



Figure 10.5 Volumetric or constant infusion pump. Devices may warn of the presence of air or occlusion of the infusion line.



Figure 10.6 Syringe driver (syringe pump). Many types of electrically driven syringe drivers are available. Some must be used with a specified size of syringe, others can be used with a variety of syringe sizes.

barrel of the syringe is stationary and the unit controls the rate of plunger travel to ensure an accurate volume delivery.

Although many infusion pumps have audible alarms that indicate line occlusion, infusion into perivascular tissues may not achieve a high enough pressure to trigger the occlusion alarm. Thus, the site of catheter placement

must be regularly checked to confirm that fluid is being delivered intravenously and not subcutaneously or into surrounding bandage or drapes.

The infusion pump rate may be changed manually to adjust administration of anaesthetic agents. A target controlled infusion pump (TCI) is available for administration of propofol where the anaesthetist sets a target blood or effect-site concentration and the computerized infusion device makes the necessary changes to the infusion rate (Chapter 1). This device is expensive and the benefits of TCI over manual control of propofol administration have not yet been confirmed (Leslie et al., 2008). Nonetheless, protocols are being developed for use of this modality in veterinary patients.

ADMINISTRATION OF INHALATION AGENTS

The anaesthesia machine can be complex or simple in appearance (Fig. 10.7). The essential components are the same in all machines: the anaesthesia workstation and a patient delivery circuit through which oxygen (O₂) and anaesthetic gas are delivered to the patient via a mask or tracheal tube.

Anaesthesia workstation

The anaesthesia workstation comprises an O₂ source, a pressure regulator (reducing valve), a flowmeter, and a vaporizer(s). In addition, a pressure gauge measures

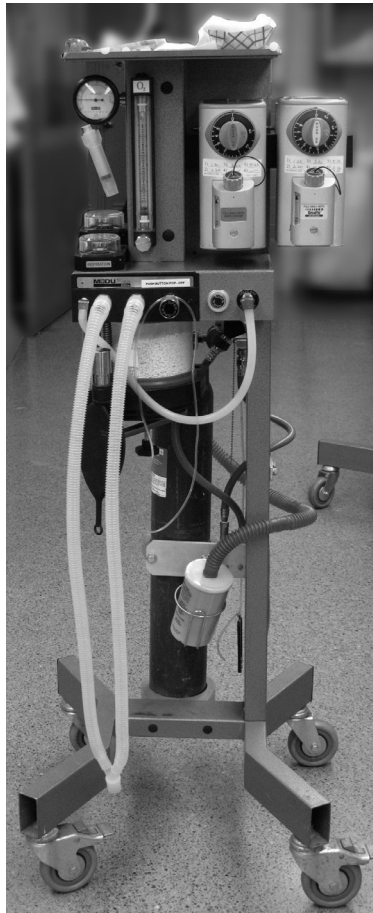


Figure 10.7 Anaesthesia machine for small animals.

pressure at the O₂ source, and an emergency 'flush' valve will deliver O₂ directly from the outlet of the regulator to the patient breathing circuit (Fig. 10.8).

Gases and cylinders

There are many different sizes of cylinders (also known as tanks) for different gases. Each cylinder is coded by a letter of the alphabet, and the type of gas by the colour of the cylinder (Table 10.1), although availability of cylinder sizes differs between countries and colour coding of the cylinders is not universal (see later). A new standard governing the colour coding of transportable gas cylinders is in transition in Europe. Designed to improve safety standards, the cylinder shoulders (the curved part at the top of the cylinder) are painted to warn of potential hazards: bright green is an inert gas, light blue is an oxidizing gas, yellow is a toxic gas, red is flammable, and white is oxygen. The product label must always be checked to identify the cylinder contents and the medical gas cylinders have distinctive colouring.

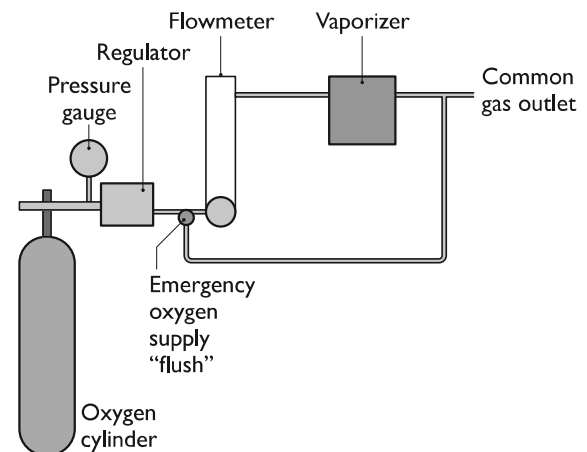


Figure 10.8 Components of an anaesthesia workstation.

Table 10.1 Characteristics of medical oxygen cylinders

Cylinder code	E ^a	E ^b	F ^a	G ^a	H ^b
Contents (L)	680	625	1360	3400	7100
Approximate dimensions mm	865 × 102	660 × 108	930 × 140	1320 × 178	1295 × 235
inch	34 × 4	26 × 4.25	36.6 × 5.5	52 × 7	51 × 9.25
Valve outlet connection	Pin-index	Pin-index	Bullnose	Bullnose	Bullnose

^awww.bocmedical.co.uk; ^bAirgas South, Inc., Georgia, USA

Small cylinders are commonly attached to small animal anaesthesia workstations whereas large cylinders must be secured by chains to the wall, supported in a portable cradle, or placed in a room distant from the patient procedures. The cylinder outlets are of several designs but two, the pin-index and bullnose, are commonly used in veterinary medicine. Cylinders with the pin-index system have holes in the head of the cylinder with an arrangement that is specific to each gas. Pins on the yoke that includes the reducing valve and outlet attachment must exactly match the pin-index arrangement on the cylinder, thus making it impossible to connect an incorrect cylinder. The bullnose connections screw into place, are tightened with a wrench, and do not require a sealing washer. The DISS (diameter index safety system) system employs different diameter connections and different screw threads.

Oxygen

Medical grade oxygen cylinders are colour-coded white in Europe and Canada and green in the USA. The cylinders contain compressed oxygen to a pressure of 2000–2200 psi (pounds per square inch) (USA) or 137 bar (UK) when full. Oxygen in the cylinder is in gaseous phase and the cylinder pressure decreases linearly as oxygen is used. Consequently, a half-full cylinder has a pressure of half the full pressure. Observation of the pressure gauge on the cylinder and knowledge of the cylinder capacity permits an easy calculation of the current contents. Veterinary hospitals with high O₂ usage may have a series of several large O₂ (or nitrous oxide) cylinders that are attached to a manifold and automatically switch from one cylinder to another cylinder as the contents are depleted, or from one series (bank) of cylinders to another.

Liquid oxygen

Bulk oxygen supply in the form of a cylinder of liquid oxygen is often chosen by large hospitals. Liquid oxygen is stored in a cryogenic cylinder that is an insulated, vacuum-jacketed, pressure container equipped with pressure-relief valves and rupture discs to protect the cylinder from increased pressure. The capacity of the cylinder is between 80 and 450 L of liquid oxygen at a pressure of 350 psi and, at 20°C (68°F), the expansion ratio, liquid to gas, is 1 to 860. Strict adherence to safety protocols is essential to avoid personal injury when handling the storage cylinder.

Oxygen generators

Oxygen generators that produce a continuous supply of medical grade 93% O₂ are available for veterinary practice. Convenience, safety, and decreased cost per litre are suggested reasons for using a generator, but it is essential to be certain that O₂ can be generated at a sufficient rate for an emergency situation. Oxygen generators are available in the USA that can generate sufficient O₂ for those

practices that have multiple anaesthesia machines and utilize oxygen cages, mechanical ventilators, or offer hyperbaric chamber O₂ therapy.

Nitrous oxide

Nitrous oxide (N₂O) is available in cylinders that are colour-coded blue or, in Europe, with a dark blue shoulder and white body. During the filling process, N₂O is compressed to a liquid so that a full cylinder is approximately one-third liquid and two-thirds gas and exerts a pressure of approximately 760 psi (USA) or 44 bar (UK). As N₂O is used during anaesthesia, liquid is vaporized to replace the lost gas and pressure is maintained constant. Use of a high flow of N₂O may be accompanied by formation of ice crystals on the outside of the cylinder and a slight fall in cylinder pressure; when the cylinder rewarms to room temperature, the cylinder pressure returns to 760 psi or 44 bar if there is any liquid remaining. Consequently, the pressure gauge cannot be used to determine the volume of contents, as all the liquid is not vaporized until the cylinder is approximately 80% used, at which point the pressure reading decreases. Nitrous oxide is also available in different sizes of cylinders.

