Chapter 17

Anesthetic Machines and Breathing Systems

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Introduction

The halogenated hydrocarbon anesthetics are liquids that must be vaporized for administration. These volatile drugs are potent and should be delivered with accuracy. Nitrous oxide (N_2O) is a gas anesthetic, normally used in high concentrations. It should be administered with enough oxygen to assure an adequate inspired concentration of oxygen. Using contemporary methods, anesthesia machines and breathing systems are required for administration of inhalant anesthetics. Standards for performance and safety of anesthesia machines designed for use in human patients have been published.[1–4] Newer veterinary anesthesia machines meet some of these standards, but are not required to comply fully with the American Society for Testing and Materials (ASTM) guidelines.

Anesthesia Machines

Anesthesia machines have certain basic components, and are compatible with various breathing systems. An anesthesia machine prepares a precise, but variable, gas mixture (oxygen and anesthetic) for delivery to a breathing system.[2] The breathing system supplies oxygen and anesthetic to patients, eliminates carbon dioxide from exhaled gases, and provides a means for controlled ventilation. Sources for medical gases (e.g., cylinders for oxygen and N_2O), a regulator and a flowmeter for each gas, and a vaporizer for each volatile anesthetic are fundamental to the operation of an anesthesia machine.[5]

Pressures of gases vary at different locations in an anesthesia machine,[2,3] and knowledge of these pressures facilitates the evaluation and safe operation of these machines. There are low-, intermediate-, and high-pressure areas. The high-pressure area accepts gases at cylinder pressure and reduces and regulates the pressure; this area includes gas cylinders, hanger yokes, yoke blocks, high-pressure hoses, pressure gauges, and regulators, and the pressure may be as high as 2200 pounds per square inch (psi). The intermediate-pressure area accepts gases from the central pipeline or from the regulators on the anesthesia machine and conducts them to the flush valve and flowmeters; this area includes pipeline inlets, power outlets for ventilators, conduits from pipeline inlets to flowmeters, and conduits from regulators to flowmeters, the flowmeter assembly, and the oxygen-flush apparatus. The pressure usually ranges from 37 to 50 psi, although it may be lower on newer anesthesia machines. The low-pressure area consists of the conduits and components between the flowmeter and the common gas outlet; this area includes vaporizers located outside the breathing system, piping from the flowmeters to the vaporizer, conduit from the vaporizer to the common gas outlet, and conduit from the common gas outlet to the breathing system, and the pressure is only slightly above am-

Fig. 17.1. Primary and reserve banks of large oxygen cylinders supplying the central medical gas pipeline system at a veterinary teaching hospital. The primary bank supplies oxygen to the pipeline system until the cylinders are depleted, at which time the system is automatically switched to the reserve bank.

bient. Pressures in the breathing system itself vary, but usually range from 0 to 30 cm of water (cm H_2O) when used with normal, healthy patients.

Medical Gases

An anesthesia machine typically has two sources for each medical gas. First, small compressed-gas cylinders attach to the machine and the hanger yokes, and, second, the hospital's central gas supply enters the machine at pipeline inlets. Ideally, the hospital's pipeline should be the primary source of medical gases, and small cylinders should be reserved for emergencies or transport.[6] Generally, bulk sources of medical gases are more economic than small cylinders.

The pipeline source for N_2O originates from the bank of large (G or H) compressed-gas cylinders, and oxygen may be supplied similarly (Fig. 17.1). Alternately, the central source of oxygen may emanate from a bulk tank of liquid oxygen (Fig. 17.2) or possibly from an oxygen-concentrating system. The latter will not reliably deliver 100% oxygen. Pipeline systems (Fig. 17.3) convey gases from the central source to terminal units (station outlets) throughout the hospital. A noninterchangeable gas-specific connector at the station outlet accepts only its corresponding connector, which attaches to the pipeline inlet of an anesthetic machine through a flexible, high-pressure hose. The connector may be a threaded diameter index safety system (diss) or a proprietary (manufacturer specific) nonthreaded, noninterchangeable quick connector (Fig. 17.4).[3] The high-pressure hose connects to the anesthesia machine at a pipeline inlet, which is usually a diss male connector (Fig. 17.5).

Gases move to and from a cylinder through a brass valve (Fig. 17.6). The valve stem controls flow, and a safety relief device (e.g., a fusible plug with a low melting point) allows emergency escape of gas to prevent bursting of a cylinder during exposure to high temperatures.[2] The threaded outlets of the valve bodies on

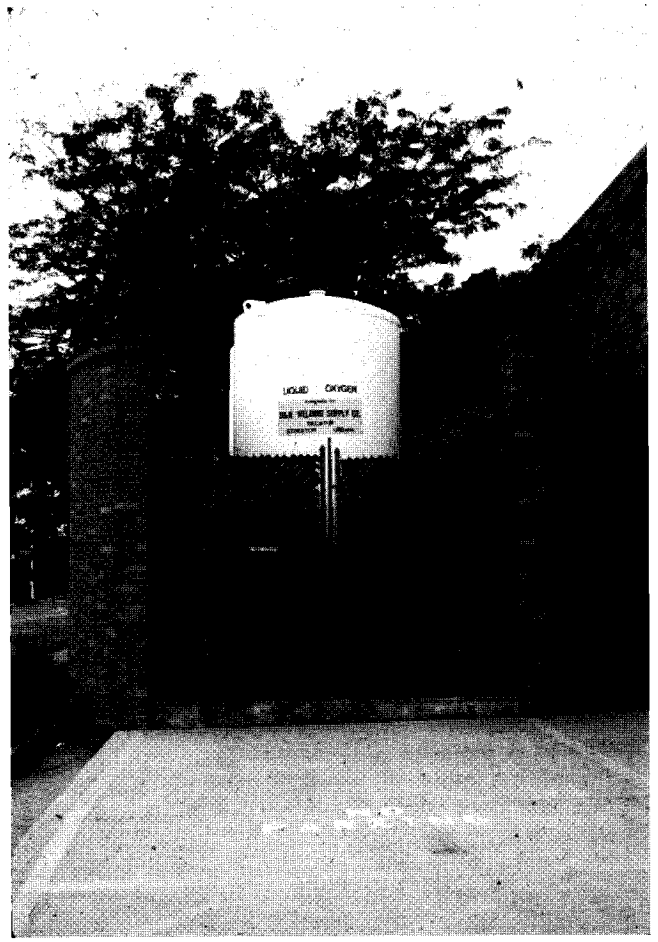

Fig. 17.2. An outside bulk container for liquid oxygen supplying the central medical gas pipeline system of a large hospital.

large cylinders (G and H) are designed to prevent the accidental interchange of oxygen, N_2O, and other gases at regulators or manifolds. The valve bodies of small (E) cylinders of oxygen and N_2O attach directly to anesthesia machines at the hanger yokes, and they use the pin-index safety system (Fig. 17.7) to prevent interchange of oxygen and N_2O. Two pinholes and a port in the valve body correspond to two pins and a nipple on the hanger yoke. Spacing of the pins for each medical gas precludes the interchange of gases under ordinary conditions (Fig. 17.8).

Although the pin-index system is effective, the system has been defeated.[2] The pins can be removed (Fig. 17.9), bent, broken, or forced deeper into the yoke. The nipple can be stacked with enough washers to allow attachment of the wrong cylinder. Yoke blocks coupled to high-pressure hoses will accommodate alternate gas sources. Some of the older yoke blocks do not have pinholes, and some short blocks can be attached upside down (Fig. 17.9), allowing connection of the wrong gas. Older anesthesia machines should be inspected to assure the integrity of the pin-index system for oxygen and N_2O. Small cylinders should be aligned correctly to the hanger yoke to prevent the creation of a potential hazard. Directing the retaining screw into the safety relief device instead of the conical depression has caused rapid decompression of a cylinder (Fig. 17.10).[7,8] If an anesthesia machine has multiple hanger yokes, each yoke should be fitted with a cylinder or a yoke plug (Fig. 17.11) when the machine is in operation.

An oxygen cylinder's service pressure is about 2200 psi. An E cylinder contains about 700 L of gaseous oxygen and an H cylinder about 7000 L (Table 17.1). The pressure is proportional to the contents, and an E cylinder with a pressure of 1100 psi contains about 350 L of oxygen. The pressure in a full N_2O cylinder is

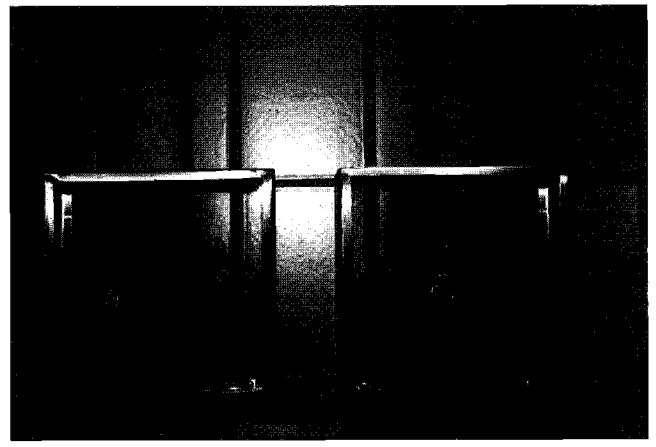

Fig. 17.3. A set of emergency shutoff valves for oxygen and nitrous oxide in a central pipeline system for medical gases in a veterinary teaching hospital. These valves should be placed strategically throughout the gas distribution system to control the flow of gases during emergencies or maintenance.

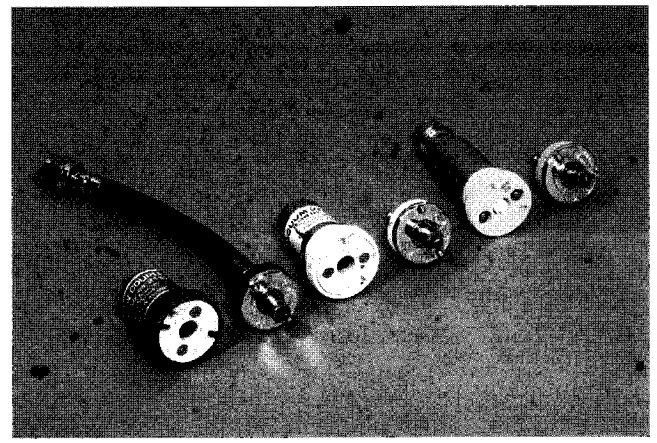

Fig. 17.4. A set of proprietary (Ohio or Ohmeda, Madison, WI) quick connects (quick couplers) for oxygen (male and female on the *left*), vacuum (male and female in the *center*), and air (male and female on the *right*). The female connectors are usually present at the site of use (station outlet) for attachment to the male counterparts from the anesthesia machine or other equipment via high-pressure flexible hose. Inadvertent interchange of the gases is prevented by variations in the spacing of corresponding components of the couplers.

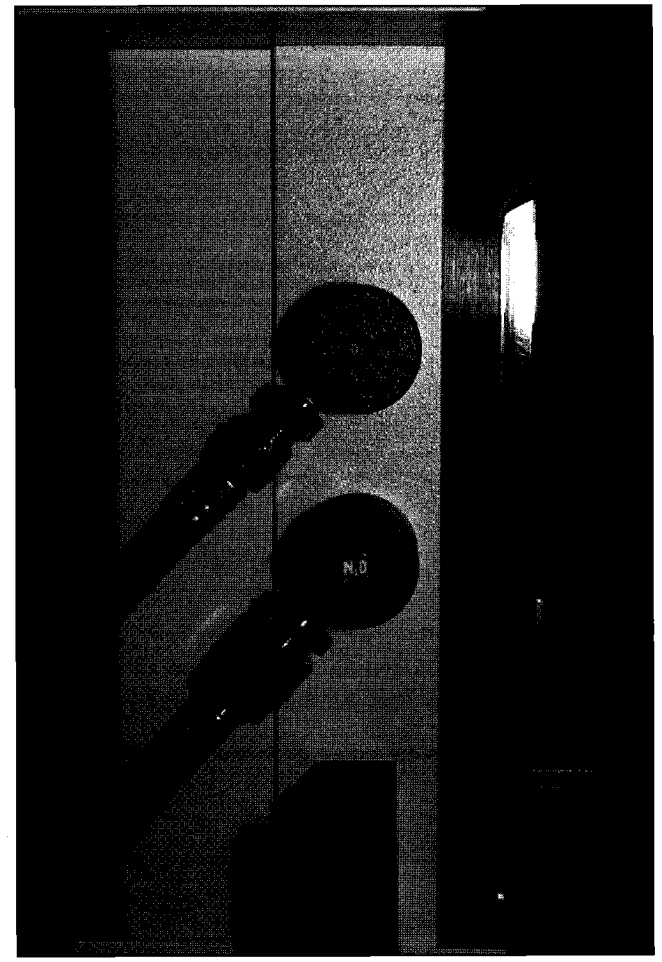

Fig. 17.5. Pipeline inlets for oxygen (*top* connector labeled as O_2) and nitrous oxide (*bottom* larger connector) on a Drager anesthesia machine (North American Drager, Telford, PA). The female diameter index safety system (diss) connectors from the high-pressure hoses couple to the male diss pipeline inlets on the anesthesia machine.

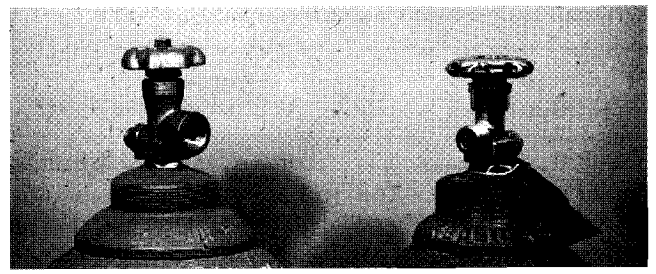

Fig. 17.6. Brass valves on large gas cylinders. The valve outlets on these two cylinders are designed to prevent an inadvertent connection to the wrong cylinder of gases. The valve on the *right* has external threads, whereas the one on the *left* has internal threads. The valve outlet for a large cylinder is distinguished by diameter, number of threads per inch, and type of threads (right hand or left hand and internal or external).

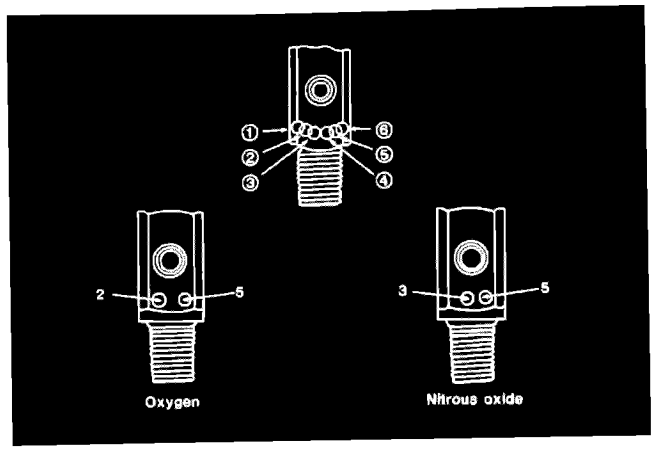

Fig. 17.7. Diagram of the pin-index safety system. The spacing between the valve outlet and the pinholes in the valve bodies for oxygen and nitrous oxide cylinders are illustrated. The pinholes and outlets correspond to the nipple and pins of hanger yokes on anesthesia machines and help to prevent the inadvertent incorrect use of medical gases. Note that pinholes 2 and 5 are used for oxygen, whereas pinholes 3 and 5 are used for nitrous oxide. From Hartsfield.[5]

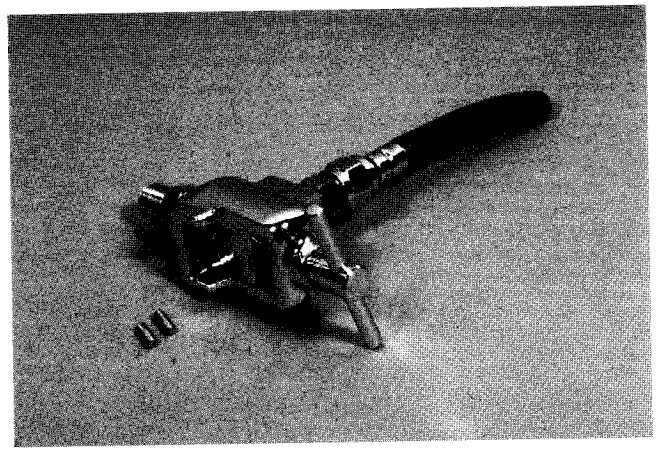

Fig. 17.9. An oxygen yoke showing a way in which the pin-index system for small gas cylinders can be defeated. The pins have been removed, and a short yoke block has been inserted upside down. Both will defeat the effectiveness of the pin-index system and allow connection to an inappropriate cylinder.

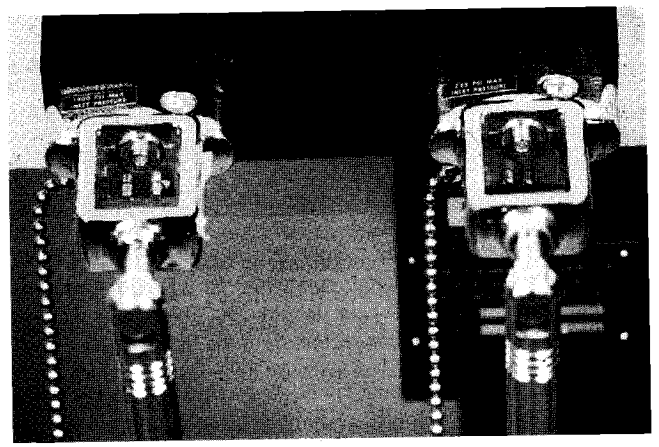

Fig. 17.8. Comparison of the yokes for small cylinders of oxygen (*left*) and nitrous oxide (*right*). The relationship of the pins and the nipple on each yoke show how the inadvertent interchange of oxygen and nitrous oxide cylinders is prevented. From Hartsfield.[5]

Fig. 17.10. The retaining screw of the yoke and a small (E) cylinder of oxygen next to a Vetaflex 5 veterinary anesthesia machine (Pitman-Moore, Washington Crossing, NJ). The retaining screw has been removed from the yoke to illustrate the pointed shape, which is intended to correspond to the conical depression of the cylinder valve and to secure the cylinder in the yoke. If the cylinder is positioned incorrectly in the yoke and the retaining screw is tightened into the fusible plug (the round, slotted device below the conical depression), the cylinder may decompress rapidly.

about 750 psi at normal room temperature, with N_2O in both liquid and gaseous phases. The vapor pressure of N_2O varies with temperature and determines the pressure in the cylinder. In a full cylinder, 95% of the volume is liquid,[9] and an E cylinder contains about 1600 L (Table 17.1). As liquid N_2O vaporizes, the cylinder cools, and frosting may occur. The contents of an N_2O cylinder is not directly proportional to the pressure. As pressure starts to decrease after all liquid N_2O has vaporized, about 25% of the original gas content remains. The remaining gas will then be depleted based on rate of flow.[10] Although the amount of N_2O is not directly related to pressure, the content of any cylinder can be determined by weight regardless of the state of the material in the cylinder.[3]

In the United States, the Department of Transportation controls the construction and testing of gas cylinders. The service pressure, defined as the maximum filling pressure at 70°F (22°C),[2] is typically 1900 to 2200 psi for oxygen. Cylinders are designated alphabetically, size A being the smallest. Sizes E, G, and H are common for medical oxygen and N_2O (Table 17.1). Permanent markings near the top of the cylinder indicate the Department of Transportation specification number, the type of material used in construction (e.g., steel or aluminum), service pressure in pounds per square inch, serial number, identification of the manufacturer, and testing dates. A five-point star after the last testing date qualifies the cylinder to be retested after 10 years.[3]

A color-coded label (green for oxygen and blue for N_2O) on the wall of the cylinder indicates the gas contents, warns of potential hazards (e.g., oxidizing agent), and names the manufacturer or distributor (Fig. 17.12). A single word appears on the label: *Danger* means an immediate threat to health or property if gas is released, *warning* indicates a less than immediate threat, and *caution* means no immediate hazard to health or property. A diamond-shaped area on the label indicates the hazard class of

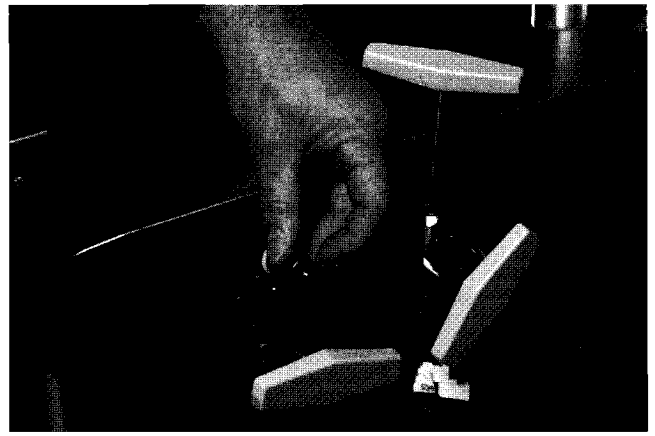

Fig. 17.11. Preparation for inserting a yoke plug into a yoke intended for a small (E) cylinder prior to use of the anesthesia machine. Since only one cylinder is present, the open yoke should be blocked with a yoke plug to prevent gas leaks, even if a check valve is present immediately upstream from the cylinder.

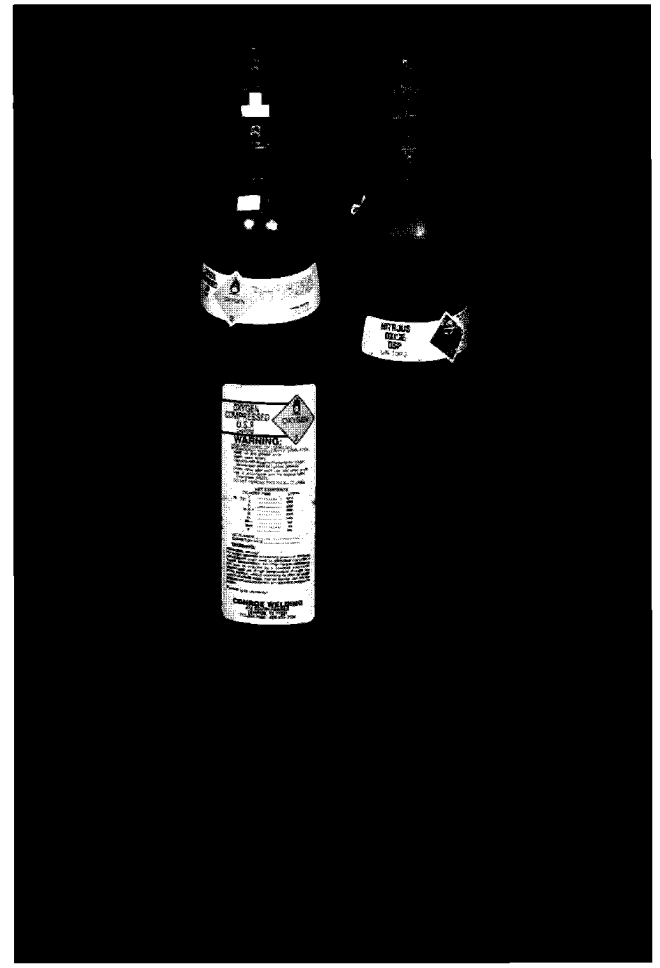

Fig. 17.12. Small (E) cylinders of oxygen and nitrous oxide, with labels and warnings. The diamond-shaped figure on each cylinder's label indicates the hazard class of the contents (yellow for oxygen, an oxidizer; and green for nitrous oxide, a nonflammable gas).

