medical gas stream is thereafter altered by manipulating the air flowmeter (G; Fig 2). Because the N_2O flowmeter is not calibrated for use with air, the effect of changing flows on FiO_2 cannot be easily calculated. This problem is simply avoided by measuring the FiO_2 at the distal end of the breathing system using an anaesthetic monitor, such as the Datex Engstrom Compact AS/3, equipped with modules measuring inspired (and expired) O_2 on a breath-for-breath basis and with a response time measured in seconds.

Modification 2 only works when the outlet pressure from the medical air regulator exceeds that of the N_2O pressure regulator on the anaesthetic machine. With the equipment described here, the maximum outlet pressure (MOP) of the medical air regulator was 420 kPa while

the N₂O regulator had an MOP of 400 kPa. When the specifications of available equipment do not allow this pressure differential to be achieved, the standard medical air regulator may be replaced by either medical air regulators that have an MOP of 700 kPa and are designed to drive surgical equipment, for example, Medical Air Regulator 7 bar MA7/Schrader (Veterinary Instrumentation), or two-stage regulators permitting outlet pressures to be adjusted between 0 and 1000 kPa (Multistage regulator 6047; Therapy Equipment). (Such devices have female Schrader outlets so a modified pipeline with a proximal male Schrader probe and a terminal attachment accommodating the 8.5 mm tapered nozzle of a 15 mm endotracheal tube connector must be used.) Alternatively, an anaesthetic machine capable of delivering N₂O from both pipelines and cylinder can be used. Such machines preferentially allow pipelined N₂O to flow when both sources are open and achieve this by regulating the cylinder MOP to 350 kPa.

Urone and Ross (1979) described a flow-dependent pressure difference of 0.13 to 2.7 kPa across rotameters, indicating that the air flowmeter (G; Fig 2) may have lowered the outlet pressure. This is potentially undesirable because when the outflow pressure from the N₂O regulator falls below the MOP of 400 kPa, the air flow through the modified cylinder will be affected by downstream pressure fluctuations caused, for example, by mechanical ventilators. Changes in airflow will cause corresponding changes in the FiO₂. Problems resulting from excessive resistance across the air flowmeter may be circumvented by fully opening the air flowmeter control knob and using the N₂O flowmeter to control air flow or by using an air regulator that does not incorporate a flowmeter.

Drilling a hole in an N₂O cylinder is not dangerous providing the cylinder is fully emptied. This can be assured by opening the pillar valve on a near-empty cylinder in an open space and closing it when gas flow becomes undetectable. The use of the modified cylinder on anaesthetic machines with the capacity to hold two 'E'-sized cylinders is also without risk providing the check valve on the hanger yoke in which the adapted cylinder sits is working effectively. Check valve failure is readily recognised by removing the adapted cylinder, opening the pillar valve on a full N₂O cylinder sited in the other yoke and detecting N₂O flow from the inlet port of the empty yoke. Check valve failure is undesirable because it may curtail airflow when modification 2 is used. Furthermore, if the anaesthetic machine is used normally with the adapted N₂O cylinder in situ, a defective check valve will allow the flow of N₂O, and possibly O₂, via the drilled hole, leading to unnecessary gas wastage and environmental contamination. For these reasons, the modified N₂O cylinder should be rendered distinguishable from unadapted (French-blue) cylinders, for example, by painting it another colour and limiting its availability to personnel who are fully aware of its function and the consequences of its misuse. Although the aforementioned measures will minimise risk when modification 2 is attempted, prior consultation with representatives of the local or institutional Health and Safety Executive may prevent unnecessary concern in those less conversant with anaesthetic machine function and the physics of compressed gases.

The decision to use either modification should consider the ease and cost of machine alteration, and their relative ease of use. Modification 1 was more easily and less expensively constructed than modification 2 but controlling FiO₂, Fe'AA and Fe'CO₂ was less straightforward when used in the circumstances described. These variables were more

readily controlled with modification 2, although this involves the increased cost of irreversibly modifying an N₂O cylinder, for which the gas company may require compensation. The costs of constructing modification 2 is also increased if a second medical air regulator is necessary.

These considerations should be weighed against two hitherto unmentioned options: purchase of a new or re-conditioned anaesthetic machine capable of delivering medical air, or replacement of the flowmeter block on an existing machine with one that incorporates medical air. The latter requires the means of delivering medical air at regulated pressures into the flowmeter tube, that is, a medical air regulator. In terms of cost, this option would only compare favourably with modification 2 if a flowmeter block incorporating air could be purchased for less than the price of acquiring and drilling an 'E'-sized N₂O cylinder.

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Fig 1. Medical air enters the gas stream downstream from the vaporiser, and thereby dilutes both oxygen and anaesthetic concentrations in delivered gas

Fig 2. Medical air enters the gas stream above the vaporiser, and thereby reduces oxygen, but not anaesthetic concentrations in delivered gas