Air

Compressed medical grade air containing 21% oxygen is available in cylinders for use blended with oxygen for long-term ventilation of dogs and cats in the Intensive Care Unit or for inhalation anaesthesia. In Europe, the colour code of medical grade air is a white and black shoulder with a white body.

Carbon dioxide

Carbon dioxide (CO₂) is available in cylinders colour-coded grey or a grey shoulder with a white body. Currently, CO₂ is more commonly used in veterinary practice independently of the anaesthesia machine to produce pneumoperitoneum during laparoscopy.

Helium–Oxygen

Helium–oxygen (Heliox) 65:35, 70:30, or 80:20 mixtures are available in cylinders for special anaesthesia circumstances, such as anaesthesia or ventilation of people with respiratory distress from airway obstruction where turbulence of airflow in the trachea or bronchi produces resistance to breathing. The density of helium is lower than oxygen and the lighter helium–oxygen mixture tends to maintain laminar flow in the airways, increase flow rate, and decrease work of breathing. The improved airflow in and out of the lungs may support improved blood gases. Use of helium in anaesthesia is not widespread as although there are published case reports in human literature supporting beneficial effects of helium use, studies in larger groups of patients are not conclusive (Harris & Barnes,

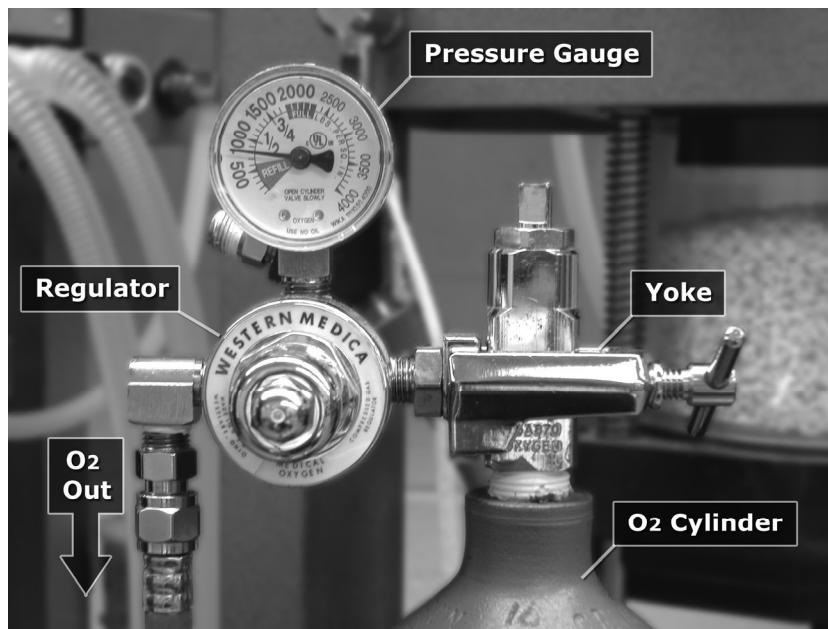


Figure 10.9 A yoke connects an oxygen cylinder to the regulator.

2008; Maggiore et al., 2010). The pressure in a full cylinder is 2000 psi (USA) or 137 bar (UK).

Pressure gauges

Cylinders are connected to pressure gauges that register the pressure of gas within the cylinder from which the anaesthetist may be able to determine the volume of cylinder contents (Fig. 10.9). Pipeline pressure gauges must also be installed close to the locations of use when the gas supply cylinders are situated at a distance.

Regulators

Delivery of pressure as high as in the O₂ cylinder directly to the patient will cause lung damage and, therefore, a regulator (also known as a reducing valve) is necessary to decrease the pressure to a safer workable pressure. The regulator decreases the pressure to 50 psi (4 bar, 350 kPa) and maintains the outlet pressure constant for flows up to 15 L/min. Further, the outlet pressure is maintained as the pressure decreases inside the cylinder. The regulator attachment (yoke) that is placed around a pin-index cylinder head (see Fig. 10.9) or into the outlet of larger cylinders is designed to fit only a cylinder of a specific gas. Where large O₂ cylinders are situated away from the operating room, regulators, similar to those on the simple workstation, reduce the pressure to a working level. Gas is then transported from the remote site through pipes to the hospital rooms where they exit the walls or ceilings. Safety features

to prevent mixing gas supplies are in the form of different sized screw threads for attachment of hoses on the anaesthesia machines or by quick-connect couplings with different configurations. A pressure drop along the pipes generally occurs, consequently, the origin outlet pressure must be adjusted to maintain the pipeline outlet pressure at slightly higher than the workstation regulator outlet pressure. Some large animal mechanical ventilators are unable to function properly if the O₂ pressure decreases.

Flowmeters

Gas flows to the patient breathing circuit are controlled by flowmeters. These are calibrated for each gas in mL/min or L/min as the density and viscosity of each gas determines rate of flow (Fig. 10.10). The calibrations range from 10 mL/min to 10 L/min for small animals and up to 10 or 15 L/min for large animals. The rotameter type of flowmeter consists of a glass tube inside which a rotating bobbin is free to move up and down, allowing gas to flow around it (Fig. 10.11). The tube is tapered with the diameter of the tube gradually increasing from the bottom to the top so that the annular space between the tube and rotameter (orifice) becomes wider as the rotameter rises in the tube, allowing the flow of gas to increase. The rotameter has an upper rim that is of a diameter slightly greater than that of the body, and in which specially shaped channels are cut. The gas flowing through the channels causes the rotameter to spin with the result that it rides on a cushion of gas thereby eliminating errors due to friction

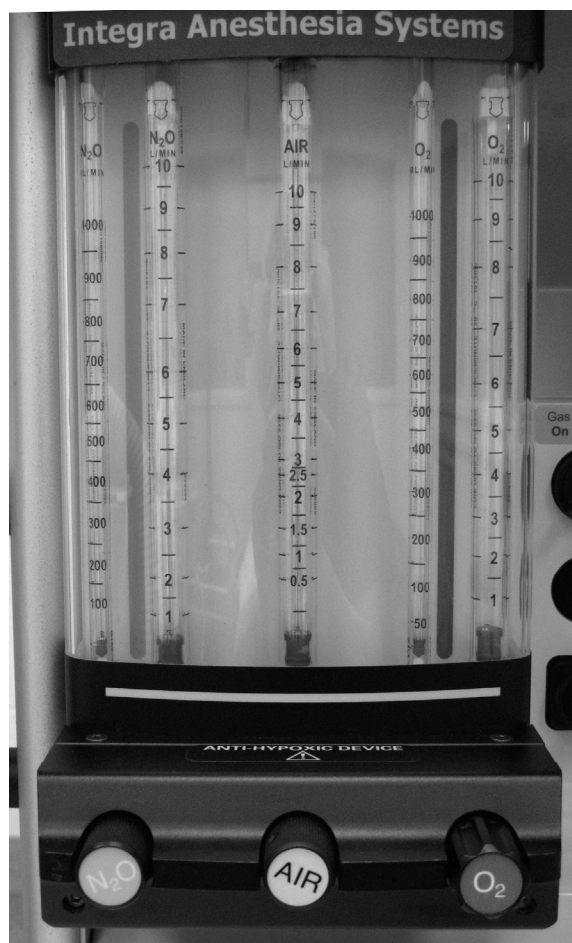


Figure 10.10 Oxygen and nitrous oxide flowmeters each have two tubes on this anaesthesia machine, one is expanded flow 0–1 L/min for accuracy and the other 1–10 L/min. Gas flow is read from the top of the rotameter. The air flowmeter is a single tube.

between the tube and the bobbin. Flow is read accurately from the top of the rotameter against a scale etched on the outside of the glass tube. Flow is accurate ($\pm 2\%$) for the calibrated gas if the flowmeter (anaesthesia machine) is absolutely upright.

Ball flowmeters, like the rotameter, are also tapered and are, therefore, variable orifice meters. Flow rate is read from the middle of a ball when there is only one, or when there are two balls, from the point of contact between the two balls.