Table 17.1. Characteristics of medical gas cylinders[3]

Size	Gas	Gas Symbol	Color Code (U.S.)	Capacity and Pressure (at 70°F)	Empty Cylinder Weight (pounds)
E	Oxygen	O_2	Green	660 L 1900 psi	14
E	Nitrous oxide	N_2O	Blue	1590 L 745 psi	14
G	Nitrous oxide	N_2O	Blue	13,800 L 745 psi	97
H	Oxygen	O_2	Green	6900 L 2200 psi	119
H	Nitrous oxide	N_2O	Blue	15,800 L 745 psi	119

psi, pounds per square inch.

the gas by words (oxidizer, nonflammable, or flammable) and color code (yellow, green, and red, respectively).[3] Distributors often attach a color-coded tag to the valve body, identifying a cylinder's contents. Tags incorporate sequential perforated tabs imprinted with the terms *full*, *in use*, and *empty* to track the use of the cylinder.

Extensive descriptions of the appropriate handling, storage, and use of compressed gas cylinders have been published.[2–4,8,11] Briefly, cylinders should not be stored near flammable materials and should be properly secured at all times, even during transport. Cylinders should be stored in a cool, dry, clean, well-ventilated room that is constructed of fire-resistant materials.[3] Before using a cylinder, the contents should be clearly identified from the label. The valve port should be pointed away from the operator, opened briefly to clear possible debris, and then closed before connection to a hanger yoke, regulator, or manifold. A sealing washer should be placed between a small cylinder valve and the hanger yoke. The valve should be opened slowly to pressurize the regulator and then opened fully.[2,3] Defective cylinders should not be used.

Pressure Gauges

Each compressed gas supplied to an anesthesia machine should have a corresponding pressure gauge (Fig. 17.13)[1–3] that is attached to the regulators for large cylinders and to manifolds for banks of cylinders. The gauge indicates pressure on the cylinder side of the regulator. Gauges are identified by the gas's chemical symbol or name and are usually color coded. The scale is graduated to indicate the units of measure in kilopascals (kPa) and pounds per square inch.[1] Bourdon tube-type gauges are typical for anesthesia machines.[12] Earlier standards for anesthesia machines required that the gauge's full-scale reading should be at least one-third greater than the maximum cylinder pressure, and that, on a given anesthesia machine, all gauges should displace a similar arc from the lowest to highest readings.[2] Pressure gauges are also incorporated into pipeline distribution systems at various locations. In addition, pressure gauges may be used on anesthesia machines to report pipeline pressure.[1,3] Pressure gauges do not accurately report the quantitative contents of a cylinder containing liquid gas.[1]

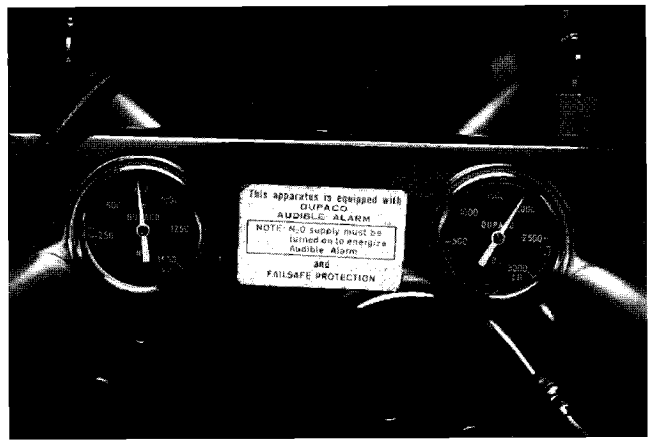

Fig. 17.13. Pressure gauges for oxygen (1900 psi) and nitrous oxide (750 psi) on a veterinary anesthesia machine.

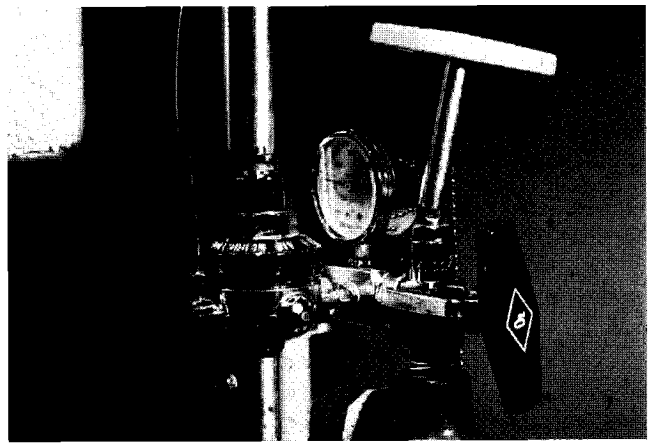

Fig. 17.14. Pressure regulator on a Pitman-Moore 970 veterinary anesthesia machine (Pitman-Moore, Washington Crossing, NJ). The triangular shaped regulator for oxygen is shown in-line between the yoke for the oxygen cylinder and the small-diameter oxygen line to the flowmeter. The pressure gauge indicates the pressure in the cylinder, and the pressure downstream from the regulator is reduced to 50 psi by the regulator.

Regulators

An anesthesia machine should have a regulator for each medical gas supplied to the machine (Fig. 17.14).[1] The pressure in a gas cylinder varies with its content and temperature, and the pressure in a full cylinder is relatively high (e.g., 2000 psi in an oxygen cylinder). A regulator reduces the high and variable storage pressure to a lower and more constant pressure that is appropriate for the anesthesia machine.[6] By reducing and controlling pressure as gas exits a cylinder, a regulator maintains constant flow to the flowmeter, even though the pressure in the cylinder decreases as the contents are depleted.

Although regulators on newer anesthesia machines designed for human patients may be quite sophisticated, a simple regulator has a high-pressure chamber separated by a valve port from a low-pressure chamber (Fig. 17.15).[12] Movement of a flexible diaphragm opens or closes the valve, regulating a variable opening, and consequently the pressure in the low-pressure chamber. Increasing pressure on the low-pressure side tends to close the valve. The amount of pressure required to close the valve depends on a spring opposite the diaphragm. The exact construction varies among regulators, but the function is consistent. Regulators are designed for safety relief (at two to four times the pressure in the low-pressure chamber) in order to protect equipment and personnel.[3,12]

Regulators produce a safe operating pressure, prevent flowmeter fluctuations as cylinders empty, and decrease the sensitivity of the flowmeter indicator to slight movements of the control knob. The ASTM standard requires that regulators on anesthesia machines be set so that the pipeline gases are used preferentially.[1] Therefore, regulators may be set at about 45 psi (if a power outlet is present for a ventilator) or at 37 to 42 psi (without a power outlet), since pipeline pressure is usually 50 psi. Older anesthesia machines that have regulators set at 50 psi and open E cylinders located on the machine can allow E cylinder gas flow rather than pipeline gas flow when a pipeline check valve is not present, possibly depleting gases from the cylinder that should be saved for emergency situations (e.g., pipeline failure). Contemporary anesthesia machines designed for human patients have additional regulators (second stage) that deliver gases to the flowmeters at much lower pressures (e.g., 12 to 16 psi) to increase the constancy of the flowmeter.[3,6]

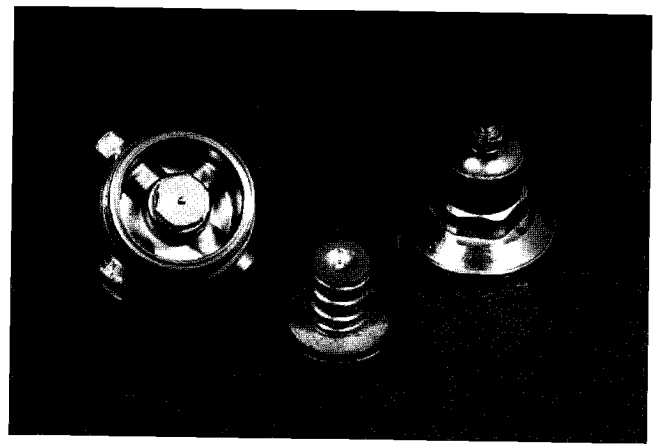

Fig. 17.15. A simple pressure regulator for oxygen that has been separated into its component parts. Shown are the body of the regulator with the entry port for high-pressure gas at 7 o'clock (*left*), the diaphragm and spring (*center*), and the cover (*right*) with holes for pressure relief through the diaphragm and the adjusting screw.

Flowmeters

Flowmeters for medical gases are positioned downstream from the regulators for each corresponding gas, and the portion of the flowmeter that is downstream from the flow-control valve is part of the low-pressure system of an anesthesia machine. A flowmeter measures and indicates the rate of flow of gas,[3] and enables precise control of oxygen or N_2O delivery to an out-of-system vaporizer and to the common gas outlet.

Gas moves through the flow-control valve to enter the bottom of the glass tube (i.e., Thorpe tube) of the flowmeter assembly. The gas then courses around a movable indicator (float) in the annular space between the indicator and the wall of the tube, and exits at the top of the tube (Fig. 17.16). The tube is larger at the top than at the bottom, and a greater volume of gas moves around the indicator as it rises.[2] The scale associated with the tube indicates rate of gas flow in milliliters per minute (mL/min) or in liters per minute (L/min). Some flowmeters, especially those on older anesthesia machines, have double tapers (Fig. 17.16). A slight taper in the lower part of the tube promotes accuracy at low flows (mL/min), and a greater taper at the top allows higher flow rates (L/min). The current machine standard requires that the scale be on the glass tube itself or be located to the right of the tube (viewed from the front of the anesthesia machine).[1] The scale may be on the left in older anesthesia machines, and the operator should assure the proper adjustment of flowmeter control knobs when older equipment is used.[3]

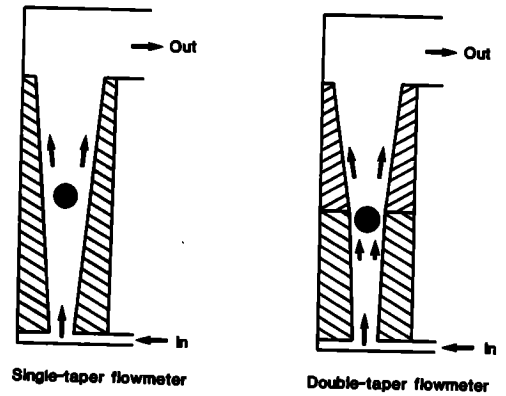

Fig. 17.16. Flowmeter diagram illustrating gas flow from bottom to top through flowmeters with single and double tapers. As the indicator (*black dot*) rises, flow increases because orifice size increases. The double taper tube allows increased accuracy at the lower end of the tube while accurately metering higher flow rates at the top. From Hartsfield.[5]

Flowmeters are calibrated at 760 mm Hg and 20°C, and accuracy may change under other conditions.[3] Generally, the effects of temperature on flowmeter function are minimal, but changes in barometric pressure may be significant, producing a higher flow than indicated at lower barometric pressure (altitude) and a lower flow at high pressure (i.e., in a hyperbaric chamber).[3] Since a flowmeter (tube, indicator, and scale) is calibrated as a unit, parts from different flowmeters should not be interchanged. If a flowmeter fails, the glass tube, indicator, and scale should be replaced as a unit. The lowest mark on the scale is the first accurate setting, and extrapolation to lower flow rates is unreliable.[2] A flowmeter's indicator should be read at the top (Fig. 17.17), except for a ball-type float, which is read at the center (Fig. 17.18). The point of reference for reading the indicator should be shown on the flowmeter assembly.[1] Flowmeters should be used in the position on the machine as originally designed (e.g., vertical on newer machines or slanted in some older machines).

The flow-control knob for oxygen on contemporary anesthesia machines should be as large or larger than other flow-control knobs, it should have a fluted profile (Figs. 17.17 and 17.18) as dictated by the ASTM standard, and it should project beyond the control knobs for other gases.[1] This enables the operator to "feel" which gas is being adjusted ("touch coded").[2] A control knob is labeled with the gas symbol and is color coded (Figs. 17.17 and 17.18). Good flow controls have fine threads for accuracy and stops to prevent over tightening and damage to flow-control valves.

The size of the flowmeter's indicator in relation to the scale influences accuracy. Float indicators may be longer than 1 cm, and

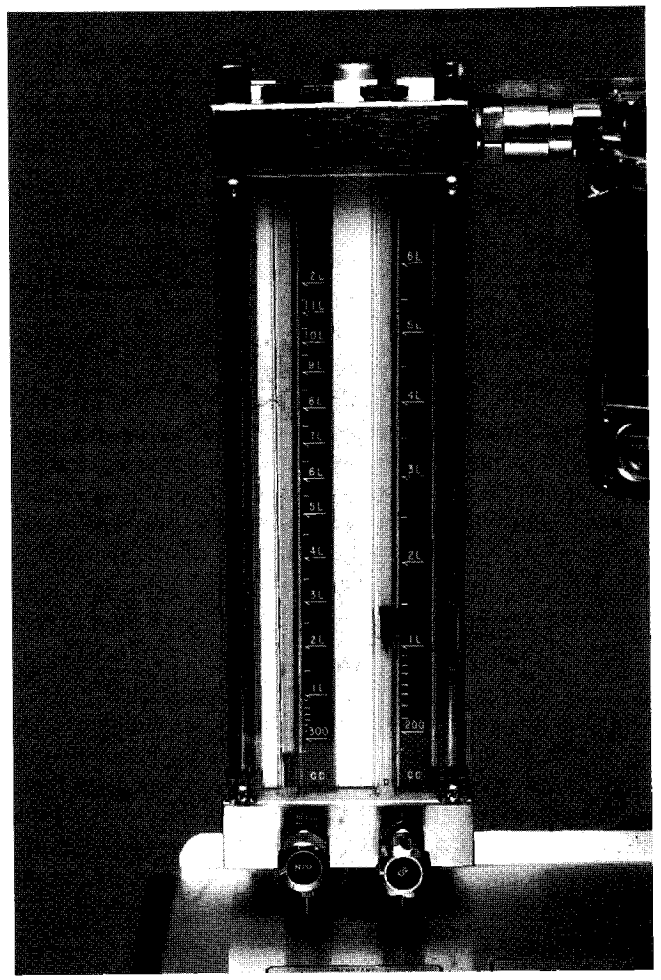

Fig. 17.17. Oxygen and nitrous oxide flowmeters on a Vetaflex 5 veterinary anesthesia machine (Pitman-Moore, Washington Crossing, NJ). The oxygen flowmeter is located to the right in the cluster, and the indicator should be read at its top (1.5 L/min). The indicator is relatively long compared with the calibrations on the scale. Erroneously reading the bottom of the indicator would result in a flow of oxygen that was 600 mL/min lower that intended. The O_2 flow-control knob is fluted and color coded.

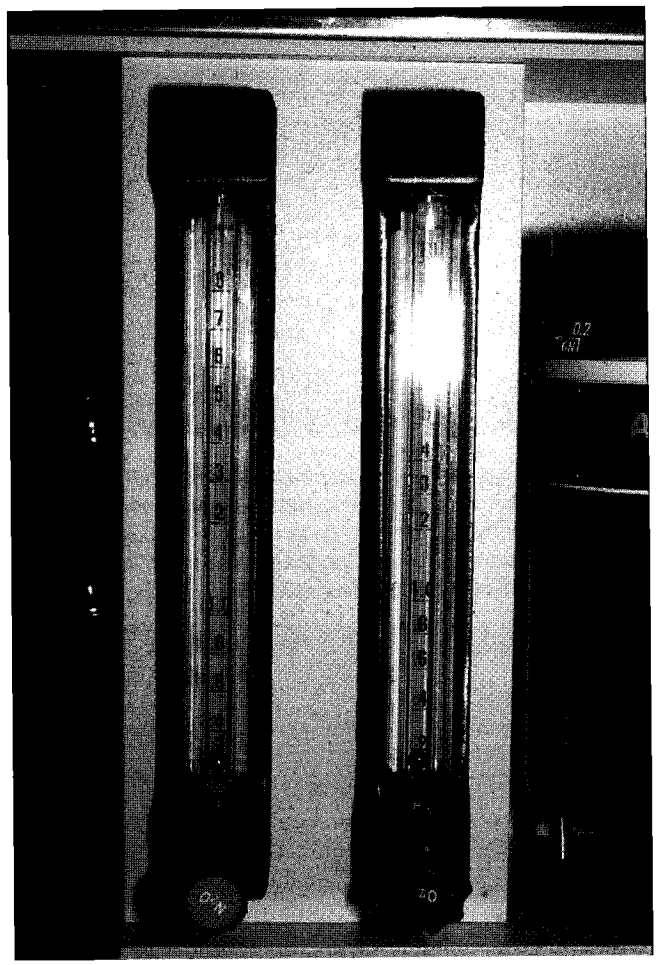

Fig. 17.18. Flowmeters for oxygen and nitrous oxide on a Drager anesthesia machine (North American Drager, Telford, PA). The oxygen flowmeter is located to the right of the nitrous oxide flowmeter, and the ball-type indicator should be read in the center (1 L/min). The flow-control knob for oxygen is fluted and color coded and is larger than the flowmeter for nitrous oxide.

reading the scale at the wrong location may affect the flow rate significantly (Fig. 17.17). Errors in reading the flowmeters for flowmeter-controlled vaporizers such as Copper Kettles and Verni-Trols may dangerously alter the inspired concentration of anesthetic. Dirt, static electricity, or a damaged float may impair movement and cause erroneous readings. The indicator should move freely in the glass tube, and a sluggish or sticking float indicates that it should be cleaned or replaced. A sticking float, which indicated oxygen flow when the oxygen cylinder was empty, has been reported as a cause of hypoxia.[2,13] Flowmeters should be off when not in use so as to prevent the sudden application of pressure to the glass tube and indicator when a gas cylinder valve is opened. Sudden high pressure may force the indicator upward, damaging the indicator or the stop. The indicator may jam at the top of the tube, where it may go unnoticed.[2]

The standard for modern anesthesia machines requires the presence of only one flow-adjustment control for each gas delivered to the common gas outlet.[1] Ideally, when there are two flowmeters for one gas, they should be connected in series and controlled by a single flow-control knob.[3] Some veterinary anesthesia machines (Fig. 17.19) and older machines for human and veterinary patients may have multiple flow controls for multiple flowmeters with different scales in a parallel arrangement, and the operator should assure proper settings with both control knobs. Similarly, the sequence of flowmeters is important with multiple gases on a single anesthesia machine. The machine standard requires that oxygen be delivered downstream of other gases when all gases use a common manifold.[1] If oxygen enters the manifold upstream from the other gases, the possibility exists for delivering hypoxic mixtures, which is a complication that has

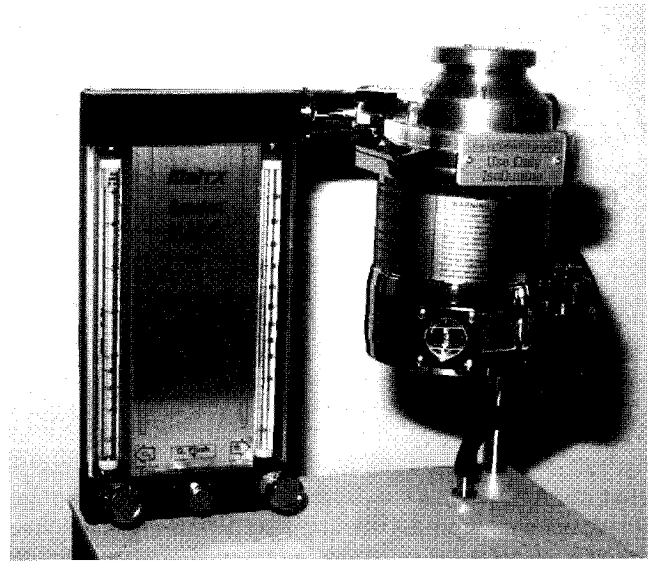

Fig. 17.19. Double oxygen flowmeters on a Matrx Spartan VMC veterinary anesthesia machine (Matrx, Orchard Park, NY). One flowmeter (*left*) is graduated from 0 to 1000 mL/min, whereas the other is graduated from 0.2 to 4.0 L/min. The intent is to increase accuracy at lower flow rates. Two flow-control knobs in parallel offer an opportunity for setting an incorrect flow of oxygen. With two flowmeters in parallel, the total flow is the sum of the flow rates set from each flowmeter.

been reported several times.[2] The U.S. and Canadian standard locates the oxygen flowmeter to the right in a cluster of flowmeters as viewed from the front of the anesthesia machine. If a specific flowmeter for a vaporizer is required, it should be to the right of the cluster, at least 10 cm from the oxygen flowmeter,[2] although flowmeter-controlled vaporizers are no longer covered in the ASTM standard.[1] For flowmeter-controlled vaporizers, this arrangement standardizes the location of control knobs and decreases the likelihood of adjusting the incorrect flowmeter. Standardization of location of the flowmeters for oxygen delivery and for vaporizers along with requiring touch-coded flow-control knobs for oxygen flowmeters are intended to reduce errors in oxygen flow rates. Locating the oxygen flowmeter to the right in a cluster of flowmeters is a North American standard, and the location may vary on older machines and in machines manufactured in other countries.[3] Other arrangements of flowmeters may exist in older anesthesia machines (e.g., oxygen flowmeter located to the left, to the right, or in the center in a cluster). The danger of delivering hypoxic mixtures by adjusting the wrong control knob when using both N_2O and oxygen must be guarded against.