Vaporizers

Vaporizers for volatile liquid anaesthetic agents consist of a chamber through which O_2 flows and carries anaesthetic

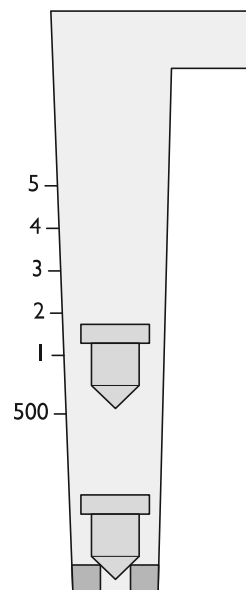


Figure 10.11 Schematic design of a rotameter flowmeter.

molecules out to the patient. In the early days of anaesthesia, vaporizers were simple and subject to changes in output according to the gas flow, temperature of the liquid, surface area in contact with O_2 , and pressure changes generated by artificial ventilation. Simple vaporizers are used today in specific circuits that involve the patient breathing through them (draw-over) such as the Komesaroff or Stephens machines. More commonly, vaporizers have been designed to compensate for extraneous factors (precision vaporizers) and accurately deliver the dialled concentration (Fig. 10.12). The surface area is standardized by use of a wick inside the vaporizer and temperature changes are compensated for by mechanisms that alter either the inflow or outflow of O_2 through the vaporizing chamber. As vaporizers are designed for use in human anaesthesia, the accuracy of the vaporizer is guaranteed only over a very limited temperature range close to 20°C (68°F). The actual specification depends on the make and model but many vaporizers may be unable to compensate for low operating room temperatures of around 17°C (63°F) resulting in low anaesthetic output and inadequate anaesthetic depth. Even more dangerous is the potential for higher than expected concentrations when working at high ambient temperatures. The anaesthetic output decreased progressively during high O_2 flow rates (10 L/min) and to a greater extent from some sevoflurane vaporizers (exceeding 20% of the dial setting) than from isoflurane vaporizers (Ambrisko & Klide, 2011). The output concentration from sevoflurane vaporizers that were only partially filled was similar to that when they were full. Supplying heat by wrapping the vaporizer in a warm cloth



Figure 10.12 Precision vaporizers for isoflurane and sevoflurane. The dials indicate % output of each vaporizer. The handwritten labels below the dials note the actual % delivered at each setting at the time of the last scheduled machine check.

will increase anaesthetic output but can result in an excessive depth of anaesthesia. A check valve on the outlet side of the vaporizer is used to prevent back-pressure from the patient circuit during artificial ventilation altering vaporization and output concentration. The output from precision vaporizers must be measured for accuracy at regular intervals which, in some countries, may be a specific time interval.

The maximum concentration of an anaesthetic agent at a given temperature depends on the vapour pressure of the agent. Isoflurane and sevoflurane have sufficiently different vapour pressures that they must be used in specifically manufactured vaporizers. The vapour pressure of isoflurane is similar to that of halothane, an older agent since discontinued in many countries, and halothane vaporizers can be serviced professionally, cleaned and recalibrated for use with isoflurane.

The fluid level in the vaporizer can be checked through a clear window on the side of the vaporizer. Filling of vaporizers is invariably accompanied by loss of anaesthetic vapour into the room. An inexpensive non-disposable filling spout can be attached to the bottle of

isoflurane or sevoflurane and will minimize spilling. New vaporizers have 'keyed' filling ports where the bottle of anaesthetic agent is attached directly to the vaporizer or by using an adapter that is totally closed.

Desflurane is a colourless liquid below a temperature of 22.8°C. It requires an expensive specialized vaporizer in which the chamber holding the liquid is heated electrically to above boiling point. The vaporizer is a dual gas blender (O₂ and desflurane vapour) with the output from the vaporization chamber pressure regulated to deliver an accurate percentage to the patient circuit. Special care must be taken to follow manufacturer's instructions when filling a desflurane vaporizer as a number of potentially harmful accidents have been reported.

A number of devices, such as the 'Selectatec', are available to enable vaporizers to be easily attached to or removed from the 'back bar' of the workstation, allowing convenient exchange of vaporizers for changing anaesthetic agent, for removal for filling elsewhere, and when a vaporizer has to be sent away for service. Tipping the vaporizer when the dial is not switched off (either when moving the vaporizer or rocking the anaesthesia machine)

may result in a surge of high anaesthetic concentration when the vaporizer is first turned on. To avoid accidental overdose, it is advisable to flush the vaporizer and hoses with oxygen before connecting to a patient.

Simple, low internal resistance, draw-over vaporizers for isoflurane or sevoflurane are situated within the circle delivery circuits of the Komesaroff and Stephens anaesthesia machines. The dials of the vaporizers are not calibrated and simply vary the proportion of gas passing through the vaporizers. The outputs of the vaporizers are largely determined by the magnitude of the patient's ventilation that flows through the circuit.

Oxygen flush valve

This valve is situated between the regulator and the flowmeter. Activation causes a flow of oxygen at a pressure of 55 psi (400 kPa) and 60 L/min to the delivery circuit, by-passing the precision vaporizer(s). The flush valve should never be employed for a non-rebreathing circuit with a 0.5 L bag when an animal is attached because of the high risk of rupturing the lungs. With a small animal circle circuit, depending on the duration of flush and the size of the rebreathing bag, use of the flush valve may not be fatal. Two consequences will occur: pressure within the circle increases and the patient's lungs will be inflated; and secondly, O₂ without anaesthetic agent is delivered and thus the circle anaesthetic concentration will decrease. If the depth of anaesthesia is too light, operating the flush valve to fill the reservoir bag will further lighten anaesthesia.

Common gas outlet

The mixture of gases leaves the workstation at the common gas outlet, to which the patient circuit is attached. The outlet configuration and size may differ between machine manufacturers and countries.

Injection vaporization

Injection of liquid isoflurane, sevoflurane or desflurane into a chamber or anaesthesia circuit by-passes the use of conventional vaporizers (Olson et al., 1993; Boller et al., 2005; Hodgson, 2006). The technique involves calculation of priming and maintenance doses based on the desired anaesthetic concentration, volume of the circuit, and the size of the patient, using equations proposed for closed system anaesthesia (Lowe & Ernst, 1981). Vaporization and uptake of anaesthetic agent by the CO₂ absorbent may alter the final anaesthetic percent, consequently, monitoring of anaesthetic gases during liquid injection technique is recommended. This technique is utilized by the Zeus® workstation (Draeger, UK) that employs computer control of the injection of the inhalation agent. A form of disposable vaporizer using liquid anaesthetic

agent is the Anaesthetic Conserving Device, AnaConDa™, so named because very little agent is used. The AnaConDa is a modified heat and moisture exchanger that is connected to the patient at the endotracheal tube. Liquid sevoflurane is supplied continuously from a syringe driver/pump to the patient side of the device, where it is immediately vaporized and delivered to the lungs on inspiration (Soro et al., 2010; Nishiyama et al., 2012). The sevoflurane infusion rate is altered periodically to adjust the depth of anaesthesia.

Magnetic resonance imaging (MRI) compatible machines

The static magnetic field inside the MRI scanner will exert an attractive force on ferromagnetic objects. The degree of attraction depends on the strength of the magnet, the mass of the object, shielding, and the distance to the magnet but can be of sufficient force to generate a projectile effect with potential damage to the magnet, the patient, and to the anaesthetist. It must be remembered that the magnet is continuously on even when no imaging is occurring. Special non-ferrous anaesthesia machines and monitoring equipment are commercially available and must be used for patients in the MRI scanner. An exception may be made if the anaesthesia machine can be located in an adjacent room and either the breathing circuit has really long tubes or a long tube carries O₂ and anaesthetic gas to an MRI compatible circuit (such as the Humphrey ADE) located near the scanner. Equipment may be designated MR conditional, MR safe, or MR unsafe (Farling et al., 2010). MR conditional applies to equipment that has been demonstrated to pose no known hazards with specified conditions of use in an MR environment. The anaesthetist should be familiar with the manufacturers' instructions related to all equipment used in MRI. Monitors should have visual warning alarms as auditory alarms may not be heard. All personnel remaining in the scanning room should wear ear protection.

Delivery (breathing) systems

A breathing circuit is used to deliver O₂ and anaesthetic gas from the workstation to the patient. The circuit may be designed to allow partial or complete rebreathing of exhaled gases after removal of exhaled CO₂. Recycling of gases allows the O₂ inflow to be decreased, even as low as the volume of O₂ needed to supply only metabolic demand of the patient. Low O₂ flows are economical and rebreathing circuits with low O₂ flow maintain humidity of inspired gases and may help to prevent heat loss in patients (Table 10.2). Circuits that have no rebreathing deliver fresh gases to the patient for each breath. The higher O₂ flow required for these circuits results in wastage of significant amounts of volatile anaesthetic gas and increased expense (Table 10.3). Consequently,

non-rebreathing circuits are primarily used in small patients such as small cats and dogs, rats, rabbits, small birds, and small wildlife, where required O_2 flow rates are low.

Breathing circuits are available made of heavy-duty materials that are intended for long-term use or made of light plastic materials intended for disposable or semi-disposable use. The 'disposable' circuits are lightweight and less likely to drag on the endotracheal tube and cause accidental extubation. The hoses are available in different lengths and may be manufactured with a colour coding, with the fresh gas being delivered via the blue or green tube. Plastic hoses are transparent and the inside can be observed easily when cleaning. Tubing with a smooth intraluminal wall has better flow characteristics than a wall that is corrugated. Heated hoses are also available in dog and cat sizes.

Rebreathing circuits

All partial or complete rebreathing circuits must have a means of absorbing exhaled CO_2 before delivering the gases back to the patient (Fig. 10.13). The absorber canister consists of one or two transparent plastic canisters

filled with granules, short strands, or spheres, of absorbent filled from large containers or airtight foil-lined bags or by insertion of prepackaged disposable cartridges. The granules for an anaesthetic circuit must be of a size that will allow gas to flow through easily but with sufficient surface area exposed to ensure effective absorption. Sometimes efficiency is reduced when the settling of granules forms channels through which the exhaled gases can pass without all CO_2 being removed. Furthermore, some absorbents contain dust that mixes with water formed from the chemical reaction with CO_2 and forms a paste (caking) which may also interfere with absorption by filling spaces between granules. The standard commonly used absorbent is sodalime (such as Sodasorb®) that consists of 80% calcium hydroxide, 2% sodium hydroxide

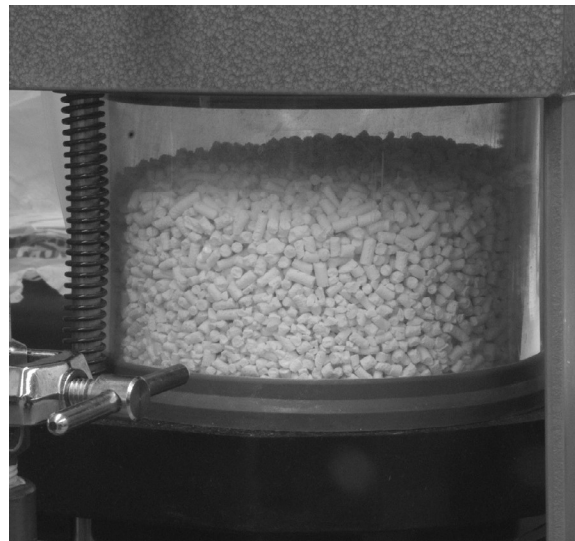


Figure 10.13 A canister containing granules of CO_2 absorbent is an essential component of a rebreathing circuit.

Table 10.2 Rebreathing circuits

Advantages	Disadvantages
Low O_2 inflow 1. decreases volume of waste gases 2. decreases cost 3. retains water vapour and facilitates humidification of inspired gases	Hoses and CO_2 absorbent offer resistance to breathing Deadspace in hoses may be greater than in non-rebreathing circuits Circuit concentration slow to change Inspired concentration may be lower than vaporizer % when low O_2 inflow rates are used

Table 10.3 Non-rebreathing circuits

Advantages	Disadvantages
Minimal resistance to patient's breathing Inspired anaesthetic concentration equals vaporizer setting, facilitating control of depth of anaesthesia Inspired anaesthetic concentration changes within seconds of changing vaporizer % Circuits with small internal volume of connector to endotracheal tube (apparatus deadspace) minimize CO_2 rebreathing No CO_2 absorbent 1. decreases cost 2. no dust 3. no anaesthetic agent breakdown Disposable system can be discarded after bacterial contamination	Inhaled gas is dry and cold, potentiating hypothermia and mucosal desiccation High O_2 flow results in relatively more vaporization of anaesthetic gases and that 1. requires increased pollution management 2. increased cost due to wastage of anaesthetic gas and O_2

(NaOH), <1% potassium hydroxide (KOH), and water. However, carbon dioxide absorbents that contain strong bases (NaOH and KOH) promote the formation of Compound A (2-(fluoromethoxy)-1,1,3,3,3-pentafluoro-1-propene) from sevoflurane and also of carbon monoxide (CO) and other toxic compounds from isoflurane and desflurane (Clarke, 2008). Under a set of specific conditions CO can be formed from sevoflurane. Compound A is nephrotoxic in rats but there have been no reports of damage in our domestic species. An absorbent containing barium hydroxide (Baralyme®) was found to have excessive product breakdown particularly when dessicated (Steffey et al., 1997), and has now been withdrawn. Sodalime breakdown is accelerated by use of dry absorbent and by increasing temperatures. Absorption of CO₂ is an exothermic reaction so that the temperature of sodalime increases and, at high temperatures, high concentrations of CO may be produced. Newer absorbents such as Sodasorb® LF (low flow), Amsorb® Plus, and Loflosorb® are available that are 75–85% or more calcium hydroxide and lack strong bases. A number of published investigations have sought to determine differences in CO and Compound A production from different absorbents and comparison of moist versus dessicated absorbents (Stabernack et al., 2000; Versichelen et al., 2001; Kharasch et al., 2002; Yamakage et al., 2009). Only absorbents without both potassium and sodium hydroxide (e.g. Sodasorb® LF, Amsorb® Plus, LoFloSorb®) do not produce compound A.

Carbon dioxide is absorbed by a series of chemical reactions. First, CO₂ and water form carbonic acid, and then the acid reacts with the hydroxide to form carbonate, water, and heat. A pH indicator, ethyl violet, is added to the absorbent to indicate when the absorbent is exhausted. The indicator is colourless at a high pH but, as CO₂ is absorbed, the pH decreases and the indicator changes to a violet colour, resulting in an absorbent colour change from white to violet. Once the absorbent has been exhausted, as indicated by a change in colour, it is no longer functional. Absence of visible colour change in a circuit without a patient attached is no guarantee that the absorbent is unused because the violet colour may fade shortly after disconnection of a patient due to temporal deactivation and deactivation by fluorescent lights.

Rebreathing circuits must have a bag to act as a reservoir of gas (reservoir bag, rebreathing bag) to supply the next inhalation. Bag sizes vary from 250 mL to 40 L and are chosen to match the size of the patient. The bag should be large enough to accommodate a deep breath. Conversely, excessively large bags (1) increase the volume of the circuit and slow rate of change of anaesthetic agent concentration, and (2) obscure assessment of ventilation as small tidal volumes produce small movement in large bags.

Rebreathing circuits must have a spring-loaded adjustable valve ('pop-off' valve) to prevent pressure rising in the

circuit when the O₂ inflow exceeds the patient's metabolic oxygen requirement. These valves consist of a simple disc-type valve that can be closed by tightening the screw onto the disc. When this screw is not tightened, the valve is designed to remain closed and prevent leakage of gas from the circuit until the circuit pressure increases to 1–2 cmH₂O, at which point it opens, allows excess gas to exit, and the circuit pressure decrease to 0 cmH₂O. The valve can be screwed down when an increase in circuit pressure, generated by squeezing the reservoir bag, is to be maintained for artificial ventilation of the patient's lungs. If the valve is left closed when the O₂ flow exceeds metabolic oxygen requirement the reservoir bag will exceed its normal capacity and the circuit pressure will no longer return to zero between breaths. This is a life-threatening situation as the increase in intrathoracic pressure decreases return of venous blood to the heart and cardiac output and blood pressure will progressively decrease to zero. Pop-off valves may be adjustable pressure limiting (APL) valves that will automatically discharge when pressure exceeds 60 cmH₂O (adult) or 30 cmH₂O (paediatric). This safety mechanism may avoid pulmonary barotrauma should the circuit pressure abruptly increase following activation of the O₂ flush valve but cardiovascular collapse will occur before these pressures are reached when circuit pressure builds slowly with O₂ inflow from the flowmeter. It is recommended that, if adjustable pressure is a feature, the APL valve be manually set to discharge 5 cmH₂O above the inspiratory pressure needed for a normal lung inflation. Another safety mechanism available is a pop-off valve with an alternative method of closing other than screwing it closed. Either the head of the valve or a button on the exit side of the pop-off valve can be temporarily depressed to occlude gas outflow (Fig. 10.14). This feature can be employed when inflating the patient's lungs to test for an endotracheal tube cuff leak, or when sighing the patient, and can be used during manual artificial ventilation. An additional safety device inserted into the circle circuit will provide a high-pressure audible alert. The device may have an adjustable trigger pressure and be battery powered.

Circle circuit

The components of a circle circuit are arranged in a circle (Fig. 10.15) and two unidirectional valves (one-way valves) ensure that the exhaled gas passes through the CO₂ absorber before returning to the patient (Fig. 10.16). Placement of the reservoir bag in relation to O₂ inlet and CO₂ absorber varies between machine models. One concept is that ideally the reservoir bag should be on the inhalation side of the circuit so that there is least resistance to inhalation, and the CO₂ absorber should be on the exhalation side because the granules offer the most resistance to gas flow. The circle circuit usually has corrugated breathing hoses to decrease the risk of occlusion when bent. Most hoses are corrugated on the inside and tend to create turbulent gas flow. Some hoses are corrugated on



Figure 10.14 The anaesthetist is depressing the 'quick-close' button of the pop-off valve with the thumb of one hand while squeezing the reservoir bag to inflate the dog's lungs with the other hand.

the outside and smooth within the lumen and this feature facilitates increased airflow. Hose diameter varies according to the size of the patient: from 5 cm diameter for horses to 15 mm or 22 mm for small animals to 7 mm for animals <2 kg (Fig. 10.17). The volume of gas within the Y-piece connector to the patient constitutes the apparatus deadspace of the circle because it contains exhaled CO_2 that will be breathed in as part of the next inhalation. As the deadspace volume increases in relation to the patient's tidal volume, the greater the impact on PaCO_2 .