The arrangement of flowmeters on older models of Drager anesthesia machines allowed delivery of hypoxic mixtures if both oxygen and N_2O were used and a leak developed at the base of the oxygen flowmeter (Fig. 17.20). This malfunction caused the death of a horse.[14] Similarly, cyanosis and light anesthesia were produced shortly after intubation and attachment of a dog

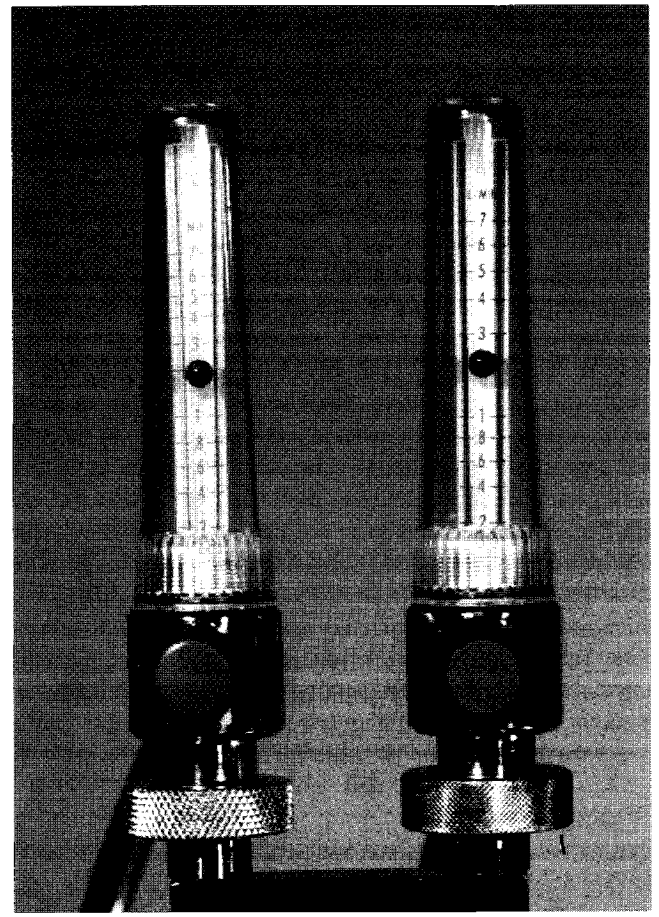

Fig. 17.20. Flowmeters for oxygen (*left*) and nitrous oxide (*right*) on a Drager Narkovet Stand Model anesthesia machine (North American Drager, Telford, PA) for small animals. A leak at the seal created by the nut below the flowmeter could result in delivery of a low or hypoxic concentration of oxygen to the breathing system.

to an anesthesia machine;[15] evaluation of the oxygen flowmeter revealed a leak at its base caused by a faulty seal with a folded washer. Because of this flowmeter's design, the indicator showed a correctly adjusted flow rate for oxygen, although total gas flow to the vaporizer and breathing system was very low. Leaks associated with flowmeters can occur at several locations, including cracks in the glass tube, as well as problems with O-rings and gaskets.[6] Leaks in the flowmeter should be detected by leak tests performed on the low-pressure area of an anesthesia machine.[16]

Flowmeters should be adjusted to assure an adequate total volume and an appropriate concentration of each medical gas. Flow rates should meet or exceed the patient's oxygen consumption and deliver an adequate inspired-oxygen concentration (usually a fraction of inspired oxygen [F_IO_2] ≥ 0.3). Delivery of an appropriate concentration of oxygen, as well as an adequate quantity of oxygen, is essential for saturating hemoglobin and for supplying the patient's metabolic needs. Accuracy becomes especially important with the administration of N_2O and with closed and low-flow breathing systems. The accuracy of flowmeters signifi-

cantly decreases with flows lower than 1 L/min.[2] With low-flow systems, scrutiny of F_IO_2 becomes important; continuous monitoring of oxygen concentration on the inspiratory limb of the breathing system has been recommended. Indeed, to meet the ASTM standard, an oxygen analyzer is a required component of the anesthesia machine.[1,6]

Safety Devices for Oxygen Pressure and Flow

Anesthesia machines may be designed to alert the operator to a dangerously low pressure of oxygen flow.[3,4] When the oxygen pressure reaches a certain value, the machine may alert the user with an alarm, or the machine may be engineered to cut off the supply of all other gases (e.g., N_2O) to prevent the delivery of hypoxic mixtures. In addition, some anesthesia machines incorporate proportioning devices to assure that oxygen is flowing at some preset minimum portion of the total fresh gas flow. Dupaco anesthesia machines were once popular in veterinary anesthesia and incorporated an audible alarm if the pressure of oxygen became dangerously low. The Metomatic veterinary anesthesia machine reduces the flow of other gases (i.e., flow through the Verni-Trol) if oxygen flow is reduced. These safety mechanisms may malfunction, and continuously monitoring gases on the inspiratory limb of the breathing system is a more reliable way to assure the delivery of an adequate concentration of oxygen.

Flush Valves

Oxygen is supplied at approximately 50 psi to the flush valve of an anesthesia machine. The flush valve delivers a high, but unmetered, flow (35 to 75 L/min is the ASTM standard)[1] of oxygen to the common gas outlet or directly to the breathing system in some simple veterinary machines (e.g., Matrx small animal anesthesia machine). The contemporary machine standard does not allow piping of oxygen from the flush valve through the vaporizer. However, older anesthesia machines, especially those with precision vaporizers added after the machine was manufactured, may increase oxygen flow through the vaporizer, with the potential for increased output of anesthetic.[6]

At a flow rate of 50 L/min, oxygen from the flush valve can quickly fill the breathing system. In general, pediatric breathing systems (i.e., pediatric circles, Mapleson systems, or valved nonrebreathing systems) should not be filled via the flush valve because of the danger of overpressurizing a patient's respiratory system. Current machine standards require that the actuating device for the flush valve be recessed to prevent inadvertent activation and delivery of a high volume of gas to the breathing system (Fig. 17.21).[1] Other problems involving the flush valve include leaks in the flush-valve assembly and sticking of the flush valve in the on position.[3] A leak at the flush valve reportedly resulted in loss of anesthetic and oxygen at flow rates of less than 1 L/min, making it impossible to maintain surgical anesthesia with the typical fresh gas flow rates used with a semiclosed circle breathing system.[17]

Vaporizers

Except for N_2O, modern inhalant anesthetics are delivered with vaporizers. Concentration-calibrated, variable-bypass vaporizers,

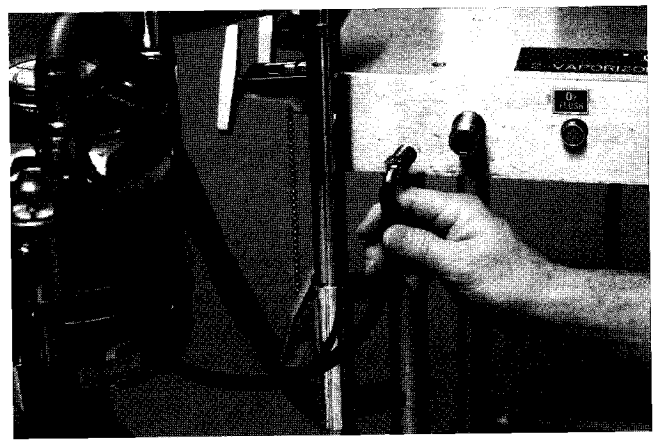

Fig. 17.21. Flush valve and common gas outlet on a veterinary anesthesia machine. The flush valve (labeled on the machine) is protected from inadvertent activation by a circular stainless-steel guard. The common gas outlet (open hole) received a connector to link the anesthesia machine through a rubber hose to the fresh gas inlet of the breathing system.

which are temperature, flow, and back-pressure compensated, are standard in human anesthesia and are recommended for delivery of volatile inhalant anesthetics to veterinary patients. However, nonprecision, uncompensated vaporizers (e.g., Stephens vaporizer) have also been marketed to veterinarians as a part of a complete anesthesia machine. In addition, an older vaporizer designed for less volatile inhalant anesthetics (Ohio #8 glass bottle), when modified by removal of the wick, has been evaluated for the delivery of halothane or isoflurane to veterinary patients.[18,19] Administering highly volatile, highly potent inhalant anesthetics with nonprecision, uncompensated vaporizers is associated with a high degree of risk unless instrumental monitoring (e.g., of inspired or expired anesthetic concentration) is available.

A vaporizer is designed to change a liquid anesthetic into its vapor and to add a specific amount of vapor to the gases being delivered to a patient.[2] Carrier gas, oxygen alone or with N_2O, passes through the vaporizer to acquire anesthetic vapor. Because the saturated vapor pressures of most inhalant anesthetics are significantly greater than the partial pressures required for clinical anesthesia (i.e., significantly greater than the minimum alveolar concentration [MAC]), a vaporizer should deliver a concentration that is close to the setting on the vaporizer control dial. Otherwise, the inspired concentration of anesthetic should be monitored. In general, the design of precision vaporizers allows dilution of a high concentration of anesthetic vapor from the vaporization chamber to a clinically usable and safe concentration.

Physics of Vaporizer Design and Function

Several principles of physics are involved in the function of a vaporizer for inhalant anesthetics.[2–4] Heat is required for vaporization of liquid anesthetics; the *latent heat of vaporization* is defined as the number of calories required to change 1 g of liquid into its vapor. This heat requirement causes liquid anesthetic to cool during vaporization. The vapor pressure of an anesthetic is the partial pressure of the aesthetic gas above the liquid at equilibrium, and vapor pressure varies directly with temperature. Thus, uncontrolled cooling limits a vaporizer's maximum output. A vaporizer made of a substance (e.g., copper) with a high *specific heat* (the quantity of heat required to raise the temperature of 1 g of the substance 1°C) supplies heat to the liquid anesthetic during vaporization, retarding the cooling process. If a vaporizer is constructed of a material with a high *thermal conductivity* (the rate at which heat flows through a substance), such as copper, heat flows from warmer ambient air into the vaporizer to impede cooling. Materials including copper and bronze are used in the construction of vaporizers because of favorable values of these metals for specific heat and thermal conductivity. More recently, stainless steel has been used in the construction of vaporizers.[4] The output of concentration-calibrated vaporizers is generally expressed as volume percent of anesthetic vapor in the gases exiting the vaporizer. This relative value changes with variation in barometric pressure.

Compensatory Mechanisms for Vaporizers

The conditions of use affect the performance of vaporizers and must be stated in the operation manual for a concentration-calibrated vaporizer to meet the ASTM standard.[1] The effects of changes in carrier-gas flow, temperature, ambient pressure, and back-pressure should be delineated. Vaporizers compensate in various ways for changes in flow, temperature, and pressure.[2–4]

Compensation for variations in temperature of the liquid anesthetic during vaporization can be accomplished by several mechanisms. As previously mentioned, copper and bronze materials with high specific heat and thermal conductivity values supply and conduct heat efficiently to the liquid anesthetic to promote a relatively constant temperature. This "heat sink" mechanism attenuates changes in temperature, producing a degree of thermostability. Bimetallic strip valves in Tec vaporizers, a gas-filled bellows linked to a valve in the bypass gas flow in Ohio calibrated vaporizers, and an expansion member (silicone cone) in Vapor/vaporizers that expand(s) and contract(s) with temperature changes, alter(s) carrier-gas flow through the vaporization chamber and controlling anesthetic output.[4] Manual adjustments in carrier-gas flow are required to compensate for temperature variations in measured-flow vaporizers (e.g., Verni-Trol vaporizer) and older Vapor vaporizers. Other vaporizers are electrically heated, and the mechanism for control of the temperature of the anesthetic is supplied heat (e.g., Verni-Trol vaporizer on the Ohio DM 5000 anesthesia machine). The Tec 6 vaporizer for desflurane is electrically heated and thermostatically controlled at 39°C.[16]

Differences in carrier-gas flow rates alter the output of uncompensated vaporizers. Modern flow-compensated vaporizers produce relatively accurate anesthetic concentrations over an approximate range of 250 mL/min to 15 L/min.[6] The *splitting ratio* (ratio of the bypass to the gas passing through the vaporization chamber) determines the output of vapor,[4] and the resistance to flow through each of the two channels in the vaporizer allows the splitting ratio to be maintained at various rates of flow.[3] Below 250 mL/min and above 15 L/min, the output from most concentration-calibrated vaporizers is variable, and performance data outside that range may not be available. Output from older variable-bypass vaporizers (e.g., Fluotec Mark 2) may vary significantly from the setting on the control dial at flow rates less than 4 L/min. Measured-flow (flowmeter controlled) vaporizers (e.g., Copper Kettle) require adjustments in the flow of oxygen to the vaporization chamber when the total flow of gas is changed.

Vaporizer output may vary with the composition of the carrier gas; the output of anesthetic with oxygen as the carrier gas may differ from the output with a combination of oxygen and N_2O as the carrier gas.[2,4] The magnitude of effect is variable, depending on the specific vaporizer. With N_2O, newer vaporizers initially deliver concentrations that are less than the control-dial setting. With the Fluotec Mark 3, N_2O has little effect on output. However, N_2O as the carrier gas in the Fluotec Mark 2 increases the output of halothane.[2]

Back-pressure compensation is a design feature of modern vaporizers. Intermittent pressure transmitted to a vaporizer during activation of the flush valve and during application of positive-pressure ventilation may increase vaporizer output compared with output of anesthetic during free flow of gases through the vaporizer.[6] Newer vaporizers prevent or minimize this "pumping effect" by use of small vaporization chambers (e.g., Tecs), long spiral tubes at the inlet to the vaporization chamber (e.g., Vapor), pressure-check valves just downstream from the vaporizer, and relief valves at the vaporizer outlet.[2,3,6]

Effects of Barometric Pressure on Vaporizer Function

Variations in barometric pressure (e.g., high altitude or hyperbaric chambers) alter vaporizer output expressed in volume percent. A specific partial pressure of inhalant anesthetic (e.g., 1 MAC) represents the same anesthetic potency (partial pressure) at various barometric pressures.[20] However, anesthetic concentration is expressed as volume percent on most vaporizers, and MAC expressed as volume percent increases as barometric pressure decreases. Changing the barometric pressure also alters the viscosity and density of gases flowing through vaporizers and flowmeters and affects the output concentration.[20] The ASTM standard states that the effects of barometric pressure on the performance of a vaporizer must be described in catalogs and operation manuals.[1,3]

With decreasing barometric pressure, most concentration-calibrated vaporizers (e.g., Fluotec Mark 3) are considered "self-compensating" and deliver about the same partial pressure, but an increasing volume percent of anesthetic.[3,20] Basically, the vaporizer can be set normally in volume percent even though the volume-percent setting on the control dial is inaccurate.[20] In theory, a halothane vaporizer at an ambient pressure of 500 mm Hg should deliver twice the concentration on the control dial in volume percent and approximately 1.3 times the dialed concentra-

tion in terms of MAC or potency.[4] Since variations in resistance of flow through the vaporizer at differing ambient pressures cause small changes in concentration output,[3] the best approach is to measure partial pressure of anesthetic in inspired or expired gases when working at atypical barometric pressures.

With measured-flow vaporizers (e.g., Copper Kettle), changes in barometric pressure affect both partial pressure and volume percent of the delivered anesthetic.[20] If barometric pressure is low, the output expressed as volume percent and as partial pressure increases. When the barometric pressure is high, measured-flow vaporizers deliver a lower anesthetic concentration, expressed as either volume percent or partial pressure. Temperature, barometric pressure, and vapor pressure of the anesthetic all affect the final anesthetic concentration, but the greatest effects are on anesthetics with low boiling points and with vapor pressures that are near the barometric pressure.[3,20]

Changes in barometric pressure also affect the function of flowmeters. Actual flow increases, becoming higher than the indicator and scale of the flowmeter show, as barometric pressure decreases.[20] In, contrast, a flowmeter will deliver less flow than indicated when ambient pressure is higher than the barometric pressure at which the flowmeter was calibrated.[3]

Potential Problems with Vaporizers

The arrangement of vaporizers on anesthesia machines and how vaporizers are maintained affect their safety under clinical conditions. Filling errors, improper transport, using vaporizers in series, and improperly connecting a vaporizer to a machine may cause significant variations in output.

Veterinary practices often stock more than one inhalant anesthetic, and a vaporizer may be inadvertently filled with the wrong drug, especially if the vaporizer has a screw-cap filler port in contrast to a keyed filler port. Keyed filler systems are designed to prevent the introduction of the wrong anesthetic into a vaporizer (Fig. 17.22). However, they are more inconvenient, and screw-cap filler ports and a simple bottle adapter will decrease spillage (Fig. 17.23). Admittedly, there is an increased chance for incorrect filling of vaporizers (Fig 17.24). If an agent-specific vaporizer for a drug with a lower vapor pressure (e.g., methoxyflurane) is filled with a potent, highly volatile anesthetic, dangerously high concentrations may be produced. If this occurs, the vaporizer should be decontaminated before it is used for a patient. The best approach is to have the vaporizer serviced by a qualified vaporizer technician. For Ohio calibrated vaporizers, service is required because the paper wicks must be replaced. For a contaminated Tec vaporizer, an option is to drain the vaporizer, flush it with an oxygen flow of 5 L/min for 45 min or until no trace of a contaminant is present, allow it to stabilize thermally for about 2 h, and refill it with the appropriate anesthetic. Vaporizers contaminated with a nonvolatile contaminant (e.g., water or thymol) should be drained and serviced.[4]

Filler ports and sight glasses are designed to preclude overfilling of modern vaporizers, primarily to prevent liquid anesthetic from entering the fresh gas line of the vaporizer (Fig. 17.25). Recent designs for some vaporizers prevent liquid from entering the fresh gas line even during tipping or inversion. However, tipping of certain vaporizers may introduce liquid anesthetic into the bypass channel.[3] If this occurs, a high concentration of anesthetic vapor may be delivered: Tipping a vaporizer that was not securely attached to an anesthetic machine has reportedly caused a human patient's cardiac arrest.[21] Also, moving a vaporizer on a mobile anesthesia machine may alter vaporizer output if the machine is tipped or liquid anesthetic is sloshed as the machine is moved over doorway thresholds. Generally, vaporizers should be emptied before transport. Even portable anesthesia machines should be moved with care. If tipping occurs, a high flow of oxygen through the vaporizer for 20 min with the control dial at a low setting has been recommended, but servicing may be required.[2]

One anesthesia machine may be fitted with multiple vaporizers (Fig. 17.24). Modern anesthesia machines designed for use in human patients are equipped with interlocking mechanisms that do not allow two vaporizers to be on simultaneously.[6] Few veterinary practices have the luxury of owning anesthesia machines with interlocking vaporizers. In-line, noninterlocked vaporizers offer the possibility of operating two vaporizers concurrently, conceivably producing an excessive depth of anesthesia.[2] The simultaneous use of more than one vaporizer in series also increases the probability of contaminating a vaporizer with an inappropriate agent. If vaporizers are placed in series, the best order is methoxyflurane, sevoflurane, isoflurane, and halothane from upstream to downstream: This reduces the chance of contamination by taking into account both vapor pressure and potency.[3,4] Anesthesia machines with vaporizers in series should be used carefully if an interlocking mechanism is not in place.

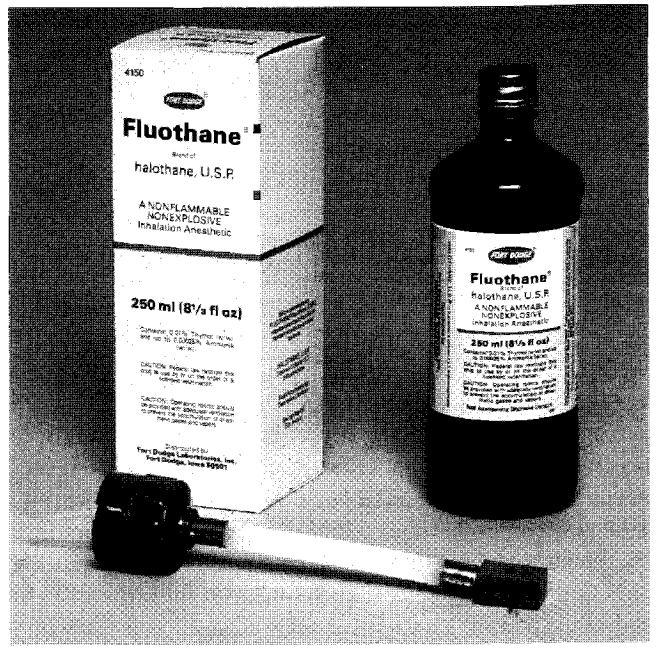

Fig. 17.22. Bottle adapter for halothane vaporizers with keyed filler systems. Such systems reduce the likelihood of introducing an inappropriate anesthetic into an agent-specific vaporizer. The larger end (*left*) of the device attaches to a bottle of halothane, and the opposite end corresponds to the vaporizer filler receptacle. A screw in the receptacle enables a tight seal to be created during the filling process. Bottles of inhalant liquid have a color-coded collar to accept only the correct bottle adapter (see Fig. 17.23).

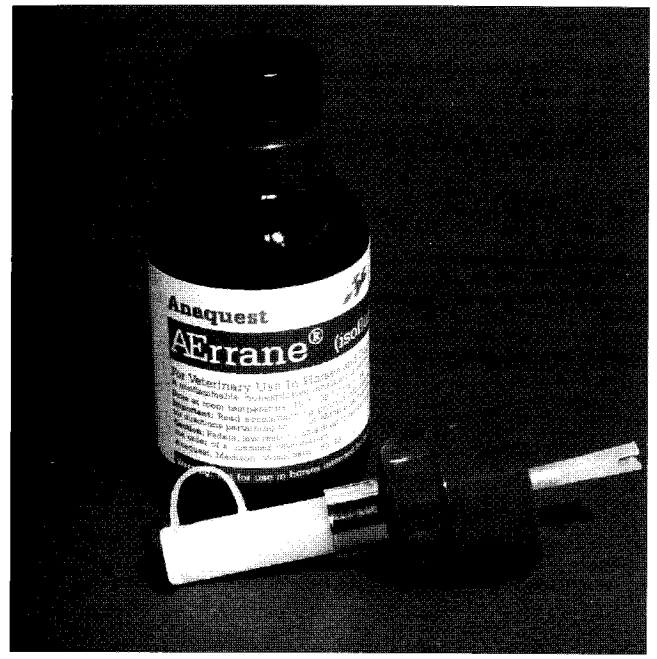

Fig. 17.23. Bottle adapter (Southmedic, Beaumont, TX) for filling isoflurane vaporizers with screw-cap filler ports. The isoflurane bottle has a color-coded collar corresponding to the color on the bottle's label and the color of the bottle adapter. This type of bottle adapter is intended to reduce spillage during the filling of vaporizers with screw-cap filler ports.

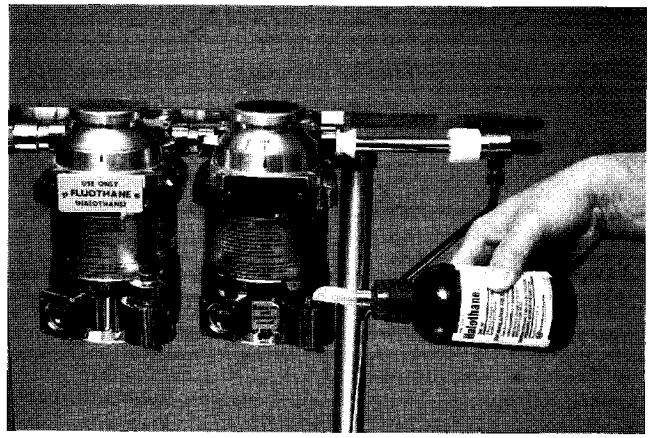

Fig. 17.24. Filling a vaporizer with a screw-cap filler port. Halothane is about to be poured into an isoflurane vaporizer, illustrating the possibility of filling a vaporizer with a screw-cap filler port with the wrong anesthetic. Tec 3 vaporizers for halothane (Fluotec Mark 3) and isoflurane (Isotec 3) are shown in series. The ideal order would be to reverse these vaporizers with the isoflurane immediately downstream from the flowmeters, followed by the halothane vaporizer (see the text for explanation).

Occasionally, veterinarians will use a freestanding, concentration-calibrated vaporizer that is periodically connected between the common gas outlet and the breathing system or between the outlet of another vaporizer and the breathing system. Also, freestanding vaporizers are commonly used with pump oxygenators for cardiopulmonary bypass procedure.[4] A freestanding vaporizer offers a greater opportunity for tipping. The flow through the vaporizer might be inadvertently reversed when vaporizer connections are changed periodically, and oxygen may be forced through the vaporizer with the flush valve if the vaporizer is located downstream from the flush valve. All of these situations lead to a significant increase in the output concentration.[6] Use of a freestanding vaporizer is not the safest approach for access to a second inhalant anesthetic.