The coaxial circle circuit (Universal-F; UniFlo) is designed with the inspiratory hose positioned within the expiratory hose (Fig. 10.18). Advantages are that the two-hoses-in-one is less cumbersome when positioning the animal and, potentially, the inspired gases are warmed by the warm expired gases in the surrounding hose. A disadvantage is the resistance to breathing is increased as the diameters of the tubes are less than those of conventional parallel systems. These circuits should not be used for animals accommodating an endotracheal tube size with an internal diameter that is larger than the internal diameter of the inspiratory hose.

Oxygen inflow to circle circuits should be no lower than the patient's metabolic oxygen demand, approximately 6 mL/kg/minute for anaesthetized dogs and cats and 3 mL/kg/minute for anaesthetized horses and cattle. If the

O_2 flow rate is less than the metabolic O_2 demand of the patient, the reservoir bag will progressively collapse (when O_2 alone is the carrier gas) and when empty, the patient becomes hypoxaemic. A closed system of administration is when O_2 flowing into the circuit exactly equals O_2 used so that there is no excess to leave by the pop-off valve. Note that the pop-off valve does not have to be screwed closed to operate a closed system. A higher flow of O_2 will result in gas leaving through the pop-off valve and this is called a semi-closed system of administration. A semi-closed system of administration can use low, medium or high O_2 flows. Medium and high O_2 flow rates are commonly used early in anaesthesia with precision vaporizers to compensate for the initial high uptake of anaesthetic agent by the patient and the CO_2 absorbent, and dilution by air in the circuit. The vaporizer dial percentage and O_2 flow rate are subsequently decreased for maintenance of anaesthesia. Continued use of high flows increases the amount of liquid anaesthetic agent that is vaporized and the wastage is costly. Low flow rates for small animals are in the range of 10–20 mL/kg/min.

The addition of N_2O automatically requires use of high gas flows because of the risk of the inspired concentration of O_2 decreasing below 30%. Insertion of an oxygen monitor into the inspiratory limb of the circle is recommended for improved safety. Nitrous oxide has low

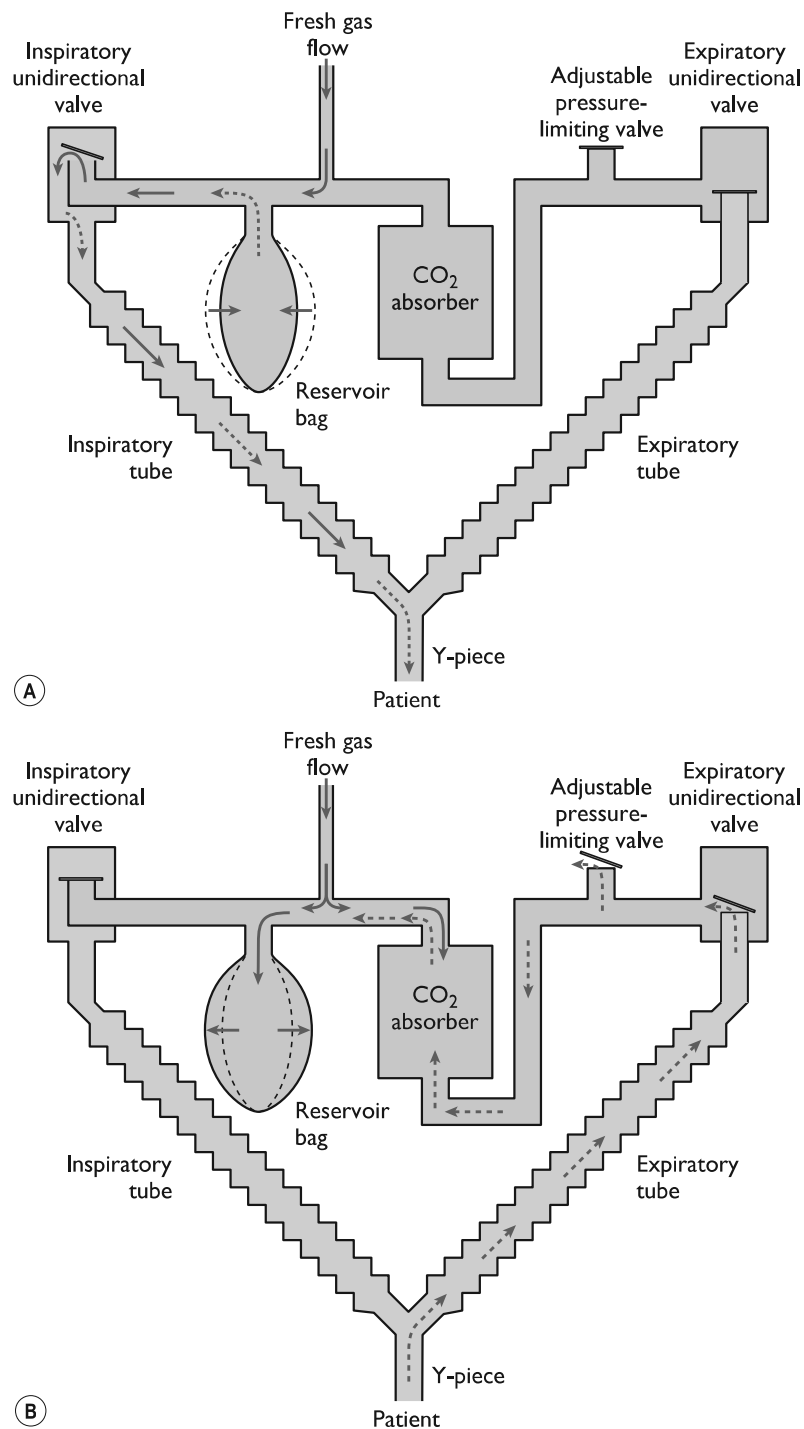


Figure 10.15 (A) Schematic design of a circle rebreathing circuit showing gas movement during spontaneous inhalation. During inhalation, the negative pressure in the inspiratory tubing opens the inspiratory unidirectional valve allowing flow of gas (mixture of fresh gas and exhaled gas with CO₂ removed) from the reservoir bag. FGF = fresh gas flow, APL = adjustable pressure-limiting valve (or pop-off valve), P = patient, → = fresh gas, - - → = exhaled gas. (B) Schematic design of a circle rebreathing circuit showing gas movement during spontaneous exhalation. During early exhalation, the exhaled gas passes through the expiratory tube, through the expiratory unidirectional valve, through the CO₂ absorber, and into the reservoir bag. Fresh gas continues to flow into the reservoir bag. Towards the end of exhalation, the reservoir bag becomes full, and exhaled gas ceases to flow through the absorber, and when the circuit pressure rises above 1–2 cmH₂O pressure, excess gas exits through the APL to the scavenger. FGF = fresh gas flow, APL = adjustable pressure-limiting valve (or pop-off valve), P = patient, → = fresh gas, - - → = exhaled gas.



Figure 10.16 Inspiratory and expiratory one-way valves in a rebreathing circuit direct expired gases through the CO₂ absorber.

solubility and equilibrates with the pulmonary blood within several minutes, at which point uptake slows dramatically. Commonly used mixtures O₂:N₂O are 1:1 or 1:2. Supplying a 40:60 mixture of O₂ and N₂O at low flows results in the bulk of the O₂ being absorbed for metabolic needs with little N₂O absorption. As the minutes pass, the proportions of O₂ and N₂O within the circle change from 40:60 towards an ever decreasing concentration of O₂, even to the point of a hypoxic mixture. The recommended gas flows for a small animal circle circuit are O₂ 30 mL/kg/min with N₂O added to that flow. For an adult horse connected to a large animal circle, 4 L each of O₂ and N₂O generally will maintain 40–50% O₂ concentration in the circle, however, presence of an O₂ monitor within the circle is a safety factor. Circle systems such as the Komesaroff and Stephens machines have vaporizers placed within the circle circuit. With each recycling of gases around the circle, O₂ containing isoflurane by-passes the vaporizer and joins with an increased concentration of

Box 10.3 Is it safe to leave the reservoir bag on a circle circuit full?

Yes, if the pop-off (APL) valve is open.