In anesthesia machines designed for veterinary use, a concentration-calibrated vaporizer can be connected in reverse, even though the connections are labeled and different sizes. In this configuration, the vaporizer output can potentially be twice that indicated on the control dial.[6]

Fig. 17.25. Screw-cap filler system and sight glass for a Fluotec Mark 3 vaporizer. The location of the filler port prevents the operator from filling the vaporizer excessively because liquid will overflow if the maximum level on the sight glass is exceeded significantly. The plastic tubing on the bottom of the filler system facilitates drainage of the vaporizer.

Classification of Vaporizers

Vaporizers have been classified according to several major characteristics:

1. Method of output regulation
2. Method of vaporization
3. Location
4. Mechanism of temperature compensation
5. Agent specificity
6. Resistance

Even though some authors have used only one feature in classifying vaporizers, such schemes are incomplete because of the variations among vaporizers.[3] As examples of classification

Table 17.2. Classification characteristics of some vaporizers used in veterinary anesthesia[2–4]

Vaporizer	Method of Output Regulation	Method of Vaporization	Location	Temperature Compensated	Resistance	Specificity
Ohio #8	VBP CC–	FO/wick	VIC	No	Low	No
Stephens	VBP CC–	FO/wick	VIC	No	Low	No
Tec 2	VBP CC+[a]	FO/wick	VOC	Yes	High	Yes
Tec 3	VBP CC+	FO/wick	VOC	Yes	High	Yes
Vapor	VBP CC+	FO/wick	VOC	Yes	High	Yes
Vapor 19.1	VBP CC+	FO/wick	VOC	Yes	High	Yes
Ohio Calibrated	VBP CC+	FO/wick	VOC	Yes	High	Yes
Siemens	NA CC+	Inject	VOC	No	High	Yes
Copper Kettle	MF CC–	Bubble-through	VOC	Yes	High	No
Verni-Trol	MF CC–	Bubble-through	VOC	Yes	High	No

CC+, concentration calibrated; CC–, not concentration calibrated; FO, flow-over; MF, measured flow through the vaporizer; NA, not applicable; VBP, variable bypass; VIC, vaporizer in circuit (i.e., in the breathing system); VOC, vaporizer out of circuit (i.e., out of the system).
[a]A Tec 2 vaporizer is concentration calibrated at higher flows of carrier gas, but output varies with low flows.

nomenclature, the characteristics of several vaporizers are summarized in Table 17.2.

1. Regulation of Output

Anesthetic output is regulated in volume percent by variable-bypass or measured-flow mechanisms.[3,4] With variable-bypass vaporizers, all fresh gas flows into the vaporizer, part being directed through and part bypassing the vaporization chamber. The gases rejoin before exiting the vaporizer, establishing the anesthetic concentration dialed with the control knob. The standard for these vaporizers is for the control dial to be turned on in a counterclockwise direction.[1] Concentration-calibrated variable-bypass vaporizers are quite accurate (e.g., Tecs), but uncalibrated variable-bypass vaporizers (e.g., Ohio #8) are inaccurate.

Measured-flow (flowmeter controlled) vaporizers are considered non–concentration-calibrated.[4] They route a small flow of carrier gas (i.e., oxygen) through the vaporizer, and this gas becomes fully saturated with anesthetic. A second source of gas (i.e., oxygen and possibly N_2O) that never enters the vaporizer dilutes the saturated gas to the desired concentration. Calculations are necessary to determine the concentration of anesthetic that is delivered to the common gas outlet and breathing system.

Fig. 17.26. Ohio calibrated vaporizer with paper wicks and copper spacers. The wicks function to increase the surface area for vaporization of inhalant anesthetic.

2. Method of Vaporization

The method of vaporization can be flow-over, bubble-through, or injection.[2–4] *Flow-over* vaporizers direct carrier gas over the surface of the liquid anesthetic. The surface area may be increased with wicks to improve the efficiency of vaporization (Figs. 17.26 and 17.27). The Stephens vaporizer can be used with or without a wick, depending on the anesthetic and the decision of the anesthetist.[22] The *bubble-through* method of vaporization delivers carrier gas below the surface of the liquid through a diffuser (a sintered bronze disk in the Copper Kettle) that disperses bubbles of carrier gas through the liquid anesthetic to increase the liquid-gas interface.[4] Efficiency of vaporization increases with smaller bubbles, deeper bubble dispersion, and slower carrier-gas flow.[2] *Injection* vaporizers deliver a known amount of liquid anesthetic or pure vapor into a known volume of gas to deliver an accurate concentration.[3]

3. Vaporizer Location

In relation to the breathing system, a vaporizer may be located either out of the system (vaporizer out of circuit [VOC]) (Fig. 17.28) or in the system (vaporizer in circuit [VIC]) (Fig. 17.29).[2] High-resistance vaporizers are used as VOC units, and low-resistance vaporizers are necessary for VIC use (because the patient must inspire through the vaporizer). Traditionally, highly potent, highly volatile anesthetics have been administered with VOC vaporizers. However, some VIC vaporizers have been used for delivery of isoflurane and halothane. VIC-type vaporizers have been characterized as being unpredictable in output.[3,23]

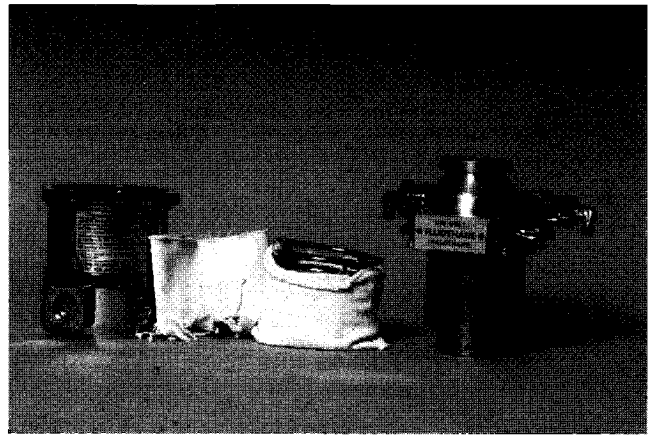

Fig. 17.27. Fluotec Mark 3 vaporizer with cloth wicks. The wicks function to increase the surface area for vaporization of inhalant anesthetic. From Hartsfield.[5]

4. Temperature Compensation

As discussed previously, heat is required to vaporize liquid anesthetics. To prevent or compensate for cooling that alters the rate of vaporization of the liquid anesthetic, heat must be supplied to maintain the temperature of the liquid anesthetic, or the flow of carrier gas through the vaporizer must be adjusted to account for the changing rate of vaporization. Heat may be supplied from the vaporizer itself if it is made of a material with high specific heat and high thermal conductivity (thermostability).[4] Electric heaters and warm-water jackets were used to supply heat for older vaporizers, and an electric heating device has been incorporated into newer vaporizers (e.g., the Tec 6) designed for desflurane.[16] In other vaporizers, alternative thermostatic mechanisms (e.g., a change in carrier gas flow through the vaporization chamber) have been used to counterbalance changes in temperature and vaporization. Manual adjustments of flow through the vaporization chamber are made to offset variations in temperature that occur with measured-flow vaporizers.

5. Agent Specificity

Vaporizers can be either *agent specific* (designed for a particular inhalant anesthetic) or *multipurpose* (used with any volatile liquid anesthetic).[2] A vaporizer that is designed and used for multiple agents should be clearly labeled with the name of the agent currently in the vaporizer. If the anesthetic is changed, the vaporizer should be cleared of the original anesthetic before another anesthetic is introduced into the vaporizer, and draining alone may not eliminate all of the original anesthetic.[3] The trend for vaporizer type has been toward agent-specific, concentration-calibrated vaporizers.

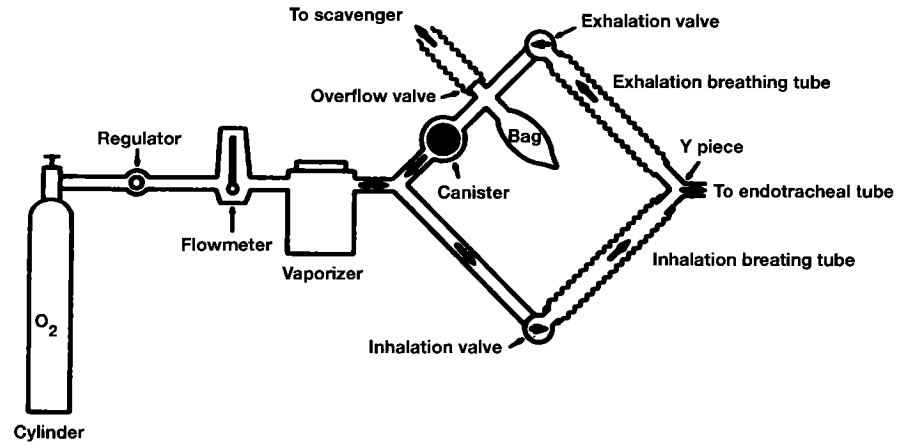

Fig. 17.28. Diagram of a vaporizer located outside the breathing system (vaporizer out of circuit [VOC]) and its relationship to the other basic components of the anesthesia machine and circle system. From Hartsfield.[5]

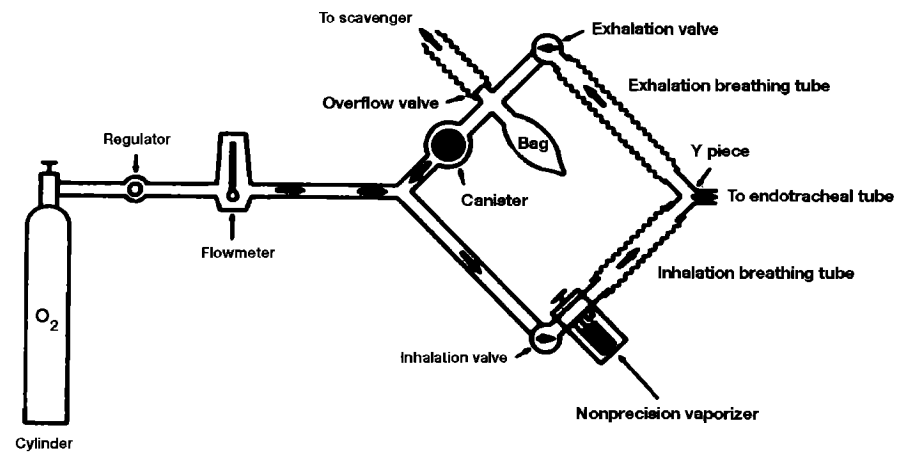

Fig. 17.29. Diagram of the vaporizer located inside the breathing system (vaporizer in circuit [VIC]) and its relationship to other basic components of the anesthesia machine and circle system. From Hartsfield.[5]

6. Resistance

Vaporizers have been classified according to resistance to flow.[3] Plenum-type vaporizers are high-resistance vaporizers designed for location outside of the breathing system, and high resistance is characteristic of contemporary concentration-calibrated, variable-bypass vaporizers. Low-resistance vaporizers are those designed for incorporation into the breathing system[3] and include the Ohio #8 and the Stephens vaporizers.

In-circuit Vaporizers (VICs)

Nonprecision, draw-over, VIC vaporizers were commonly used in veterinary anesthesia for many years. Until the introduction of halothane into veterinary anesthesia, perhaps the most widely used vaporizer for veterinary patients in the United States was the Ohio #8 glass bottle. Although it is no longer manufactured, it was the basic vaporizer on many veterinary anesthesia machines (Pitman-Moore models 960 and 970) sold in the 1970s for administration of methoxyflurane. In the 1990s, the Stephens vaporizer was also marketed for use in veterinary patients. Nevertheless, for safety reasons, VIC vaporizers have generally been recommended for use only with anesthetics of low potency (e.g., ether) or low vapor pressure (e.g., methoxyflurane). In human patients, the Ohio #8 glass bottle was used mostly for administration of diethyl ether and, to a lesser extent, methoxyflurane. The use of halothane and isoflurane in nonprecision vaporizers located within the circuit has been described specifically when used with low-flow or closed breathing systems.[24]

With VIC vaporizers, the inspired anesthetic concentration varies with a patient's respiratory minute volume, use of positive-pressure ventilation, changes in carrier-gas flow rate, and variations in temperature. At a given vaporizer setting, increased spontaneous ventilation, positive-pressure ventilation, and lower fresh gas flows increase the inspired anesthetic concentration. As has been stated specifically for the Ohio #8 vaporizer, "The delivered concentration is unknown and changes unpredictably with use."[23] Without instrumental monitoring of the inspired or expired anesthetic concentration, the anesthetist is completely dependent on the response of the patient to determine appropriate settings for the vaporizer. This is often referred to as *qualitative anesthesia* in contrast to *quantitative anesthesia*, where a known concentration of inhalant (with knowledge of its potency [i.e., MAC value]) is continually delivered to a patient.

Ohio #8 Glass-Bottle Vaporizer

The Ohio #8 vaporizer is classified as variable bypass, flow-over with wick, non–temperature-compensated, VIC, low resistance, and multipurpose.[2] It is designed very simply: The vaporization chamber is made of glass, and a cloth wick creates a large surface area for vaporization (Fig. 17.30). The vaporizer is not calibrated; thus, it is considered nonprecision. The vaporizer has no method of controlling the temperature of the liquid. Its low resistance allows it to be situated in the breathing system (VIC), usually on the inspiratory side of the circle. If positioned on the expiratory limb, the vaporization chamber may become contaminated with water condensing from expired gases. The control arm of the lever is adjustable from zero, corresponding to no gas flow through the vaporization chamber, to 10, corresponding to total inspiratory flow through the vaporization chamber (Fig. 17.31). The possibility of diverting all gas flow through the vaporization chamber makes the use of highly volatile anesthetics particularly dangerous, especially if the wick is in place. The concentration delivered is unknown and may change unpredictably. The function of this vaporizer is probably best summarized by the following statement: "Because of the variability associated with an in-system vaporizer, it is not possible to give performance data."[2] The Ohio #8 vaporizer is no longer being manufactured, and finding expertise and parts for repairing it may be difficult.

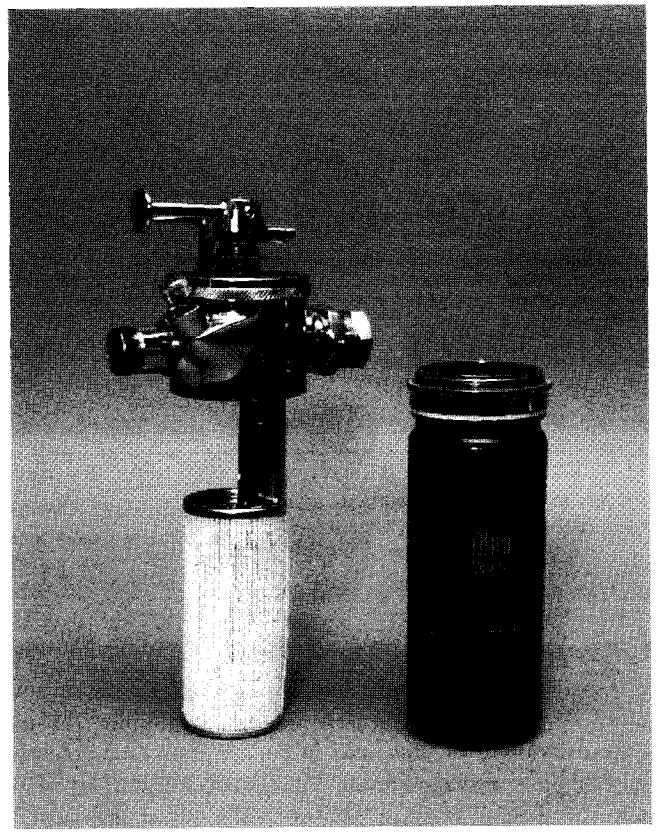

Fig. 17.30. Partially disassembled Ohio #8 glass bottle vaporizer. The cloth wick (*left*) functions to increase the surface area for vaporization of the anesthetic.

The Ohio #8 vaporizer, modified by the removal of the wick, has been proposed as an inexpensive alternative for administration of isoflurane[18] and halothane.[19] Use of an Ohio #8 vaporizer for administration of halothane or isoflurane with the wick in place is dangerous owing to the high concentration of anesthetic that may be delivered in the inspired gases, especially if all carrier gases are diverted through the vaporization chamber. Even with the wick removed, recommendations for using the Ohio #8 vaporizer for isoflurane include familiarity with guidelines for its use and understanding of its limitations.[18] The Ohio #8 vaporizer also has potential for leaking anesthetic into the breathing system when the control lever is off.[2] With age, the vaporizer's valves may not seat properly (Fig. 17.32), allowing continuous passage of fresh gases through the vaporization chamber and production of anesthetic-rich gases.

Fig. 17.31. Control lever for the Ohio #8 jar vaporizer set at position 2. The numbered positions (0 to 10) on the vaporizer correspond to increasing flow of carrier gas through the vaporization chamber. At the closed position (0), all gas entering the vaporizer should bypass the vaporization chamber, and, at full open (10), all gas entering the vaporizer should move through the vaporization chamber.

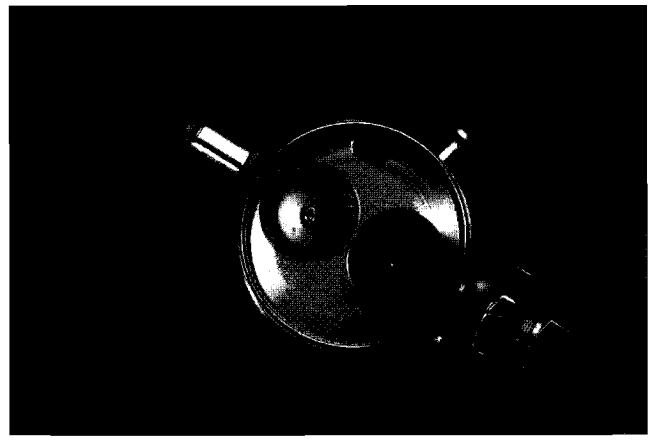

Fig. 17.32. Underside of the head of an Ohio #8 vaporizer showing valves and seats through which gases enter and leave the vaporization chamber. The integrity of these valves in the off position may be lost because of wear or corrosion leading to carrier-gas flow through the vaporization chamber, even when the control lever is in the zero or off position.

Stephens Vaporizer

The Stephens vaporizer is classified as variable bypass, flow-over, non–temperature-compensated, VIC, low resistance, and multipurpose. It is not a precision vaporizer. The vaporizer's low resistance allows it to be located within the breathing system on the inspiratory side. The vaporization chamber is made of glass

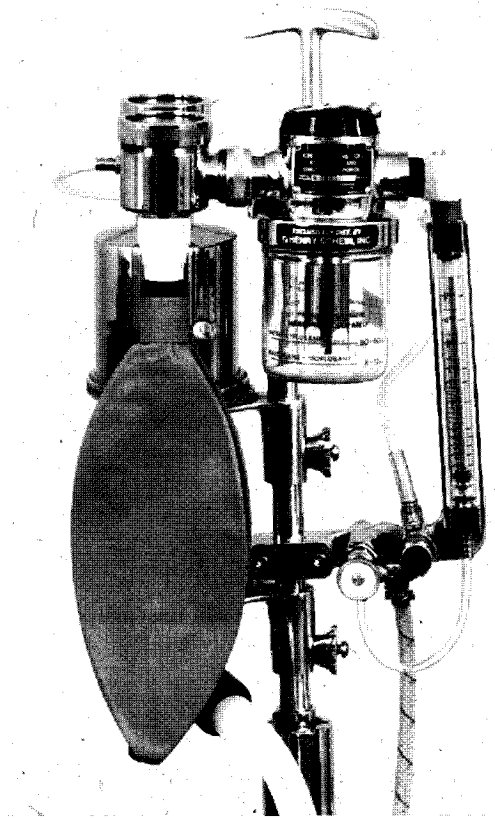

Fig. 17.33. Stephens anesthesia machine and vaporizer (Henry Schein, Port Washington, NY). The glass vaporizer can be set at the off and full-on positions with incremental settings marked in eighths. This vaporizer has been used with methoxyflurane (with a wick in place) and for halothane or isoflurane with the wick removed.

(Fig. 17.33), and a wick is provided for administration of methoxyflurane. The wick should not be used for administration of halothane or isoflurane.[22] The vaporizer is not calibrated and has no method for controlling the temperature of the liquid. The control knob is adjustable from the off position to the full-on position in increments of eighths. The off position indicates no flow through the vaporization chamber, and the on position corresponds to complete flow through the vaporization chamber. The Stephens vaporizer is intended for use in a low-flow circle breathing system.[22]

Out-of-circuit Vaporizers (VOCs)

Modern concentration-calibrated vaporizers located outside of the breathing circuit are considered precision vaporizers: Any volatile liquid anesthetic can be administered safely with a concentration-calibrated, agent-specific, VOC vaporizer. Several brands of VOC-type vaporizers are common in veterinary anes-

Table 17.3. Approximate output (vol%) from a Fluotec Mark 2 vaporizer at various flow rates and dial settings[15]

Dial Setting	1 L/min	2 L/min	3 L/min	4 L/min	6 L/min	8 L/min
0.5%	0	0	0	0.5	0.5	0.5
1.0%	0	0.5	1.0	1.0	1.0	1.0
1.5%	0.5	1.5	1.5	1.5	1.5	1.5
2.0%	1.8	2.0	2.0	2.0	2.0	2.0
2.5%	3.0	2.5	2.5	2.5	2.5	2.5
3.0%	4.0	3.1	3.0	3.0	3.0	3.0
3.5%	5.0	4.0	3.5	3.5	3.5	3.5
4.0%	6.5	5.0	4.1	4.0	4.0	4.0

thesia. Many older models of vaporizers, although no longer being manufactured, remain serviceable and may be purchased as used equipment. Newer VOC-type vaporizers are temperature, flow, and back-pressure compensated. The performance of older VOC-type vaporizers varies with changes in temperature, flow, and back-pressure, and performance data should be reviewed before using them. The concentration control dial and the vaporizer output generally are linear over a wide range of flow rates and temperatures in newer VOC-type vaporizers. The following discussion, though not exhaustive, includes information about several out-of-circuit vaporizers commonly used in veterinary anesthesia.

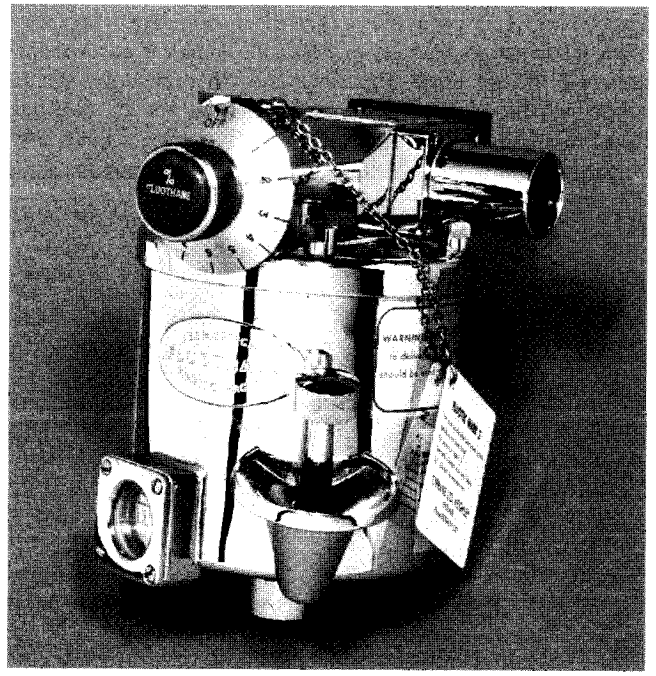

Fig. 17.34. Fluotec Mark 2 vaporizer. The performance characteristics for variations in carrier-gas flow are included on the plastic card attached to the vaporizer (see Fig. 17.35).