Explanation: The pop-off valve is designed to remain closed until the reservoir bag is full; it will open at 2 cmH₂O pressure which is too low to cause resistance to the patient's breathing. The reservoir bag will fill any time the flowmeter is set at a value exceeding metabolic oxygen consumption. The circuit pressure gauge can be checked to confirm that the circle pressure is low.

Box 10.4 Is it safe to empty the reservoir bag by squeezing it while dog or cat is connected?

Only if the pressure generated by the squeeze does not exceed pressure normally used to ventilate artificially that size animal and only if duration of squeeze is not more than 2–3 seconds.

Explanation: Squeezing the bag increases the circuit pressure and inflates the patient's lungs. High pressure can rupture alveoli. Increased intrathoracic pressure decreases flow of blood to the heart, followed by decreased stroke volume and arterial pressure.

Maintaining increased intrathoracic pressure for 5–7 seconds decreases blood pressure.

anaesthetic leaving the vaporizer, and so the inspired isoflurane concentration progressively increases with time. Consequently, a low FGF such as 100 mL/min is commonly used because a higher flow of O₂ would dilute the circle isoflurane concentration. Monitoring the patient for depth of anaesthesia is used to assess the need to adjust the vaporizer. These vaporizer-in-circle (VIC) systems are chosen because they are economical to use and produce less waste anaesthetic gases. Isoflurane and sevoflurane can be used in these machines. One investigation found that the Komesaroff machine did not reliably maintain surgical anaesthesia with sevoflurane in dogs (Laredo et al., 2001) but this finding was not confirmed by Straker et al. (2004) who found the system effective and economical in dogs over 10 kg body weight. Disadvantages included an empty vaporizer and exhausted CO₂ absorbent before the surgery was completed. Artificial ventilation of a patient connected to a system with the vaporizer-in-circle can generate dangerously high anaesthetic concentrations. One investigation of controlled ventilation in dogs connected to a Komesaroff machine documented that increased respiratory rates increased circuit anaesthetic concentrations and that vaporizer settings >2.5/4 produced unnecessarily high anaesthetic concentrations

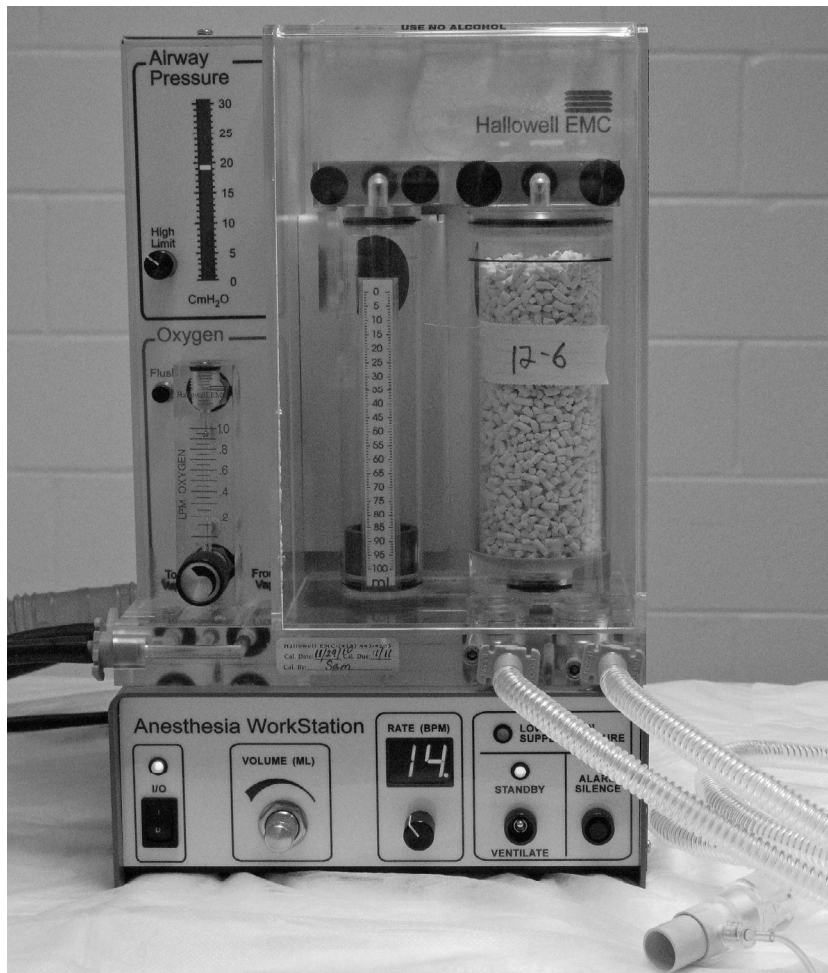


Figure 10.17 Hallowell workstation for animals <2 kg.

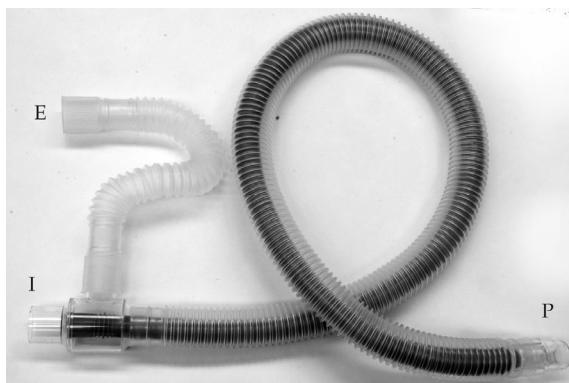


Figure 10.18 Coaxial circle circuit. I = connects to inspiratory valve, E = connects to expiratory valve, P = connects to endotracheal tube. The inner tube is inspiratory.

(Laredo et al., 2009). The transition from induction to maintenance of anaesthesia was made with the vaporizer full-on, then the vaporizer was decreased to 1/4 for isoflurane and 1.5/4 or 2.0/4 for sevoflurane which generally achieved end-tidal anaesthetic concentrations between 1 and 1.2× minimum alveolar concentration (MAC) value. The end-tidal anaesthetic agent concentration measurements also confirmed that deeper anaesthesia was achieved when 14 breaths/min were used compared with 9 breaths/min.

To-and-Fro

In a to-and-fro circuit, the animal's exhaled gases pass through the CO₂ absorbent into a bag and return through the absorbent during inhalation without the use of unidirectional valves (Fig. 10.19). The circuit is cumbersome because the CO₂ absorber is located close to the patient.

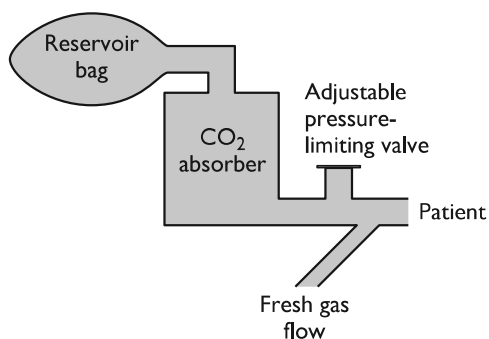


Figure 10.19 To-and-fro rebreathing circuit. FGF = fresh gas flow, APL = adjustable pressure-limiting valve (or pop-off) valve, P = patient.

Inhalation of absorbent dust is more likely to occur with this configuration than in a circle circuit.

Non-rebreathing circuits

Non-rebreathing circuits contain no valves and no CO₂ absorbent to offer resistance to breathing (see Table 10.3). High O₂ flows are used to prevent rebreathing of exhaled CO₂ and provide fresh gas for each breath. A decrease in O₂ flow required to eliminate CO₂ for a given body size can be achieved by rearranging the components of the circuits, thereby increasing feasibility for use in larger animals. Many circuits are available but they are all variations of those originally classified by Mapleson (Fig. 10.20) (Mapleson, 1954).

T-piece

The simplest circuit is the T-piece (Mapleson E) which is commonly used today in its modified form with a reservoir bag attached (Mapleson F, Jackson-Rees) (Fig. 10.21). The T-endotracheal tube adapter can be replaced with an adapter (Norman elbow) that delivers the fresh gas directly to the endotracheal tube and eliminates all circuit deadspace. The constant flow of fresh gas enters close to the endotracheal tube connector and flushes the patient's exhaled gas through a corrugated tube into the reservoir bag and through the exit hole into the waste anaesthetic gas scavenger. The patient inhales fresh gas from the corrugated tube and there is no rebreathing provided that the volume of the tube exceeds one tidal volume of the patient (Fig. 10.22). The fresh gas flow high enough to flush the corrugated tube between breaths must be 2.5 to 3 times the patient's minute volume (MV, breaths per min × tidal volume), or at least 450 mL/kg bodyweight/min. The origin of this FGF calculation has been previously referenced (Hall & Clarke, 1983). The FGF required to prevent CO₂ rebreathing in cats in a more recent investigation was 455 ± 77 mL/kg/min (Holden, 2001). Recent evaluations of respiratory parameters in unsedated young and adult

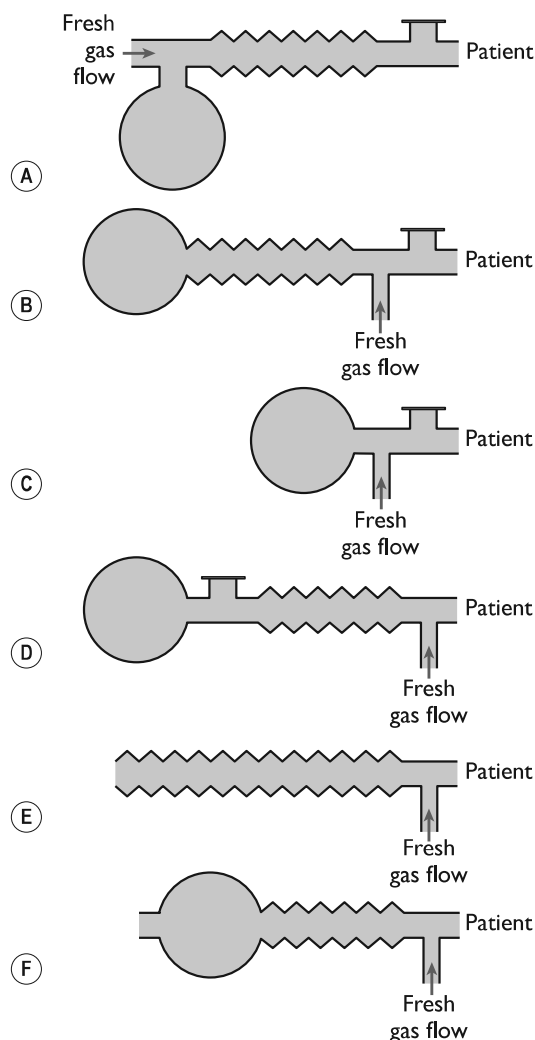


Figure 10.20 The Mapleson classification of patient delivery circuits A to F. FG=fresh gas flow, P=patient.

cats and medium-sized dogs have measured MV as approximately 230 mL/kg/min (Issa & Bitner, 1993; Kirschvink et al., 2006; Fraigne et al., 2008).

The exit hole from the bag into the scavenger may be too small to accommodate O₂ flows higher than 3 L such that pressure builds up in the circuit and interferes with the animal's breathing. Larger animals fair better when attached to a different non-rebreathing circuit that functions with a lower/kg flow rate, such as the Lack circuit, or attached to a paediatric circle circuit.

Bain circuit

The Mapleson D circuit functions similarly to the Mapleson E and F circuits. The Mapleson D incorporates a pop-off valve between the corrugated tube and the reservoir

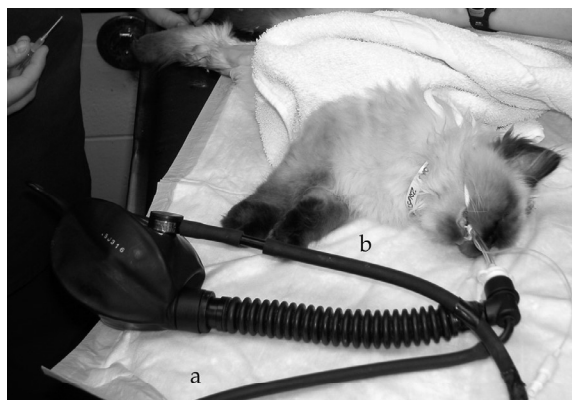


Figure 10.21 A modified T-piece non-rebreathing circuit. Oxygen and anaesthetic agent flow to patient in tube (A) and waste gases leave the circuit in tube (B).

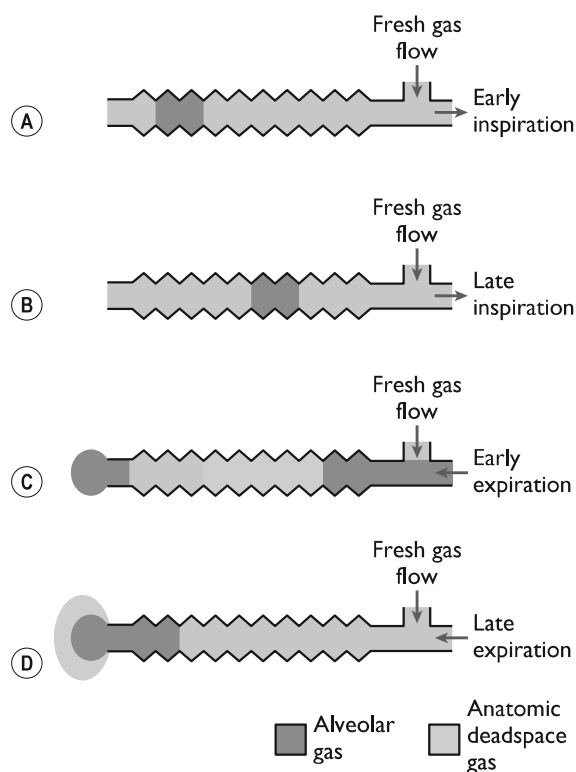


Figure 10.22 Function of the T-piece system in preventing rebreathing when the fresh gas flow exceeds at least twice the patient's minute volume.

bag. The Bain circuit is a modification in which the corrugated tube has been lengthened and the inspiratory and expiratory gases confined to separate tubes (Fig. 10.23). The reservoir bag and pop-off valve remain on the expiratory side of the circuit. The tubes may be parallel

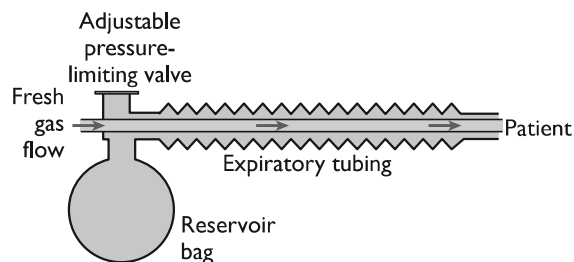


Figure 10.23 Bain circuit (coaxial version) modification of Mapleson D. Note that the bag is on the expiratory limb. The Bain is also available as a parallel system where the inspiratory tubing is a separate, wide-bore corrugated tube. FGF = fresh gas flow, APL = adjustable pressure-limiting valve (or pop-off) valve, P = patient.

(side-by-side) or coaxial, where the inspiratory tube is inside the expiratory tube. The Bain circuit terminates in a block comprising the reservoir bag, the pop-off valve, with or without a pressure gauge, that can be conveniently mounted on the anaesthesia machine. The FGF required to prevent rebreathing has been reported as approximately 260 mL/kg/min (Almubarak et al., 2005). Inspiratory and expiratory resistances are low with this system, but increase with increasing FGF.

Magill and Lack circuits

The Magill circuit (Mapleson A) incorporates a reservoir bag on the inspiratory limb, wide bore corrugated tubing, and a pop-off valve leading to a scavenging system. Rebreathing is prevented by maintaining the FGF slightly in excess of the patient's respiratory minute volume. The animal inhales from the bag and wide bore tubing; the exhaled mixture passes back up the tubing displacing the gas in it back into the bag until it is full. The exhaled gases never reach the bag because the capacity of the tubing is too great and once the bag is distended the increased pressure inside the circuit causes the pop-off valve to open so that the terminal part of expiration (the alveolar gas high in CO₂) passes out of the valve into the scavenger system (Fig. 10.24). During the pause following expiration and before the next inspiration, fresh gas from the workstation pushes the rest of the exhaled gases from the corrugated tube through the pop-off valve.

The Lack circuit is a modification of Mapleson A that has an expiratory tube running from the patient to the pop-off valve (Fig. 10.25). The tubes may be parallel (side-by-side) or coaxial where the expiratory tube runs inside the inspiratory tube (opposite arrangement to the Bain circuit). The FGF required to prevent rebreathing is of the order of 130 mL/kg/min. A smaller version of the parallel form (mini-Lack) is suitable for small patients.