Tec Vaporizers

Tec vaporizers specifically designed for halothane or isoflurane vaporization, particularly the Fluotec Mark 3 and Isotec 3, are commonly used in veterinary anesthesia. They are considered reliable because they are temperature, flow, and back-pressure compensated under normal operating conditions. The Fluotec Mark 3's predecessor, the Fluotec Mark 2, is no longer being manufactured, but may still be available as used equipment. In some veterinary practices, Fluotec Mark 2 vaporizers remain in use. Tec 4, 5, and 6 vaporizers have superseded the Tec 3 vaporizers for use in contemporary human anesthesia machines.[6,16] Although these vaporizers have not been as commonly used in veterinary anesthesia, various publications and the specific operation manuals offer information about their use and performance.[3,4,6,16]

Fluotec Mark 2

This vaporizer (Fig. 17.34) is classified as variable bypass, flow-over with wick, VOC, temperature compensated, high resistance, and agent specific.[2] Temperature compensation is with a bimetallic strip valve at the outlet to the vaporization chamber.[3] Performance data show that the Mark 2 becomes imprecise at flow rates below 4 L/min, and inaccuracy increases distinctly below 2 L/min.[2] At flow rates and dial settings likely to be selected for small veterinary patients, the Mark 2's actual output tends to be lower than control-dial settings of less than 2% and higher than dial settings of 2% or greater (Table 17.3).

At the very low flow rates required for closed and low-flow maintenance techniques, the Mark 2's output may decrease to zero or increase to concentrations much higher than the dial settings. Because of its unpredictable output characteristics, the Mark 2 has been categorized as unsuitable and unreliable for use with low fresh gas flow rates.[2,22,25] Back-pressure (e.g., positive-pressure ventilation) increases the output of the Mark 2 dramatically at flow rates less than 2 L/min.[2,26] A pressurizing valve was developed for the Mark 2 to minimize the effects of back-pressure,[2] but it may not be present on all Mark 2 vaporizers. The operator should fully understand the Mark 2's relatively poor performance characteristics before using the vaporizer clinically, and the output diagram for the Mark 2 should be available for consultation during clinical use (Fig. 17.35).

Tec Mark 3 Vaporizers

These vaporizers are classified as variable bypass, flow-over, temperature compensated, agent specific, high resistance, and VOC.[2,3] This model type includes the Fluotec Mark 3, the Pentec Mark 2, and the Isotec 3 vaporizers (Fig. 17.24). The Tec 3 vaporizer is temperature compensated with a bimetallic, temperature-sensitive element associated with the vaporization chamber. Output from the Tec 3 vaporizer is nearly linear over the range of concentrations and flow rates that would typically be selected for veterinary patients (250 mL/min to 6 L/min). Back-pressure compensation is accomplished in the internal design of the vaporizer with a long tube leading to the vaporization chamber, an expansion area in the tube, and exclusion of wicks from the area of the vaporization chamber near the inlet.[2]

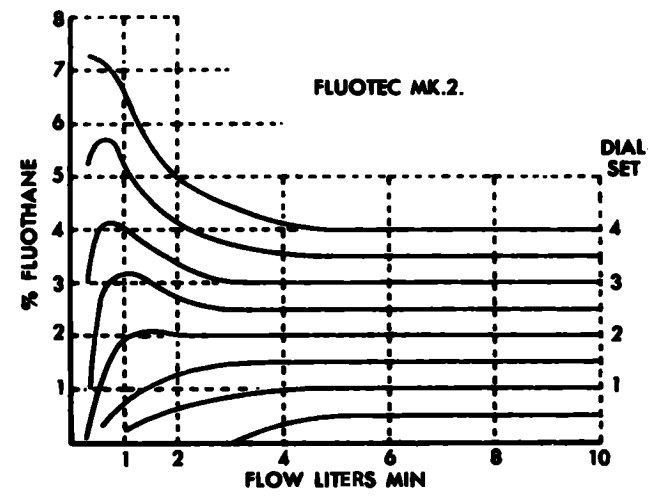

Fig. 17.35. Performance diagram for a Fluotec Mark 2 vaporizer. The diagram indicates expected output of halothane in volume percent for specific control-dial settings at specific carrier-gas flow rates.

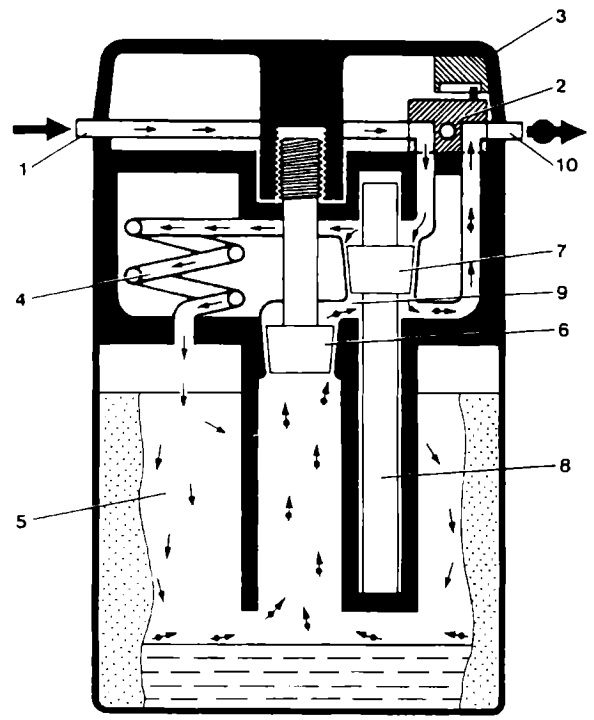

Fig. 17.36. Vapor 19.1 vaporizer (North American Drager, Telford, PA) for isoflurane and a cross-sectional diagram of the vaporizer: *1*, fresh gas inlet; *2*, on-and-off control (activated by concentration knob); *3*, concentration knob; *4*, pressure compensation; *5*, vaporizing chamber; *6*, control cone; *7*, vaporizing chamber-bypass cone; *8*, expansion member for temperature compensation; *9*, mixing chamber; and *10*, fresh gas inlet. From Lumb and Jones.[31]

Vapor Vaporizers: Vapor 19.1 and Vapor

The Vapor 19.1 vaporizer (Fig. 17.36) is classified as variable bypass, flow-over with wick, temperature compensated, high resistance, agent specific, and VOC.[2,3] Specific vaporizers are available for isoflurane and halothane administration. Temperature compensation is automatic with an "expansion member" that varies the flow of gas through the vaporization chamber with changes in temperature. Pressure compensation is accomplished by the presence of a long spiral inlet tube to the vaporization chamber.[4] This vaporizer is accurate from 0.3 to 15 L/min of fresh gas flow at the lower settings on the control dial, but complete saturation may not occur at higher settings with higher flows. The vaporizer is designed for operation (temperature compensation) in the range of 10° to 40°C.[2]

The Vapor vaporizer (Fig. 17.37) preceded the Vapor 19 and 19.1, and has been called "semiautomatic" because manual adjustments are required for complete temperature compensation (Fig. 17.38).[5] The unit is no longer being manufactured, but some vaporizers may still be in operation in veterinary practices. The vaporizer was available for both methoxyflurane and halothane administration. It is classified as variable bypass, flow-over with wick, VOC, temperature compensated by manual flow alteration, high resistance, and agent specific, and is considered to be very accurate.[2] It was designed for thermostability and is constructed of a large mass of copper as a heat sink to prevent excessive cooling during vaporization.[2,27] The concentration dial must be manually adjusted to the temperature chamber within the vaporizer and the liquid between 16° and 28°C (Fig. 17.38).[28] The unit is flow compensated over a wide range (approximately 250 mL/min to 10 L/min), with some deviation at high concentrations at high flows. The mechanism for back-pressure compensation involves a long coiled tube at the inlet to the vaporization chamber.[2]

Other Vaporizers

Ohio Calibrated Vaporizer

This vaporizer (Fig. 17.26) has been available for veterinary use and was commonly employed on human anesthesia machines for many years. This vaporizer is classified as variable bypass, flow-

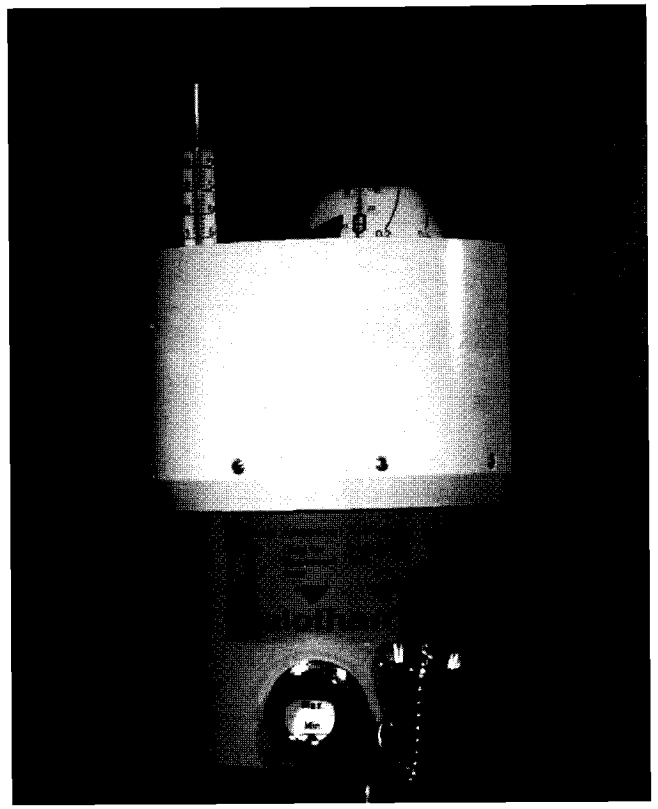

Fig. 17.37. A halothane Vapor vaporizer (North American Drager, Telford, PA).

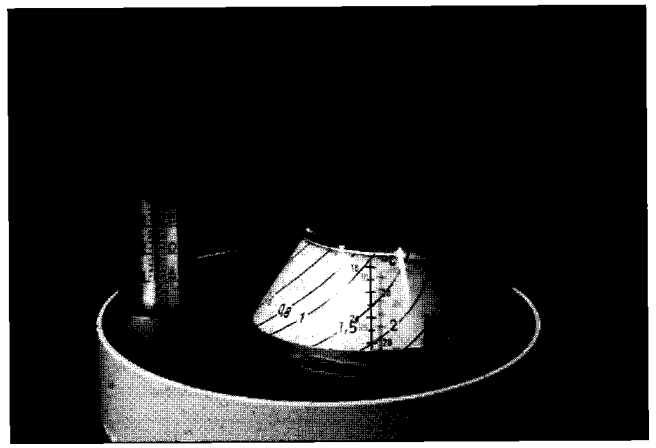

Fig. 17.38. Vapor vaporizer with a control-dial setting of 2% at 28°C. The thermometer (*left*) indicates the temperature within the vaporizer (liquid anesthetic). The control dial is used to manually align the curved line corresponding to the desired anesthetic concentration with the temperature of the liquid anesthetic (the vertical line with hash marks) within the vaporizing chamber. From Hartsfield.[5]

over with wick, automatically temperature compensated, agent specific, VOC, and high resistance.[2,3] Specific units are manufactured for isoflurane, halothane, and sevoflurane administration. These vaporizers were designed for accuracy at fresh gas flows between 0.3 to 10 L/min, and temperature compensation occurs between 16° and 32°C. Tilting these vaporizers up to 20° while in use or up to 45° when not in use does not cause problems. Greater tipping of the vaporizer may cause delivery of high concentrations. Between paper wicks, the vaporizer has plastic spacers that may react with enflurane or isoflurane to cause discoloration of the liquid anesthetic, apparently without significant consequences.[3]

Siemens Vaporizer

This vaporizer is a concentration-calibrated, injection-type, nonthermocompensated, agent-specific, and plenum (high resistance) unit.[3] It has not been used extensively in clinical veterinary anesthesia, except in laboratory-animal facilities associated with hospitals for human patients. The vaporizer was designed to couple with a specific Siemens ventilator. The function and evaluation of this vaporizer have been reviewed elsewhere.[3]

Measured-Flow Vaporizers

Verni-Trols and Copper Kettles (Fig. 17.39) are flowmeter-controlled vaporizers that formerly were popular for use in anesthesia of human patients.[2–4] Copper Kettles were the first devices to enable precise vaporization of liquid anesthetics.[2] These flowmeter-controlled vaporizers are classified as measured flow, bubble-through, high resistance, VOC, temperature compensated (thermally stable with manual flow adjustments based on temperature of the liquid anesthetic), and multipurpose. They have been classified as saturation vaporizers. These vaporizers are constructed of copper (Copper Kettle) or silicon bronze (Verni-Trol) for thermostability. Back-pressure compensation mechanisms are present on more recent models and can be fitted on older models (e.g., check valves). These vaporizers are no longer being manufactured and are not covered by the ASTM standard of 1989.[6] However, they are available on used anesthesia machines and have been purchased for veterinary patient use. Since these vaporizers are multipurpose or universal, they can accurately vaporize halothane, isoflurane, sevoflurane, or methoxyflurane, and should be clearly labeled for the agent in use.

With measured-flow vaporizers, manual adjustments in flow rates are required to account for variations in total gas flow, day-to-day changes in temperature, and changes in liquid temperature during use, especially with high fresh gas flow rates. In most cases, a calculator (Fig. 17.40) is supplied with each vaporizer for determining proper flow rates. Anesthesia machines with measured-flow vaporizers have oxygen flowmeters for two purposes: One flowmeter routes all of its oxygen through the vaporization chamber, where it is fully saturated with anesthetic; the other flowmeter supplies oxygen that bypasses the vaporizer and supplies oxygen to meet the patient's requirements. Both gas sources combine at a mixing valve to achieve the proper anesthetic concentration before gases enter the breathing system.

Since the output of a measured-flow vaporizer is oxygen fully saturated with anesthetic, the concentration of halothane or isoflurane approaches 32%. Dangerously high concentrations of anesthetic can be delivered to the breathing system if flowmeters

Fig. 17.39. Copper Kettle vaporizer (Foregger, Allentown, PA). The vaporization chamber (copper kettle) with its thermometer is behind the table top (*right rear*), and the vaporizer circuit control valve is attached to the left front corner of the tabletop. The flowmeter cluster from *left to right* includes the oxygen flowmeter to the vaporization chamber (black scale), two bypass oxygen flowmeters (green), and one nitrous oxide flowmeter (blue). This cluster does not meet recent standards for the arrangement of flowmeters. From Hartsfield.[5]

Fig. 17.40. A circular slide rule for calculation of oxygen flow rates for an anesthetic machine with a measured-flow vaporizer. The rule can be used for several different anesthetics at various total flow rates over a range of temperatures. This circular slide rule shows that 120 mL of oxygen must be supplied to the vaporizer to produce 3% halothane at a total gas flow rate of 2 L/min at a vaporizer temperature of 23°C.

are set carelessly or if the diluent flow is not turned on. It is also possible to misread the calculator and set incorrect flows.[2] Because such high concentrations can be achieved and because errors in adjustment of flowmeters are possible, the use of continuous monitoring of the inspired anesthetic agent concentration has been recommended.[4]

In addition to using a calculator, the output from measured-flow vaporizers can be calculated or estimated. Methods, including formulas, for calculating flow requirements for measured-flow vaporizers have been reviewed.[22] As previously stated, the vaporization chamber produces an anesthetic concentration equal to the anesthetic's saturated vapor pressure. Thus, if halothane's vapor pressure is 243 mm Hg at 20°C, approximately 32% halothane is delivered to the mixing valve. This concentration is diluted by bypass gases to an appropriate concentration for the patient.

If a patient is to be maintained with a total gas flow of 2 L/min and a halothane concentration of 1.5%, then 30 mL/min of halothane vapor (1.5% × 2000 m/L = 30 mL) must be delivered to the breathing system along with 1970 mL/min of oxygen. About 64 mL of oxygen must enter the vaporization chamber each minute to produce an output of 30 mL/min of halothane: 30 mL = 32% · X, where X is the total gas flow exiting the vaporization chamber; thus, X = 94 mL, and 94 mL − 30 mL = 64 mL. The bypass oxygen flow must equal 2000 mL/min − 94 mL/min or 1906 mL/min. In all calculations, the total gas flow to the patient must be considered, including oxygen, N_2O, and vaporizer flows, for determination of anesthetic requirements.

Using similar computations for methoxyflurane administration at 20°C (vapor pressure = 23 mm Hg), a maximum vaporizer output of 3% can be predicted. Thus, with 2 L/min of total fresh gas flow to the breathing system and a desired concentration of 1%, 20 mL/min of methoxyflurane (1% × 2000 mL = 20 mL) must be delivered to the breathing system. About 647 mL of oxygen must enter the vaporization chamber to deliver 20 mL/min of methoxyflurane vapor to the breathing system: 20 mL = 3% · X, where X is the total gas flow exiting the vaporization chamber; thus, X = 667 mL, and 667 mL − 20 mL = 647 mL. Therefore, 647 mL/min of oxygen must be delivered to the vaporization chamber to produce a total output of 667 mL/min, including 20 mL of methoxyflurane. The bypass flow must them be equal to 1333 mL/min, for a total flow of 2 L/min to the breathing system.

Most of the hazards associated with measured-flow vaporizers relate to incorrect use, including errors in calculation of the out-

put of vapor, failure to turn on the vaporizer flowmeter or the vaporizer circuit control valve, and careless handling of the vaporizer during filling and transport. With tipping, liquid anesthetic may enter the discharge tube of the vaporizer, ultimately delivering very high concentrations of anesthetic to the breathing system. Overfilling is also possible in older models.[2] Older vaporizers may not be equipped for back-pressure compensation, and application of positive-pressure ventilation may significantly increase the concentration delivered.[2] An inflowing gas leak at a faulty O-ring on the base of a sidearm Verni-Trol has reportedly caused reduced oxygen concentration and hypoxia in human patients.[29] Later models of the same machine incorporated a check valve to prevent loss of fresh gas flow. Finally, flow rates below the lowest mark on the scale for the vaporizer's flowmeter should not be extrapolated.

Some measured-flow vaporizers, including the Verni-Trol on the Ohio DM 5000 anesthesia machine[2] and the vaporizer on the old Pitman-Moore 980 veterinary anesthesia machine (Fig. 17.41), designed specifically for methoxyflurane,[22,30] were calibrated for the vaporizer flowmeter to be measured in cubic centimeters (milliliters) per minute of anesthetic vapor rather than in milliliters per minute of oxygen flow to the vaporizer. Consequently, using the flow-rate calculation derived from calculators accompanying Copper Kettles or other Verni-Trol–type machines with these two machines will result in erroneously high delivered concentrations to the anesthetic circuit.[22,31] Volatile anesthetics other than methoxyflurane should not be used in the Pitman-Moore 980 machine's vaporizer.[22,30]

Maintenance of Vaporizers

Vaporizers should be conscientiously maintained. In general, the best policy is to follow the manufacturer's guidelines for care and servicing of vaporizers. Recommendations for maintenance vary. Returning a vaporizer to the manufacturer yearly for cleaning and calibration has been suggested.[32] One source recommends calibration and testing for leaks every 3 to 6 months.[3] Maintenance should be performed on a vaporizer if, based on the responses of patients, the dialed anesthetic concentration is suspected to be erroneous or if any of the components of the vaporizer function improperly (e.g., the control dial is difficult to adjust). Servicing, as recommended by the manufacturer, includes an evaluation of operation, cleaning, changing of filters, replacement of worn parts, and recalibration.[2] Halothane and methoxyflurane contain preservatives (thymol and butylated hydroxytoluene, respectively) that do not vaporize and thus collect in the vaporization chambers and on the wicks, potentially affecting anesthetic output. Vaporizers should be periodically drained to eliminate these preservatives. Vaporizers should not be overfilled or tipped when filled. Vaporizers should be emptied before removal from the anesthesia machine for service. In the past, flushing a vaporizer with ether to dissolve preservatives that collect in it has been recommended. Owing to the flammability and explosiveness of ether, extreme caution should be exercised. Flushing the vaporizer does not eliminate the need for regular service by a certified vaporizer technician.

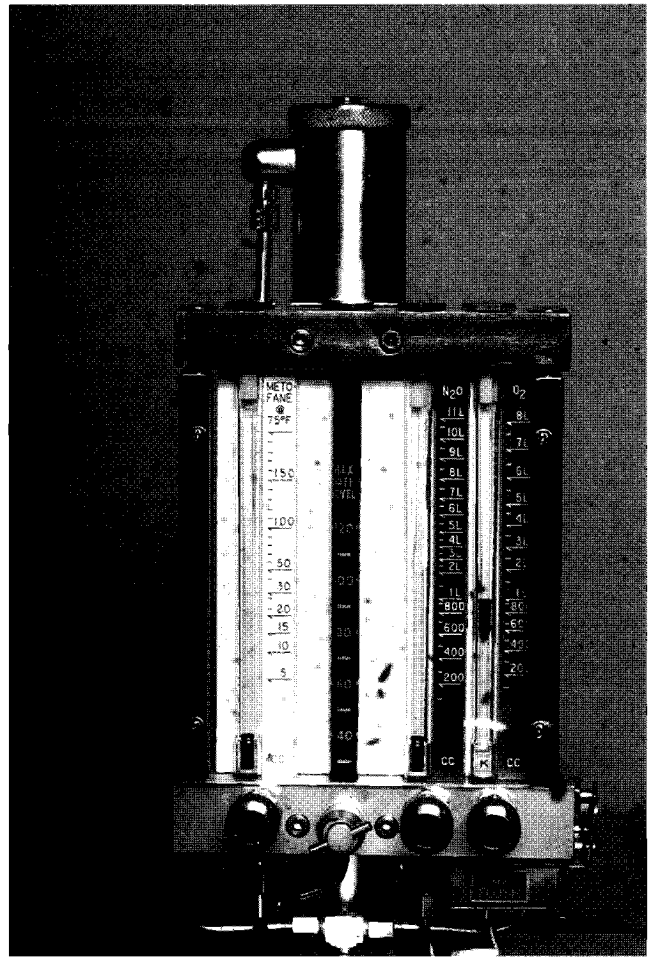

Fig. 17.41. Pitman-Moore 980 veterinary anesthesia machine (Pitman-Moore, Washington Crossing, NJ). This machine includes a Verni-Trol vaporizer with the oxygen flowmeter (*left*, white background) to the vaporization chamber calibrated in milliliters per minute of methoxyflurane vapor. From Hartsfield.[5]

Use of the Wrong Anesthetic in an Agent-Specific Vaporizer

Using an agent-specific vaporizer for an anesthetic for which the vaporizer is not calibrated is problematic, especially if the introduction of an anesthetic is unintentional (i.e., the operator does not realize the mistake). A low output of anesthetic is the expected result if an anesthetic with a lower vapor pressure is placed into a vaporizer designed for a drug with a higher vapor pressure. Conversely, a highly volatile anesthetic in an agent-specific vaporizer designed for a drug with a lower vapor pressure is likely to produce a high, potentially lethal concentration. The differential potencies of the drugs in question would be expected to affect the depth of anesthesia in either situation.

During the introduction of isoflurane into veterinary anesthesia, it was commonly administered with agent-specific, halothane vaporizers that were not recalibrated for isoflurane. Because the vapor pressures of halothane and isoflurane are similar, the output was not expected to differ greatly from the control-dial setting. Indeed, halothane vaporizers produce concentrations of isoflurane that are reasonably close to the dial setting for halothane.[33] Nevertheless, current manufacturer recommendations are against the use of isoflurane in halothane-specific vaporizers and vice versa.[3] Depending on the vaporizer and conditions of operation, isoflurane in a halothane vaporizer may produce 25% to 50% more vapor than expected, and halothane in an isoflurane-specific vaporizer usually delivers a concentration that is lower than expected.[3] If isoflurane is to be used in an agent-specific halothane vaporizer, the vaporizer should be serviced and completely recalibrated for isoflurane. Complete calibration implies that the vaporizer has been tested for accuracy with an anesthetic-gas analyzer at various carrier-gas flows and various temperatures to assure reliable function.

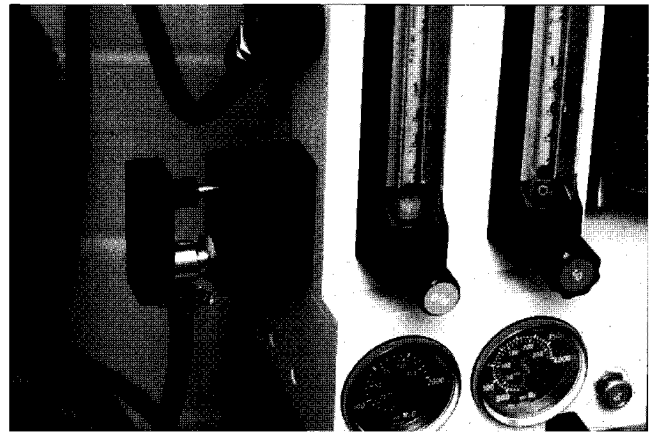

Fig. 17.42. Common gas outlet on a Drager anesthesia machine. The retaining device designed to prevent an accidental disconnection at the common gas outlet is in the closed down position.

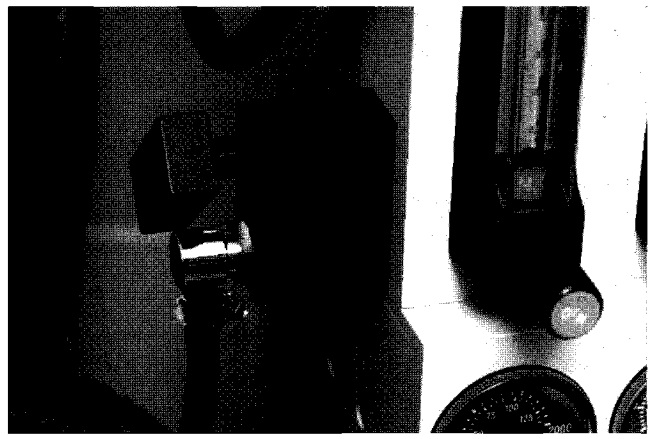

Fig. 17.43. Common gas outlet on a Drager anesthesia machine. The retaining device designed to prevent an accidental disconnection at the common gas outlet is in the open horizontal position.

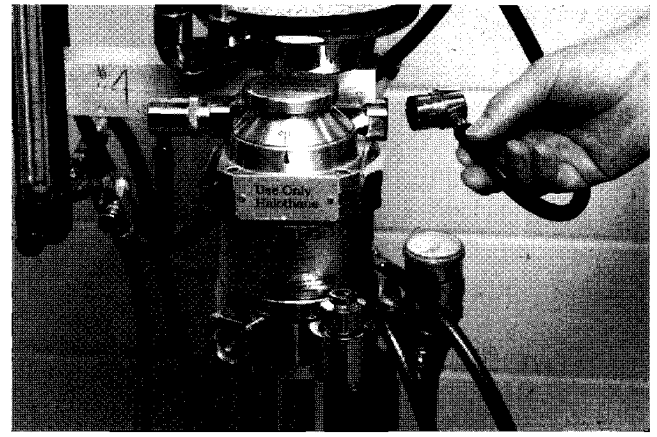

Fig. 17.44. The outlet hose on a Fluotec Mark 3 vaporizer mounted onto a small animal anesthesia machine. The vaporizer outlet connector is attached to a rubber hose that directs anesthetic and carrier gas to the circle system. Alternatively, the rubber hose could be attached to one of the Mapleson systems. A faulty connection to the vaporizer or disconnection of the rubber hose could be responsible for interfering with the delivery of oxygen and anesthetic to the breathing system.

Common Gas Outlet

This outlet is the site from which gases that have passed through the flowmeter, vaporizer (VOC), and flush valve exit the anesthesia machine on the way to the breathing system. Typically, there is a 15-mm internal diameter (ID) opening to which a fitting with rubber tubing attaches (Fig. 17.21). The other end of the tubing connects to the fresh gas inlet of the breathing circuit. In some simple veterinary anesthesia machines with VOC vaporizers, all gases flow directly from the vaporizer outlet to the fresh gas inlet of the breathing system.

Disconnections at the common gas outlet, the vaporizer outlet, or the fresh gas inlet can cause loss of gas flow to the breathing system. The ASTM standard requires that the common gas outlet incorporate a retaining device to prevent accidental disconnection (Figs. 17.42 and 17.43).[1] Disconnects should be detected during the checkout of the machine and breathing system before each case, but disconnects can occur during use of the machine if a retaining mechanism is not present.

A disconnection from the common gas outlet or from the outlet of the vaporizer (Fig. 17.44) during an anesthetic procedure may not be recognized immediately in a spontaneously breathing patient. With a circle system and a VOC, low inspired-oxygen fraction, increased respiratory efforts, and light anesthesia are likely. Some circle systems (Matrx VMS small animal circle) incorporate an air-intake valve (negative-pressure–relief valve [Fig. 17.45]) to entrain room air when the fresh gas flow is inadequate. With a non-rebreathing system and an outlet disconnect, exhaled carbon dioxide will be rebreathed, low F_IO_2 is probable, and the patient will appear lightly anesthetized with increased respiratory efforts. The use of an oxygen analyzer for continuous evaluation of inspired gases enables early detection of this problem.

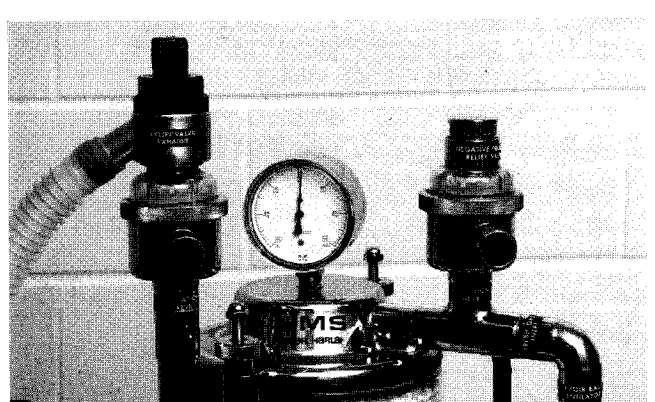

Fig. 17.45. Air-intake valve (negative pressure relief valve) on the dome of the inspiratory one-way valve of a circle system on a Fraser Harlake small animal anesthesia machine. The valve is designed to entrain room air if the supply of fresh gas to the circle breathing system is interrupted. In addition, the pop-off valve is attached to the expiratory one-way valve.

Breathing Systems

Anesthetic breathing systems deliver anesthetic gases and oxygen to the patient, remove carbon dioxide from exhaled gases, and usually provide a means to manually support ventilation. Spontaneously breathing patients inhale and exhale through the breathing system, and the breathing system should be able to supply enough gases to meet the peak inspiratory demands of the patient.

The breathing system adds resistance to the flow of gases, and the diameter of the breathing tubes and other conduits is a major factor in determining the amount of resistance. Doubling the radius decreases the resistance 16 times. Halving the length of the circuit halves the resistance. Changing the direction of gas flow or routing gases through restrictive orifices creates turbulent flow and increases resistance. Therefore, breathing systems should be as short as practical, with maximum diameters in the conduits and the fewest bends and restrictions in the path of gas flow.[2] Generally, the endotracheal tube has the smallest luminal diameter of the breathing apparatus, and the largest tube that is practical should be selected.

Classification of breathing systems has been called a favorite pastime among anesthesiology personnel.[3] Most systems of classification are confusing, not exclusive, and thus not helpful to veterinary students or personnel. When referring to a breathing system in the veterinary or medical literature, the system should be named and physically described, the fresh gas flow rates should be stated, and the patient's body weight and/or oxygen consumption should be listed.[5,34] This eliminates the need for cumbersome, obscure classification systems.

Systems Using Chemical Absorption of Carbon Dioxide

Circle and to-and-fro breathing systems use a chemical absorbent for exhaled carbon dioxide. They are termed *rebreathing* systems because part or all of the exhaled gases, after extraction of carbon dioxide, flow back to the patient. In contrast to *nonrebreathing* systems, rebreathing systems conserve anesthetic, oxygen, heat, and moisture, but impart more resistance to ventilation. Rebreathing systems are relatively expensive to purchase, but comparatively economic to operate.

Circle Systems

Pediatric, standard adult (small animal), and large animal circles differ primarily in their IDs and volumes. Arbitrarily, pediatric circles have been recommended for veterinary patients weighing less than 6.8 kg (15 lb), standard adult circles for patients between 6.8 kg and 135 kg (300 lb), and large animal circles for larger patients.[5] However, choosing the size of circle system for a veterinary patient may be influenced by the species, the practical availability of equipment, the type of ventilation used, and the veterinarian's preferences. In the anesthesia of human patients, a *pediatric circle* usually refers to a standard (adult) absorber assembly, short breathing tubes of small diameter (15 mm ID), and a small bag.[3]

All circle systems have the same basic components, arranged so that gases move in only one direction (Figs. 17.28 and 17.29). Exhaled gases enter the Y piece and flow through the expiratory breathing tube and the expiratory one-way valve. Gases may enter the reservoir bag before or after coursing through the carbon dioxide–absorbent canister. On inspiration, gases exit the reservoir bag and travel through the inspiratory one-way valve, the inspiratory breathing tube, and the Y piece to the patient.

Components of the Circle System

Y Piece This is usually constructed of plastic and unites the endotracheal tube connector and the inspiratory and expiratory breathing tubes. The Y piece contributes to the system's mechanical dead space, but a septum may be present in the Y piece to decrease dead space. It has been argued that the amount of dead space in a standard, adult (small animal) Y piece is not significantly greater than that in a non-rebreathing system.[35] A standard adult Y piece has a 15-mm female port for the endotracheal tube connector, and this port may have a 22-mm outer diameter (OD) to accept a mask. The two 22-mm male ports connect to the breathing tubes. Disposable systems may have the Y piece and breathing tubes permanently attached to each other. The dimensions of the Y piece in large animal circles vary among manufacturers, but approximate 50 mm (2 inches).

Breathing Tubes These tubes are usually made of rubber or plastic, and serve as flexible, low-resistance conduits between the Y piece and the one-way valves. Corrugations reduce the likelihood of obstructions if the tubes are bent. Breathing tubes add length and volume to the system, and increase resistance to ventilation; the tubes should have an ID larger than the ID of the patient's endotracheal tube. Standard adult breathing tubes have a 22-mm ID and have been recommended for small animals weighing more than 7 kg.[36] For smaller patients, 15-mm-ID tubes are available, whereas 50-mm-ID (2 inch) breathing tubes are used with large animal circle systems. Breathing tubes do not contribute to mechanical dead space if the one-way valves are functional.

Fig. 17.46. Components of a unidirectional valve (North American Drager, Telford, PA) of a circle breathing system. From the *left*, the plastic dome, the retaining ring for the dome, the valve itself, and the valve housing are depicted. From Hartsfield.[5]

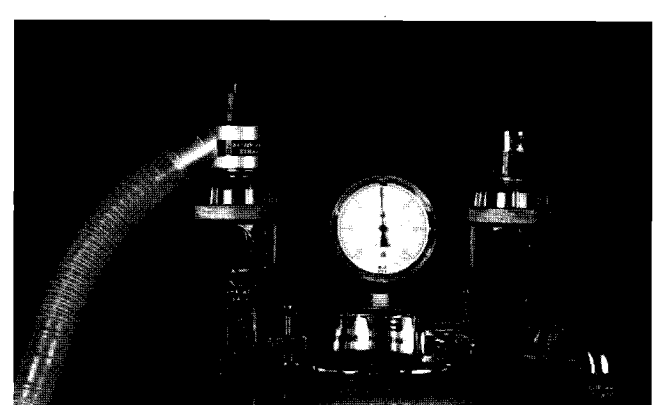

Fig. 17.47. Pop-off valve and manometer on a circle breathing system of a VMS anesthesia machine. The exhaust port (19-mm outer diameter) of the pop-off valve is attached to clear corrugated tubing, which directs waste gases to the scavenging system. The air-intake valve is mounted on the top of the dome for the inspiratory (*right*) one-way valve and functions to entrain room air if the fresh gas supply to the circle system fails.

One-way (Unidirectional) Valves These paired valves direct gas flow away from the patient on expiration and toward the patient on inspiration, preventing the rebreathing of exhaled gases before they pass through the absorbent canister. Gases enter a unidirectional valve from below, raise the disk, and pass under the dome (Fig. 17.46) to the reservoir bag, the absorbent canister, or the inspiratory breathing tube, depending on the location of the valve and the design of the circle. The one-way valves are usually attached to the canister on modern circle systems, but some older systems located the one-way valves within the Y piece, where they were more likely to become incompetent. Valves contribute to the resistance of breathing and should be inspected regularly to assure proper function.

Fresh Gas Inlet This inlet is the location at which gases from the common gas outlet of the anesthesia machine or from the outlet of the vaporizer enter the circle system. The fresh gas inlet is located on the absorbent canister near the inspiratory one-way valve or on the inspiratory one-way valve. Entry of fresh gases on the inspiratory side of the circle minimizes dilution of fresh gases with exhaled gases with a VOC, prevents absorbent dust from being forced toward the patient, and reduces loss of fresh gases through the pop-off valve.

Pop-off Valve This valve (adjustable pressure-limiting valve, relief valve, or overflow valve [Fig. 17.47]) vents gases to the scavenger system to prevent the buildup of excessive pressure within the circle, and it allows rapid elimination of anesthetic gases from the circle when 100% oxygen is indicated. The exhaust port of the pop-off valve through which overflow gases enter the scavenger system is designated to have a 10- or 30-mm male connector according to ASTM standards,[1,3] although older overflow valve ports were sized at 22 mm OD. A pop-off valve should vent gases at pressures of 1 to 2 cm H_2O when it is fully opened. Several types of pop-off valves are available, but those with a spring-loaded disk are common. The pop-off valve is most convenient and relatively conservative with absorbent if it is located between the expiratory one-way valve and the absorbent canister. This location limits waste of fresh gases during exhalation. The pop-off valve is a major safety feature of a circle breathing system regardless of the mode of operation of the circle (e.g., closed, low-flow, or semiclosed fresh gas flow rates). The pop-off valve is designed to prevent the inadvertent buildup of pressure, and it should remain open except during the administration of positive-pressure ventilation.

Reservoir Bag This bag is located on the absorber side of the circle, either upstream or downstream from the canister, depending on the manufacturer. The reservoir bag, which attaches to the bag port, has an outside diameter of 22 mm for small animal circles and 50 mm (2 inches) for large animal circle systems. Gas from an appropriately sized reservoir meets the patient's peak inspiratory flow demands and provides compliance in the system during exhalation.[3] The bag also provides a mechanism for assisted or controlled ventilation. Excursions of the bag during spontaneous ventilation enable the anesthetist to assess respiratory rate and to roughly estimate the tidal volume. In addition, if the pop-off valve is inadvertently left closed, the bag provides a compliant area of the system to prevent the immediate buildup of excessive pressure. Ideally, the bag should not allow pressures to exceed 60 cm H_2O.[3] The minimum size of the reservoir should be six times the patient's tidal volume, but as a matter of practicality, the bag's volume should exceed the patient's inspiratory capacity. Therefore, a spontaneous deep breath should not empty

the bag.[4] For small animal circle systems, 1-, 2-, 3-, and 5-L bags are common, whereas 15-, 20-, or 30-L bags are used for large animals. An optimally sized bag enables the anesthetist to manually support ventilation comfortably and to observe ventilatory excursions. An unnecessarily large bag is cumbersome, impairs monitoring, and slows changes in the inspired anesthetic concentration when settings on an out-of-circuit vaporizer are increased or decreased.

Manometer This device (Fig. 17.47) is a pressure gauge that is usually attached to the top of the absorber assembly. It is calibrated in centimeters of water (cm H_2O), although it may have a scale in kilopascals or in millimeters of mercury (mm Hg). Primarily, manometers are used to assess pressures during assisted or controlled ventilation.

Air-Intake Valve This valve (negative-pressure–relief valve) is included on some veterinary anesthesia machines (Matrx VMS small animal) (Fig. 17.47). Located on the dome of the inspiratory one-way valve in these small circle systems, the valve will entrain room air in emergencies (i.e., absence of fresh gas inflow). If fresh gas flow is interrupted, the valve allows ambient air (21% oxygen) to enter the circle and prevents the patient from inspiring against a negative pressure and becoming hypoxic.

In-circuit Vaporizers Vaporizers can be located within the breathing system (Fig. 17.29), the Ohio #8 glass bottle and the Stephens being the most likely vaporizers located in this position. The primary requirement is that the in-circuit vaporizer be of a low-resistance type, because patients must inspire through the vaporizer.

Absorber This assembly, which contains the canister for the chemical absorbent for carbon dioxide, is located between the one-way valves, on the side of the circle opposite the patient (Fig. 17.48). The canister is usually one plastic container or two stacked plastic containers. For a specific patient, the canister should be large enough to contain an airspace between chemical granules that is equal to or greater than the patient's maximum tidal volume. The intergranular space is approximately 50% when a canister is filled with standard absorbent (4- to 8-mesh size).[4] Exhaled gases may enter the top or bottom of a canister, and baffles or annular rings (Fig. 17.49) in many absorbers move gases toward the center of the canister to compensate for lower resistance to gas flow near the canister wall. Without baffles or annular rings, channeling of gases and inefficient absorption of the carbon dioxide may occur. Internal tubes for gas return from an absorber may enhance the wall effect and gas channeling.[2] Some absorber units, especially those for large animals, have drain in the bottom to discharge water that condenses from exhaled gases.

The canister filled with absorbent, besides being a source of resistance during ventilation, is an important area for malfunctions in circle systems. The canister is removed regularly to change the absorbent, and failure to create a seal adequately when replacing the canister causes leaks. Normal wear and tear may damage the canister, the caustic effects of soda lime may corrode metal parts, and aging causes gaskets to deteriorate. Simply leaving soda lime granules on the gaskets can make a tight seal impossible. One report described the bypass of soda lime with resultant hypercarbia because of the disconnection of the diffuser foot from the conduction tube in the canister on a veterinary anesthesia machine.[37] Newer circle systems are constructed with materials less vulnerable to the effects of soda lime.

Some circle systems were designed with a mechanism for purposely bypassing the absorbent canister (Fig. 17.50). The bypass was intended for use during the changing of soda lime and for intentionally elevating the inspired concentration of carbon dioxide.[2] If these obsolete systems are used in veterinary practices, the operator should understand the function of the bypass and its control apparatus and should not operate the circle in the bypass mode.

Fig. 17.48. Absorber assembly for a Matrx (Orchard Park, NY) large animal circle breathing system. Attached to the absorber canister are the unidirectional valves, the manometer, the ports for the breathing hoses and reservoir bag, and the pop-off valve.

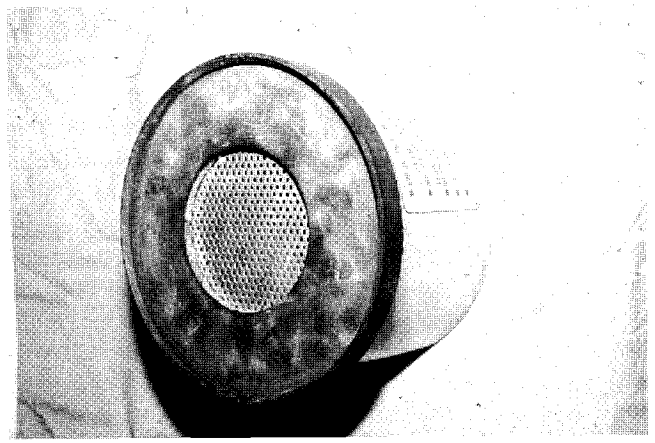

Fig. 17.49. An absorber assembly with an annular ring. The ring diameter, being smaller than the canister diameter, promotes dispersion of gases throughout the canister and helps to prevent preferential flow of gases next to the walls of the canister leading to the development of dead space.

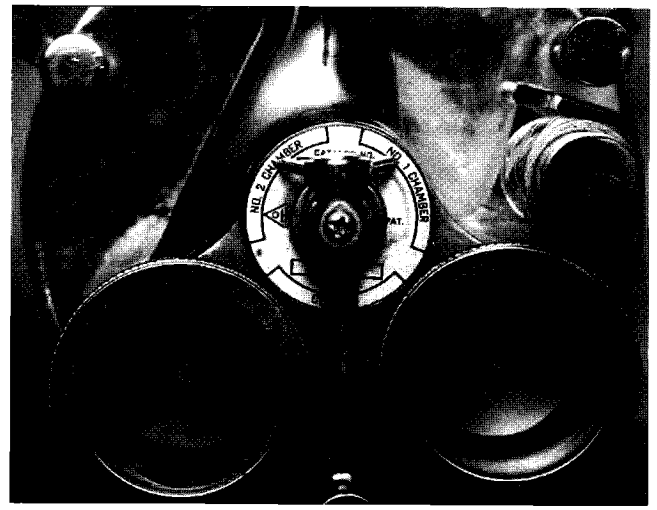

Fig. 17.50. The top of an absorber from an obsolete circle breathing system. The control on the absorber functions to direct exhaled gases through one or both chambers of the canister. With both indicators in the closed position, exhaled gases bypass the carbon dioxide absorbent completely.

Chemical absorption of carbon dioxide is a fundamental function of circle and to-and-fro breathing systems. Depending on the fresh gas inflow, all or part of the exhaled carbon dioxide may be absorbed chemically. If the fresh gas flow approximates the patient's oxygen consumption, almost all exhaled carbon dioxide will be chemically neutralized. Chemical absorption of carbon dioxide allows lower fresh gas flows, reduces wastage of anesthetics and oxygen, and lowers the cost for anesthesia. With high fresh gas flows, much of the exhaled carbon dioxide escapes through the pop-off valve and into the scavenger system, and the dependence on chemical absorption of carbon dioxide is decreased.