The Maxima circuit is also a modification of Mapleson A with a 15 mm expiratory tube parallel to the 22 mm inspiratory tube and no valve. Evaluation of the circuit

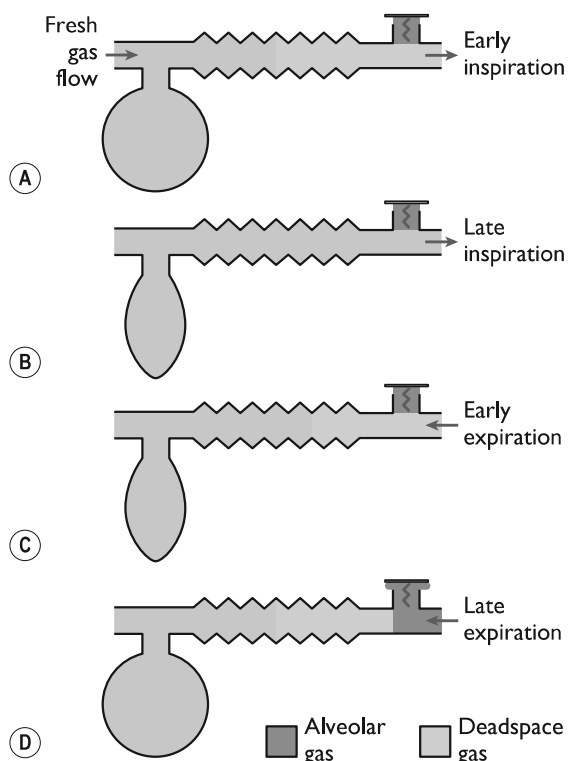


Figure 10.24 Magill circuit (Mapleson A) showing the disposition of fresh gas and exhaled gases (anatomic deadspace and alveolar) during spontaneous breathing.

with anaesthetized adult cats determined that an FGF of 242 mL/kg/min should prevent rebreathing in 95% of cats (Holden, 2001). The author noted that a higher FGF should be used in small cats to ensure accuracy of output of the precision vaporizer.

Hazards of coaxial circuits

In some cases, the internal or external tubing of coaxial circuits is of such a small bore that it imposes excessive resistance to the animals' breathing. In that case, the circuit should not be used when the internal diameter (ID) of the hose is less than the tracheal tube ID size. Also dangerous, the inner tube may become detached from the anaesthesia machine or the patient connector resulting in rebreathing of CO₂. Coaxial systems should be inspected before use and pressure checked.

Humphrey ADE circuit

The Humphrey ADE circuit is so named because it functions as a Mapleson A circuit during spontaneous breathing and as a Mapleson D or E mode during controlled ventilation. The reservoir bag is situated on the inspiratory side of the circuit and, therefore, during spontaneous breathing, gas in

the trachea and large bronchi containing no CO₂ passes back to the bag in the early part of exhalation before the FGF sweeps the remainder of the exhaled gas into the expiratory limb and scavenger. The recommended FGF for this circuit for cats and dogs <7 kg body weight is 70–100 mL/kg/min. The inside surfaces of the hoses are smooth, not corrugated, and that facilitates higher gas flow rates without turbulence (less resistance for large dogs). The FGF becomes uneconomical in larger dogs but then the circuit may be attached to a CO₂ absorber for use as a rebreathing system, and the FGF rate can be decreased accordingly.

Patient devices

Inhalation anaesthetic agents are usually delivered to the patient through a tracheal tube to avoid dilution with air and to limit exposure of personnel to waste anaesthetic gases. Facemasks are used to supply O₂ during induction and recovery from anaesthesia, to administer inhalation agents for induction of anaesthesia in some circumstances in small animals, young large animals, and in pigs, and for maintenance of anaesthesia in very small animals in which tracheal intubation may be difficult.

Facemasks

Facemasks are available in a variety of sizes and shapes (Fig. 10.26). The body or dome of the mask may be opaque or transparent. The rim of the mask that contacts the face may be rigid or a soft cushion, or fitted with a flat rubber seal. The connector is a short 15 mm or 22 mm internal diameter tube that fits into small animal rebreathing or non-rebreathing circuits. A mask should be chosen to be airtight and to conform as best as possible to the shape of the face to minimize deadspace. Care should be taken when using a facemask to avoid damage to the eyes and to avoid obstruction at the nostrils, especially in species that are obligate nasal breathers, such as foals.

Anaesthetic induction chambers

Boxes used for induction of anaesthesia of cats or other small animals are usually made of transparent plastic, so that the animal can be closely observed for movement or abnormal position that might result in airway obstruction. There is an inlet connector for administration of O₂ and inhalation agent and an outlet for connection to the waste anaesthetic gas scavenger. A much higher concentration than required for anaesthesia is administered because the volume of air in the chamber dilutes the inflowing anaesthetic. Therefore, it is important to judge accurately the time for removal of the patient from the chamber otherwise overdosage will occur. After the animal is anaesthetized, the animal is removed and anaesthesia maintained by endotracheal tube or facemask and a standard delivery circuit. Opening the chamber to remove the animal results in considerable room pollution.

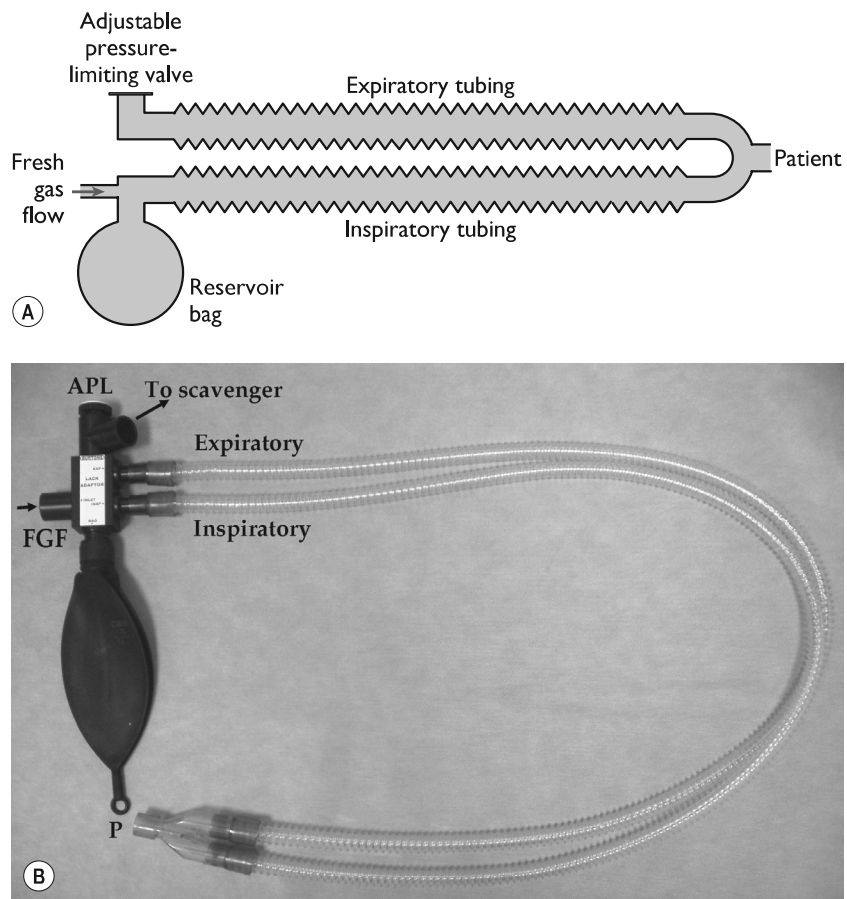


Figure 10.25 (A) and (B) Lack circuit (parallel version) modification of Mapleson A. Note that the bag is on the inspiratory limb. FGF = fresh gas flow, APL = adjustable pressure-limiting valve (or pop-off) valve, P = patient.

Photo courtesy of Dr J Cremer.

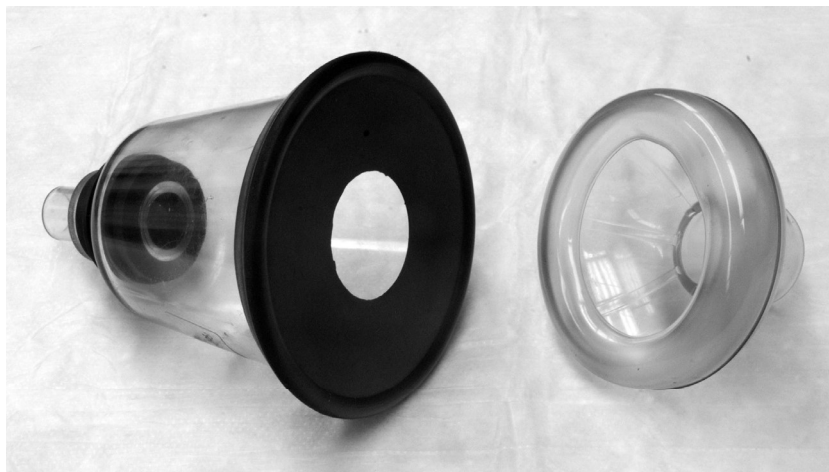


Figure 10.26 Facemasks are available in different designs to fit a variety of head shapes.