Chemical Absorption of Carbon Dioxide

Calcium hydroxide is the primary component of soda lime and barium hydroxide lime, the two most common absorbents for carbon dioxide. Small amounts of sodium and potassium hydroxide in soda lime activate the reaction, and silica and kieselguhr are included to give hardness to the granules.[2,3] Barium hydroxide lime is inherently hard owing to bound water molecules and does not require silica.[2] For optimal absorption of carbon dioxide, 14% to 19% H_2O is required in soda lime. Water formed during granule reactions with carbon dioxide can be useful in humidifying dry gases from the fresh gas inlet, but does not participate in the reactions of chemical absorption of carbon dioxide. The overall chemical reaction of carbon dioxide with soda lime includes multiple steps (e.g., carbon dioxide first reacts with water to form carbonic acid), but can be summarized as follows:

$$2\ NaOH + 2\ H_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + Na_2CO_3 + 4\ H_2O + \text{heat}$$

($CaCO_3$, calcium carbonate; $Ca[OH]_2$, calcium hydroxide; H_2CO_3, carbonic acid; Na_2CO_3, disodium carbonate; and NaOH, sodium hydroxide)

Fig. 17.51. Evaluation of the consistency of soda lime granules. Functional granules are relatively soft and easily crushed, whereas expended granules are hard.

The granule size for chemical absorbents is typically 4 to 8 mesh and represents a compromise between absorptive activity and airflow resistance.[2] Small granules offer the most surface area for chemical reactions, but large granules impose less resistance to gas flow through the canister. Proper packing of a canister is necessary to prevent flow of gases over a single pathway in the canister, creating excessive dead space. Gentle shaking of the canister upon filling it with an absorbent will avoid loose packing and reduce channeling. Packing too tightly should be avoided to prevent formation of dust and increased resistance to ventilation.[4]

During evaluation of a rebreathing system, the anesthetist should confirm that the absorbent is functional. Fresh granules of calcium hydroxide are soft enough to be easily crushed, whereas expended granules have chemically changed to calcium carbonate and are hard (Fig. 17.51). Indicators of pH are added to absorbents to show color changes as chemical reactions proceed. Soda lime changes from white to violet as the granules are exhausted. The violet may revert to white during storage, but will reappear when the granules are exposed to carbon dioxide again. Newer CO_2 absorbents will maintain this color change and are less reactant producing less heat, carbon monoxide, and compound A. The absorption of carbon dioxide is an exothermic reaction, and a "heat line" should be detectable on the wall of the canister if carbon dioxide absorption is effective. Heat is particularly notable in canisters for large animals. The amount of carbon dioxide absorption is about 26 L/100 g,[4] but efficiency may vary, depending on the design of the canister and the method of packing. When using a circle system with a chemical absorbent, the inspired carbon dioxide should be near zero.[2] Measuring the concentration of carbon dioxide in inspired gases, with 0.1% to 1.0% being acceptable[38,39] is the most accurate way to determine whether the absorbent is functional.[2,3] Without such measurements, the absorbent should be exchanged when the color reaction is apparent in approximately two-thirds of the absorbent.[2,36]

Fresh Gas Flows for Circle Breathing Systems

Fresh gas flow–rate recommendations for circle systems are somewhat controversial. Semiclosed, low-flow, and closed circles are the options, and when all factors are considered, a veterinarian's personal preference usually determines the flow of fresh gas. Nevertheless, there are differing advantages to the various fresh gas flow rates discussed. The terms *closed*, *low-flow,* and *semiclosed* are often used in reference to circle breathing systems and refer to the fresh gas–inflow rate compared with the metabolic needs of the patient. The terms do not denote any structural differences among the breathing systems, and they do *not* relate any information about the state of the pop-off valve (open or closed).

Closed Circle System

Closed-system anesthesia occurs when there is a low flow of anesthetic gases and oxygen to the patient and system.[3] Thus, the oxygen flow into a closed circle approximates the patient's oxygen consumption, which varies with the patient's metabolic rate. Metabolic rate and oxygen consumption are influenced by the patient's body weight and body-surface area, its temperature, its state of consciousness, and the type of anesthetic. Table 17.4 lists values for oxygen consumption in dogs as reported in several publications. Table 17.5 includes published recommendations for fresh gas flows for closed circle systems in dogs, and all fall within the minimum and maximum rates of oxygen consumption reported for dogs as listed in Table 17.4. In practice, observation of the reservoir bag enables the anesthetist to adjust the fresh gas flow to approximate the patient's uptake of gases when using a closed system.

Although a patient's oxygen consumption is used to guide the rate of fresh gas flow into a closed system, the minimum flow of carrier gas for accurate function of the vaporizer should be considered. Concentration-calibrated, variable-bypass vaporizers (VOCs) require a certain minimum flow to assure proper performance, and flow below the minimum may cause erratic output of anesthetic. With a vaporizer, the lowest flow known to produce a reliable output should be the minimum acceptable flow for the breathing system. Strategies for using closed-system anesthesia with both in-circuit and out-of-circuit vaporizers have been reviewed.[24]

Generally, N_2O is not used in a closed breathing system because of the potential for developing hypoxic gas mixtures with low inflow of oxygen. If N_2O is administered in a closed system, continuous monitoring of F_IO_2 is imperative. With closed systems, denitrogenation of the system by emptying the reservoir bag through the pop-off valve and refilling the system with fresh gas should be done two to four times during the first 15 min of anesthesia and each 30 min thereafter to prevent exhaled nitrogen from diluting oxygen in the system.[31,40] A closed system is completely dependent on chemical carbon dioxide absorption, and the quality of the absorbent should be assured before each use. Ideally, the inspired concentration of carbon dioxide should be monitored to assure proper function of the absorbent. Closed systems are more economic, retain more heat and humidity, and are less likely to produce operating-room pollution than other systems.

Table 17.4. Values reported for consumption of oxygen in dogs

Oxygen Consumption ($mL \cdot kg^{-1} \cdot min^{-1}$)	Conditions	Reference
6 to 8 $mL \cdot kg^{-1} \cdot min^{-1}$	Anesthetized	Soma[46]
10 to 11 $mL \cdot kg^{-1} \cdot min^{-1}$	Anesthetized	Soma[46]
4 to 8 $mL \cdot kg^{-1} \cdot min^{-1}$	Awake, resting	Haskins[63]
9 to 14 $mL \cdot kg^{-1} \cdot min^{-1}$	Ketamine anesthesia	Haskins[63]
3 to 7 $mL \cdot kg^{-1} \cdot min^{-1}$	Barbiturate and inhalant anesthesia	Haskins[63]
4 to 7 $mL \cdot kg^{-1} \cdot min^{-1}$	Basal metabolic rate	Wagner and Bednarski[24]

Table 17.5. Recommendations for oxygen flow for closed circle systems in veterinary anesthesia

Oxygen Flow Rate	Reference
11 $mL \cdot kg^{-1} \cdot min^{-1}$	Hartsfield[5]
4.4 to 11 $mL \cdot kg^{-1} \cdot min^{-1}$	Muir and Hubbell[41]
4 to 7 $mL \cdot kg^{-1} \cdot min^{-1}$	Wagner and Bednarski[24]
4.4 to 6.6 $mL \cdot kg^{-1} \cdot min^{-1}$	Muir and Hubbell[32]

Low-Flow Circle System

Low-flow anesthesia for small animals has been defined as an oxygen flow rate greater than the patient's oxygen consumption (4 to 7 $mL \cdot kg^{-1} \cdot min^{-1}$) but less than 22 $mL \cdot kg^{-1} \cdot min^{-1}$.[24] In the definition, 22 $mL \cdot kg^{-1} \cdot min^{-1}$ was used because it is the lower limit of the traditional range of flow for a semiclosed circle system.[41] The advantages of a low-flow system are similar to those for a closed system, including economy, reduced waste gas, and some retention of heat and moisture.[42] The primary disadvantage of low-oxygen-flow techniques relates to the inadequate delivery of anesthetic from a concentration-calibrated, variable-bypass vaporizer during mask induction or during the transition from a short-acting injectable anesthetic induction to the maintenance of inhalant anesthesia. The suggested solution for this problem is the use of higher fresh gas flow rates for the first 15 to 30 min of anesthesia, followed by a change to low-flow technique after the uptake of inhalant anesthetic by the patient has decreased.[24] Similarly, changing depth of anesthesia is slower with low fresh gas flow rates. To increase anesthetic concentration in the system with a concentration-calibrated, out-of-circuit vaporizer, the fresh gas flow should be increased temporarily to speed the process. To lower the anesthetic concentration, the concentration setting on the vaporizer should be decreased and fresh gas inflow increased with either an out-of-circuit or in-circuit vaporizer location. For small animals, 10 to 15 $mL \cdot kg^{-1} \cdot min^{-1}$ has been suggested as an appropriate flow rate for a low-flow system.[24]

Semiclosed Circle System

This terminology describes a system in which the fresh gas inflow exceeds the uptake of oxygen and anesthetic by the patient.

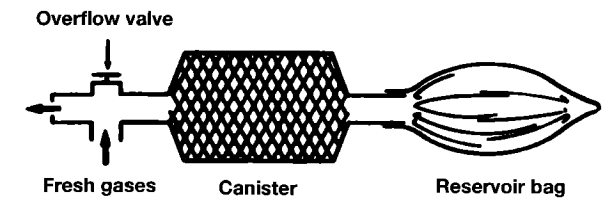

Fig. 17.52. Diagram of a to-and-fro rebreathing delivery system showing the component parts: patient connector, pop-off valve, fresh gas inlet, canister, and reservoir bag. From Hartsfield.[5]

Traditional flows for semiclosed circle systems range from 22 to 44 $mL \cdot kg^{-1} \cdot min^{-1}$.[24,41] A significant quantity of excess gas must be eliminated through the pop-off valve. The choice of flow rate for a semiclosed circle is based primarily on personal preference, but the patient's oxygen consumption times three has been a common guideline. For example, if a dog's oxygen consumption is 7 $mL \cdot kg^{-1} \cdot min^{-1}$, the fresh gas flow would be 21 $mL \cdot kg^{-1} \cdot min^{-1}$. Use of N_2O will increase total gas flow requirement. For a 50% N_2O mixture, oxygen flow would equal 21 $mL \cdot kg^{-1} \cdot min^{-1}$, and N_2O flow would equal 21 $mL \cdot kg^{-1} \cdot min^{-1}$, with a total fresh gas flow of 42 $mL \cdot kg^{-1} \cdot min^{-1}$. With a semiclosed circle, nitrogen accumulation within the system is not significant because gases are rapidly eliminated through the pop-off valve. N_2O can be used safely, the inspired anesthetic concentration can be changed rapidly, and dependency on the carbon dioxide absorbent is less because carbon dioxide is partly eliminated through the pop-off valve into the scavenging system. However, the retention of heat and humidity is lessened, and economy is less, compared with closed and low-flow systems.

Breathing systems that produce the least resistance to gas flow should be chosen for spontaneously breathing patients. Resistance to gas flow through a circle breathing system is influenced primarily by the pop-off valve, unidirectional valves, and carbon dioxide absorbent canister.[2] The total resistance in a circle system varies with the fresh gas flow rate and the type of ventilation. High fresh gas flow rates can increase flow through the pop-off valve and therefore may increase resistance to ventilation. The ventilation pattern affects the flow rate and therefore the resistance through the soda lime canister and the unidirectional valves.[2]

Resistance to breathing has been cited as a reason for not using adult circle systems for pediatric patients. However, Dorsch and Dorsch[2] suggest that the use of circle systems in spontaneously breathing pediatric patients may not be contraindicated solely on the basis of resistance. For veterinary patients, it has been recommended that circle breathing systems are appropriate for healthy animals weighing as little as 2.5 to 3.0 kg.[24,43,44]

Resistance to constant flow in large animal breathing circuits has been assessed.[45] Greater resistance occurs with higher flows through all of the breathing circuits. The Drager and Fraser Sweatman circuits were intermediate in total resistance when nine different circuits were compared, and each circuit had individual parts that contributed significantly to resistance in at least one of the circuit types. Since low resistance is considered an advantage, it has been suggested that most larger animal breathing circuits be redesigned to help minimize resistance.

To-and-Fro System

This type of rebreathing system (Fig. 17.52) is much less popular than the rebreathing circle and Mapleson systems. The to-and-fro system has a carbon dioxide–absorbent canister located between the endotracheal tube connector and a reservoir bag. A pop-off valve and the fresh gas inlet are positioned between the canister and the endotracheal tube connector. A to-and-fro system is suitable for both large and small animals if proper canisters are available.[28,46] With low flows approximating the patient's oxygen consumption, carbon dioxide removal depends on chemical absorption. With higher flows, part of the expired carbon dioxide is vented through the pop-off valve.

Portability, simplicity, and ease of disassembly for cleaning are advantages of the to-and-fro system. Disadvantages are related to the position of the system, including the canister, next to the patient. Heat produced during carbon dioxide absorption may be transferred to the patient during inspiration, there is greater potential for inhalation of alkaline dust from the absorbent than with a circle system, and the system is quite cumbersome. Over time, channeling of gases through the canister may create dead space in the absorbent, causing inefficient absorption of carbon dioxide. The horizontal position of the canister is probably less desirable than the vertical position used in most circle rebreathing systems.[4] As with circle systems, denitrogenation during the early phases of anesthesia is required to prevent hypoxia, especially with lower fresh gas flows.

Mapleson Systems

Breathing systems that use no chemical absorbent for carbon dioxide, but depend primarily on high fresh gas flow rates to flush exhaled carbon dioxide from the system, have been classified as Mapleson systems. They have been called *nonrebreathing systems* as a group, though this terminology is technically incorrect because some rebreathing of exhaled gases occurs in most of these systems, especially with lower recommended flow rates.[5]

The Mapleson systems are simple and easy to use, are easily cleaned and sterilized, are lightweight and compact, can be positioned conveniently, have few moving parts, are relatively inexpensive, impart little resistance to respiration, do not require carbon dioxide absorbents, add minimal mechanical dead space, and allow the inspired concentration of anesthetic to be changed rapidly. The main disadvantages of using Mapleson systems is the requirement for higher flow rates of fresh gas, which decreases temperature and increases cost. Higher flow rates promote hypothermia and drying of the respiratory tract. The Mapleson sys-

Table 17.6. Characteristics of the Mapleson breathing systems

Class	Fresh Gas Inlet	Overflow Location	Presence of a Reservoir	Corrugated Tubing	Example System
A	Near the reservoir	Near the patient	Yes	Yes	Magill
B	Near the patient	Near the patient	Yes	Yes	[a]
C	Near the patient	Near the patient	Yes	No	[a]
D	Near the patient	Away from the patient[b]	Yes	Yes	[a]
MD[c]	Near the patient	Away from the patient	Yes	Yes	Bain
E	Near the patient	Away from the patient	No	Yes	T-piece
F	Near the patient	Away from the patientb	Yes	Yes	Jackson-Rees

[a]No system in this classification is commonly used in veterinary anesthesia.
[b]The overflow may be located between the reservoir and the corrugated tubing of the system.
[c]MD, modified Mapleson D system.

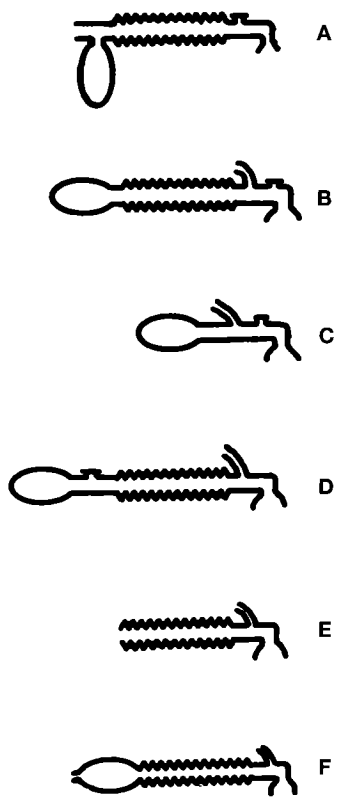

Fig. 17.53. Diagrams of each of the Mapleson breathing systems (*A–F*, Mapleson systems). From Rayburn.[64]

tems are diagramed in Fig. 17.53, and characteristics of the Mapleson systems are listed in Table 17.6.

Magill System

The Magill system (Fig. 17.54) is classified as a Mapleson A system and is characterized by a fresh gas inlet, an overflow valve near the patient, and a corrugated tube connecting the patient end of the system to a reservoir bag.[46] Fresh gas flows continuously into the reservoir bag and into the corrugated tubing, moving carbon dioxide–rich gases through the overflow valve. The system is efficient during spontaneous ventilation, but, during controlled ventilation, some rebreathing of expired gases occurs. Fresh gas inflow should approximate the patient's minute volume,[9] with flows less than 0.7 of minute volume leading to some rebreathing.[2] The N_2O flow should be calculated as a part of the total fresh gas inflow. The volume of the corrugated tubing and the reservoir bag should be equal to or greater than the patient's tidal volume. Because of the location of the overflow valve, the system is relatively cumbersome during controlled ventilation.

Bain Coaxial System

This system (Fig. 17.55) is classified as a modified Mapleson D design. It is configured as a tube within a tube.[9] The internal tube (0.7 mm ID) supplies fresh gases to the patient end of the system (Fig. 17.56), minimizing mechanical dead space. The Bain system accepts an endotracheal connector (15 mm) or a mask (22 mm). The external corrugated tube conducts exhaled gases from the patient to a reservoir bag. The reservoir bag may attach directly to the corrugated tubing, in which case the pop-off valve is built into the bag, or the corrugated tubing may attach to a metal head with drilled channels and accommodations for the reservoir bag, the overflow valve, and optionally a manometer.[2,3]

Recommendations for total fresh gas flow into a Bain system are variable for both human and animal patients. Recommendations have been based on minute volume, body weight, and body surface area.[2] During spontaneous ventilation, 200 to 300 mL $\cdot$ kg^{-1} $\cdot$ min^{-1} has been recommended for anesthesia of human patients.[9] Fresh gas flows from 100 to 150 mL $\cdot$ kg^{-1} $\cdot$ min^{-1} have been recommended for veterinary patients.[36,47] Some investigators[48] have suggested a fresh gas flow rate of 200 mL $\cdot$ kg^{-1} min^{-1} for patients weighing less than 7 kg, whereas others have recommended a flow rate of 220 to 330 mL $\cdot$ kg^{-1} $\cdot$ min^{-1}.[32] The fresh gas flow that will eliminate rebreathing during spontaneous ventilation with a Bain system differs significantly from patient to patient. After reviewing numerous references, Dorsch and Dorsch[3] concluded that most studies recommended fresh gas flows of 1.5 to 3.0 times minute volume. Less than two to three times the minute volume will result in some rebreathing of carbon dioxide, but the end-tidal carbon dioxide concentration may remain normal even with some rebreathing of carbon dioxide.[3] For spontaneously breathing patients, 440 to 660 mL $\cdot$ kg^{-1} $\cdot$ min^{-1} may be used for maintenance of anesthesia with the Bain system to assure that rebreathing of exhaled gases does not contribute to increases in arterial carbon dioxide partial pressure. Without regular monitoring of carbon dioxide tensions or expired carbon dioxide values, the exact flow requirements are difficult to define for an individual patient. Minute volumes for dogs and cats range from 170 to 350 mL $\cdot$ kg^{-1} $\cdot$ min^{-1} and 200 to 350 mL $\cdot$ kg^{-1} $\cdot$ min^{-1}, respectively.[49] Using these values for minute volume, an argument can be made for even higher flows than 660 mL $\cdot$ kg^{-1} $\cdot$ min^{-1}. In general, a total fresh gas flow of less than 500 mL/min or more than 3 L/min with a Bain system is not recommended for animals that weigh less than 6.8 kg. With controlled ventilation, 100 mL $\cdot$ kg^{-1} $\cdot$ min^{-1} is apparently an adequate flow for fresh gases.[50] For larger patients maintained with an adult Bain system, lower total fresh gas flow (e.g., 100 mL $\cdot$ kg^{-1} $\cdot$ min^{-1}) may be appropriate. Use of Bain systems has been effective in dogs weighing up to 35.5 kg.[47] Fresh gas flows higher than usually recommended are indicated in situations of increased carbon dioxide production, increased dead space, and decreased minute ventilation.[3] Flow rates of two to three times minute volume have been recommended for hypoventilating animals in which controlled ventilation was not corrective.[47]

During spontaneous ventilation, a Mapleson D system has been shown to function identically to a Mapleson F system.[2] The Bain's coaxial design has been shown to be effective in reducing loss of heat and humidity,[2] although the overall benefit is questionable in small veterinary patients maintained with relatively high fresh gas flow rates.

Ayre's T-Piece and Norman Mask Elbow Systems

Ayre's T-piece and Norman mask elbow systems (Fig. 17.57) equipped with an expiratory limb (corrugated tubing) and reservoir bag are classed as Mapleson F systems.[2] Without a reservoir bag, they are Mapleson E systems. The T piece itself is a T-shaped tube with a 1-cm ID. Fresh gas enters the tube from the side, perpendicular to the direction of gas glow during ventilation

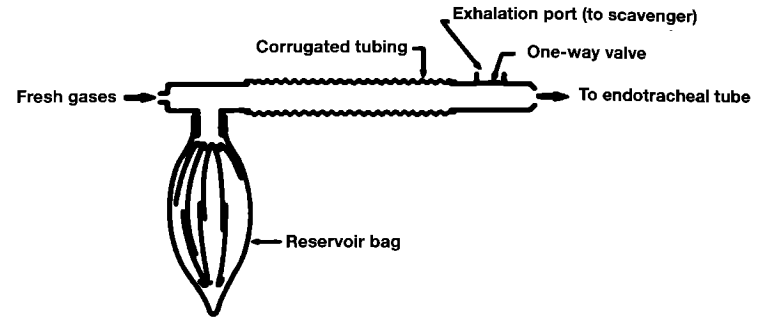

Fig. 17.54. Diagram of a Magill system illustrating the basic components and the entry of fresh gases. From Hartsfield.[5]

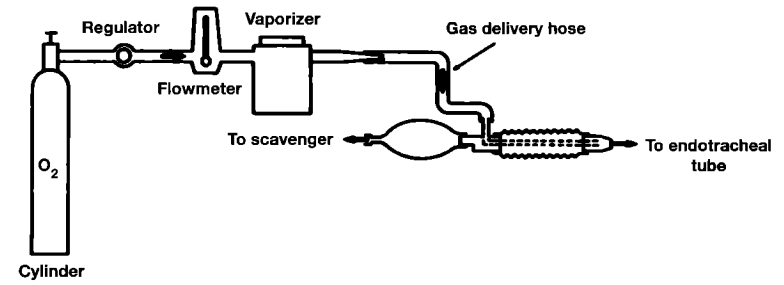

Fig. 17.55. Diagram of a Bain coaxial system attached to an anesthesia machine. Fresh gas flows from the outlet of the vaporizer or the common gas outlet of the anesthesia machine to enter the Bain system near the reservoir. Moving through the Bain's inner tube, fresh gas is delivered near the patient end of the system. Exhaled gases flow through the corrugated tubing to the reservoir and the overflow to the scavenging system.

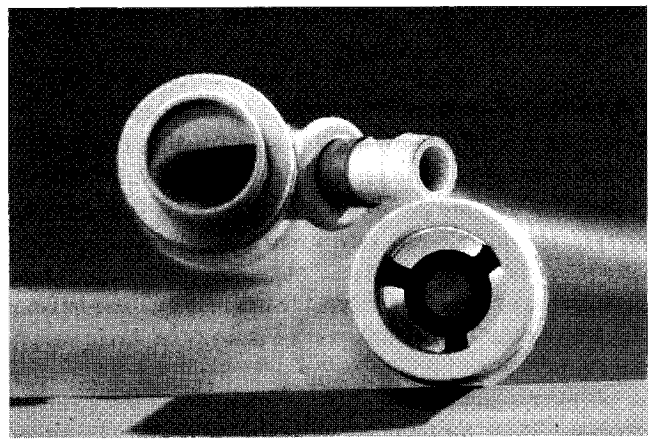

Fig. 17.56. The two ends of a Bain coaxial system showing the location for attachment of the reservoir bag (*top left*) and the endotracheal tube (*bottom right*). Fresh gases enter at the reservoir end (Y connection at the *top right*) and move through the small inner tube to the patient end of the system (triangular supports). From Hartsfield.[5]

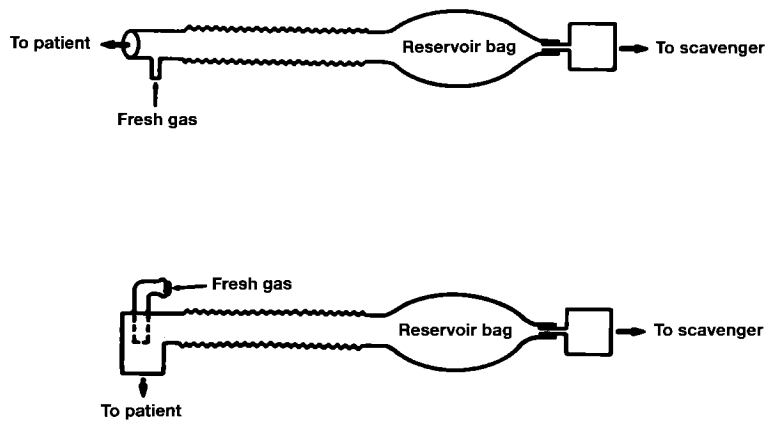

Fig. 17.57. Diagrams of Norman Mask Elbow system (*bottom*) and Ayre's T-piece system (*top*). From Hartsfield.[5]

(Fig. 17.57). One end of the tube attaches to the endotracheal tube connector, and the other end attaches to an expiratory arm (corrugated tubing equivalent to one-third of the patient's tidal volume) to which a reservoir bag may or may not be attached. The reservoir bag has an overflow valve. An Ayre's T piece with an expiratory tube and reservoir is a Rees modification of an Ayre's T piece or a Jackson-Rees system.[2]

During spontaneous ventilation, fresh gas flows to the patient during inspiration; during expiration and prior to the next inspiration, gas flows toward the reservoir. Gas flow follows the path of least resistance. Inspiratory flow requirements in excess of the fresh gas flow are obtained from the expiratory arm and reservoir. During expiration and before inspiration, high gas flow clears exhaled gases from the expiratory tube and washes out carbon dioxide. Such a system should have an ID of at least 1 cm to minimize resistance.

Generally, two to three times the patient's minute volume is recommended to prevent dilution of the inspired anesthetic concentration and rebreathing of carbon dioxide with Mapleson F systems. If N_2O is used, the desired concentration is calculated using N_2O as a portion of the total fresh gas flow. Variable recommendations for the most appropriate flow rates to use with these systems exist in the veterinary literature.

In a Norman mask elbow system, the direction of gas flow into the system is parallel to the flow of gases into the endotracheal tube during inspiration and expiration (Fig. 17.57). The fresh gas inlet is located in the center of the patient end of the system. This location probably reduces dead space slightly more than the Ayre's T-piece system. Also, the patient end of the elbow accepts a standard mask (22 mm). Recommendations for flow rates, tube sizes and volumes, and reservoir sizes and volumes are similar to those for the Ayre's T-piece system. Controlled ventilation can be used with either system by closing the overflow valve and compressing the reservoir bag. To prevent rebreathing during controlled ventilation, the expiratory tube's volume should be greater than the patient's tidal volume.

Resistance to ventilation in the Mapleson systems is minimal,[2] which may be advantageous for small patients. The advantages of modern "non-rebreathing" systems for very small patients include decreased resistance to ventilation, better gas exchange, greater control of the depth of anesthesia, and fewer mechanical problems.[48] Hazards of non-rebreathing systems relate primarily to outflow occlusion, development of excessive airway pressure, and barotraumas to the lungs, including development of pneumothorax.

Care in positioning the Mapleson systems and judicious use of overflow valves during positive-pressure ventilation are important considerations. Activation of the flush valve when a non-rebreathing system is being used can overpressurize the respiratory system, causing volutrauma (rapid overexpansion of the lungs) and subsequent pneumothorax. Therefore, the machine's flush valve should not be used when one of the Mapleson systems is connected to a patient.

Systems with Non-rebreathing Valves

Numerous non-rebreathing valves (e.g., Stephens-Slater, Fink, and Digby-Leigh) have been designed for anesthesia breathing systems, but they are not commonly used today.[3] These breathing systems with one-way valves were cumbersome, and essentially have been replaced by the Mapleson and circle systems. Presently, non-rebreathing valves are used most in self-inflating bags for resuscitation or transport of patients requiring manual ventilation.

Stephens-Slater System

This system (Fig. 17.58) was in common use in veterinary anesthesia in the 1970s, but today is mainly of historical interest. The system was designed with two one-way valves, one directing gas from the reservoir to the patient and blocking exhaled gases from the reservoir and a second valve directing exhaled gases away from the system and preventing entry of ambient gases during inspiration. Fresh gases enter the system through the reservoir bag and move through the inspiratory valve to the patient. The recommended total fresh gas flow is equal to the patient's minute volume.[2,46] The flow of N_2O, if used, is calculated as a part of the total fresh gas flow. Since the valves are located near the patient, the system is cumbersome, especially with manual ventilation, during which the exhalation valve is held closed while the reservoir bag is compressed. The reservoir must be monitored closely to assure sufficient gas to meet inspiratory demands. This valved system added minimal dead space and resistance to respiration. However, the valve flaps could stick and obstruct ventilation. The

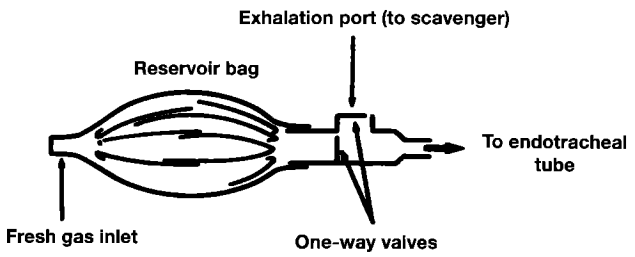

Fig. 17.58. Diagram of a Stephens-Slater system. From Hartsfield.[5]

system was popular prior to the advent of scavenging, which presents some difficulty with the Stephens-Slater system.

Resuscitation Bags

These self-inflating bags incorporate non-rebreathing valves. As an example, an Ambu bag (a bag valve mask) facilitates resuscitation and transport of apneic or anesthetized patients. Oxygen can be delivered into the reservoir bag to increase F_IO_2. When the bag is compressed, the increase in pressure closes the exhalation port and gases enter the patient's respiratory system. When pressure on the bag is released, gas flows from the patient's respiratory system through the exhalation port. With spontaneous breathing, the Ambu valve allows the patient to inhale room air only. The Ambu E2 is a modification that allows the patient to inhale both from the reservoir and from the exhalation port, creating a mixture of fresh gas and air. During controlled ventilation, all gases originate from the reservoir.[2]

Closed Containers and Masks

Closed Containers

Closed containers are used for oxygenation and inhalant inductions in small veterinary patients. Inhalant inductions have decreased in popularity because of the difficulty associated with scavenging of waste gases, especially as an anesthetized patient is removed from the chamber. Perhaps, the only completely effective way to assure elimination of waste anesthetic gases with this system is the concurrent use of a fume hood. The primary advantage of induction in a closed container is the reduced requirement for physical restraint of the patient. Induction in a closed container is very effective for aggressive cats and for some laboratory and small wild or exotic species. Often, the container can be placed over the animal, eliminating the need for any physical contact and restraint.

Most containers for inhalant inductions are constructed of glass, Plexiglas, or other clear plastic materials (Fig. 17.59), allowing the patient to be observed during induction. Since the airway might become obstructed during a closed-container induction, ventilatory efforts should be monitored throughout the process. The chamber should be no larger than necessary, but the animal should be able to lie in lateral recumbency without having to flex its neck. A chamber that is too small for the patient promotes airway obstruction. Excessive chamber volume slows the rate of rise of anesthetic concentration and the onset of induction. When the patient is induced and is manageable, it should be removed from the chamber, and the induction should be completed by mask.

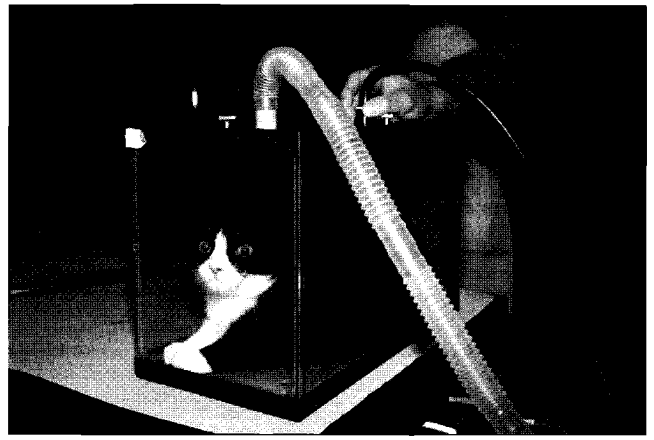

Fig. 17.59. Closed container for oxygenation and inhalant inductions in small patients. The container is clear so that the animal can be monitored during the induction process. The ports for the entrance of fresh gases and for attachment of a scavenging system are on the lid.

Relatively high flows of fresh gas facilitate inductions in closed containers. The outlet of the chamber should be attached to a scavenger system when anesthetic is being administered. Chamber inductions should be done in a well-ventilated area, ideally, under a fume hood that vents all waste gases from the working environment. Depending on the size of the chamber and the body weight of the patient, total flow of fresh gas into the chamber should be approximately 2 to 5 L/min.[51] Low flow rates of fresh gases slow induction and contribute to the development of excitement. Oxygen should be administered for about 5 min before the introduction of inhalant anesthetic. Then, the concentration of the inhalant should be increased at 0.5% increments every 10 s until 4% to 4.5% sevoflurane or isoflurane is being administered. Unless N_2O is contraindicated because of patient pathology, it can be used in concentrations of 60% to 70%.

Masks

Mask inductions (Fig. 17.60) are facilitated by anesthetic concentrations and fresh gas flows that are similar to those for closed containers. Mask inductions are smoothest in depressed, tranquilized, or sedated patients. Masks should fit snugly over the muzzle to minimize dead space, and the appropriate size for the patient should be used. A tight-fitting mask promotes a rapid induction and minimal contamination of the workplace with waste gases. A clear mask with a rubber diaphragm (Fig. 17.61) enables visualization of the nares and mouth during induction and creates a good seal around the animal's muzzle. The mask should be attached to a breathing system to provide a reservoir of gases to meet the patient's peak inspiratory flow demands, which may exceed the inflow of fresh gases. Most excess gases can be scavenged through the pop-off valve of the breathing system, but

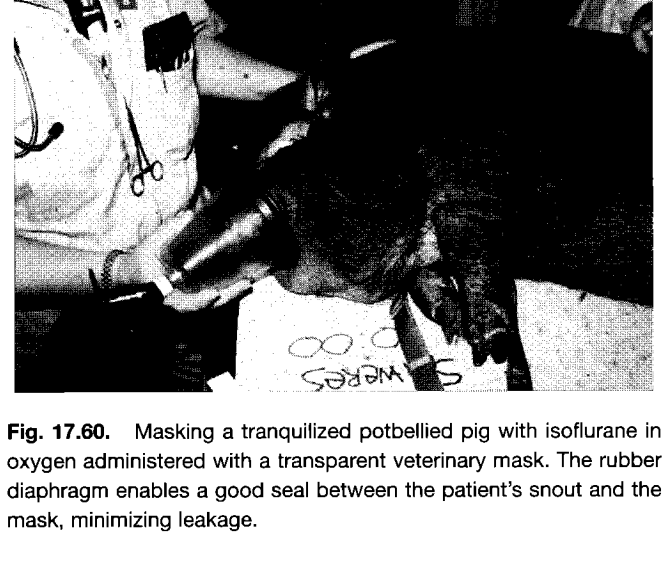

Fig. 17.60. Masking a tranquilized potbellied pig with isoflurane in oxygen administered with a transparent veterinary mask. The rubber diaphragm enables a good seal between the patient's snout and the mask, minimizing leakage.

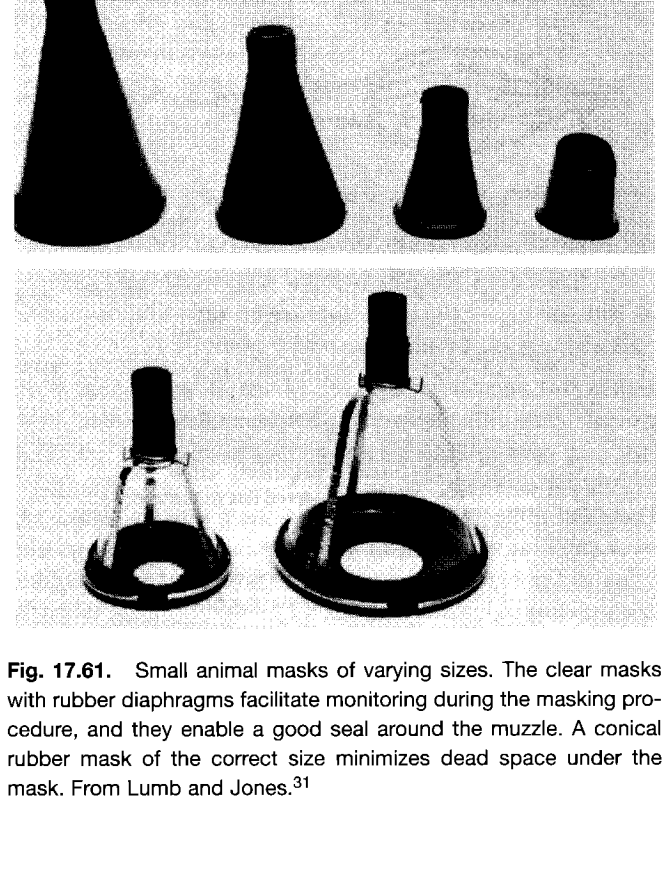

Fig. 17.61. Small animal masks of varying sizes. The clear masks with rubber diaphragms facilitate monitoring during the masking procedure, and they enable a good seal around the muzzle. A conical rubber mask of the correct size minimizes dead space under the mask. From Lumb and Jones.[31]

masking procedures should be done in a well-ventilated environment. High fresh gas flows (e.g., 3 to 5 L/min for most dogs and cats) during masking supply the oxygen demands of the patient, dilute and eliminate exhaled carbon dioxide, and provide inhalant anesthetic concentrations equivalent to the vaporizer setting (3% to 5% for isoflurane or 4% to 6% for sevoflurane) for a relatively rapid induction.

Scavenging Waste Anesthetic Gases

Over the last two decades, the exposure of medical and veterinary personnel to waste anesthetic gases has become a significant concern. A bulletin from the American Veterinary Medical Association's Liability Insurance Trust has stated the following: Numerous studies in the United States and abroad have found no conclusive evidence that waste gases or trace amounts of waste gas cause specific health problems. There is evidence, however, to suggest that removal of gases from veterinary facilities will likely improve the occupational health of the veterinary staff.[52]

At present, the Occupational Safety and Health Administration (OSHA) has no set limits for exposure to anesthetics, but OSHA can enforce recommendations of the National Institute for Occupational Safety and Health (NIOSH) under the general duty clause: The general duty of an employer is provision of a work environment that is free of recognized hazards that are likely to cause death or serious physical harm.[53,54] The recommended exposure limits from NIOSH vary from a maximum of 2 parts per million (ppm) for halogenated hydrocarbon anesthetics like halothane and isoflurane to an 8-h time-weighted average exposure to N_2O of 25 ppm. Used together, 0.5 ppm is the limit for the halogenated agent, with 25 ppm being the limit for N_2O.[55] The American Conference of Governmental Industrial Hygienists has recommended threshold-limit values of 50 ppm for halothane and N_2O as 8-h time-weighted averages.[56]

Recommendations for Controlling Waste Gases

Veterinary workers should be aware of potential risks so that they can take steps to minimize their exposure to the inhalant anesthetics. Women in the first trimester of pregnancy, individuals with hepatic or renal disease, and persons with a compromised immune system appear to be at greater risk.[57] The following considerations are important in regard to managing waste anesthetic gases:

1. All personnel should be educated about the potential health hazards associated with exposure to waste anesthetic gases.
2. Scavenger systems should be used with all anesthesia machines and breathing systems.
3. All rooms in which anesthetic gases are used should be well ventilated with an appropriate number of air exchanges (e.g., 15 air exchanges per hour).
4. Anesthetic machines and breathing systems should be maintained as leak free as possible, and the leakage tolerances should comply with established criteria (e.g., less than 300 mL/min at 30 cm H_2O for a circle breathing system with the pop-off valve closed).[3]
5. A log documenting the performance and maintenance procedures for anesthesia machines, vaporizers, and breathing systems should be maintained.
6. Personnel should minimize spillage when filling vaporizers, and keyed filling mechanisms should be considered.
7. Anesthetic concentrations in induction, operating, and recovery rooms should be periodically monitored to assure the efficacy of scavenging and other efforts to reduce contamination in the workplace.

Several ways of decreasing contamination of the occupational environment with anesthetic gases have been suggested. They include the following:

1. Avoid spills when filling vaporizers.
2. Start gas flows only after intubation of the patient.
3. Use endotracheal tubes with inflated cuffs.
4. Occlude the Y piece of the circle or the patient end of a Mapleson system if the system is disconnected from the patient.
5. Use a scavenging pop-off valve.
6. Discharge all gases through an effective scavenger system.
7. Flush breathing systems with oxygen before disconnecting the patient.
8. Use the minimum gas flow that promotes safe anesthesia.
9. Minimize the use of masks and closed containers. When using masks, be sure that they fit well, and use closed containers only in well-ventilated areas. Ideally, masks should be used under a fume hood.
10. Maintain proper ventilation in work areas and minimize exposure to exhaled gases during the initial phases of the recovery period whenever possible.

Having anesthetic machines and breathing systems properly outfitted and functional for administration of anesthetic gases is essential for assuring the minimum amount of environmental pollution. Each machine should be leak free, and each machine-breathing system combination should connect with a functional scavenger system. An efficient scavenging system is the most important factor in reducing trace anesthetic gases, because it will lower ambient concentrations by as much as 90%.[3]

Scavenging Systems

A scavenging system collects waste gases from the anesthetic breathing system and eliminates them from the workplace.[3,57] The scavenger system is composed of a gas-collecting assembly, an interface, and a disposal system (Figs. 17.62 and 17.63). Depending on the system, various types of tubing connects these parts.

The Gas-Collecting Assembly

This assembly gathers waste gases from the breathing system. At present, the exhaust outlet from the pop-off valve (Fig. 17.47) on a circle system must be either 19 mm or 30 mm in outside diameter. On older anesthesia machines, 22-mm connectors were used, which enabled the inadvertent interchange of scavenging hoses and breathing tubes. Depending on the location of the overflow in Mapleson systems (e.g., the Bain system), devices connecting the tail or the side of the reservoir bag serve as the gas-collecting assembly and attach to transfer tubing leading to the interface.

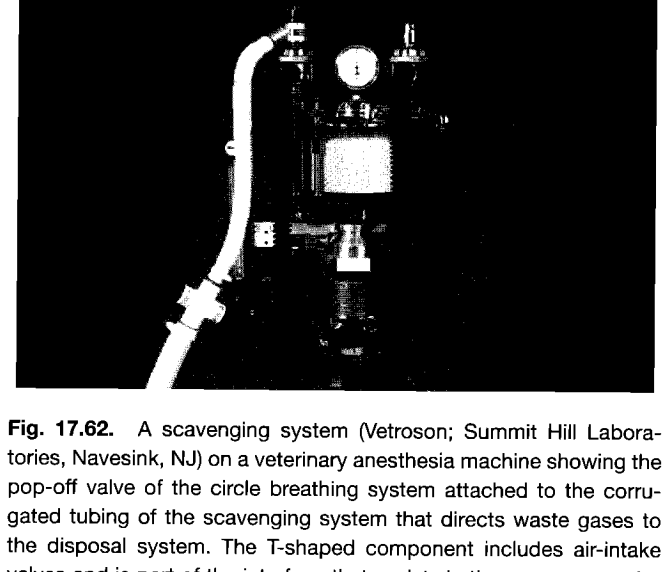

Fig. 17.62. A scavenging system (Vetroson; Summit Hill Laboratories, Navesink, NJ) on a veterinary anesthesia machine showing the pop-off valve of the circle breathing system attached to the corrugated tubing of the scavenging system that directs waste gases to the disposal system. The T-shaped component includes air-intake valves and is part of the interface that assists in the pressure regulation in the scavenging system.

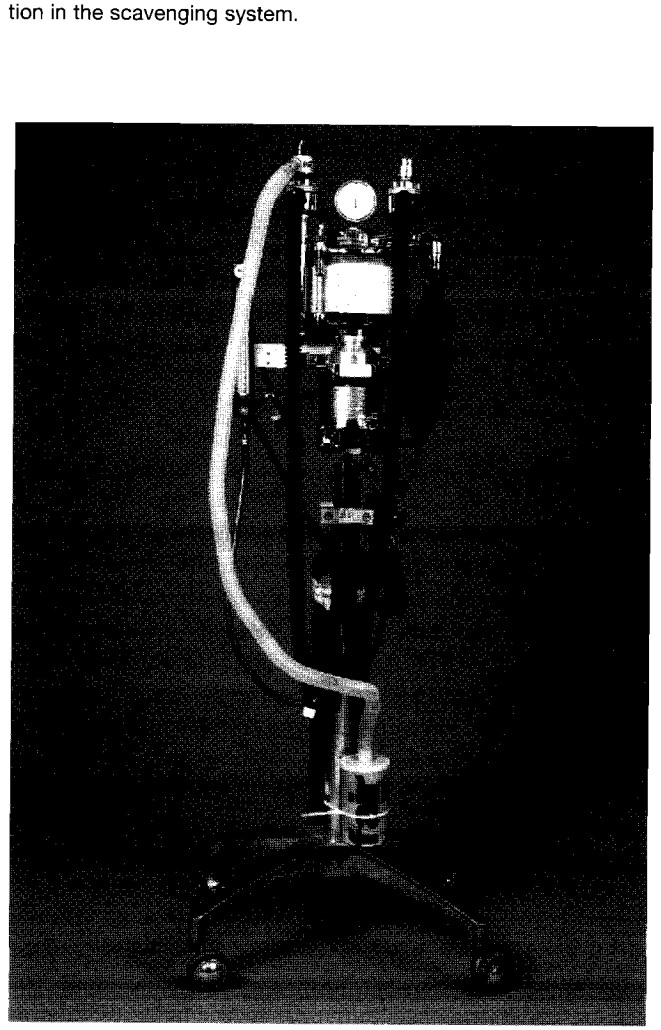

Fig. 17.63. A scavenging system including the pop-off valve, which is connected to a canister containing activated charcoal (F/air, Omnicon; Critical Care Products, Houston, TX). This system can be used for halogenated hydrocarbon anesthetics, but not for nitrous oxide.

The Interface

The interface is intended to prevent the transfer of pressure changes in the scavenging system to the breathing system. The inlet to the interface should be 19 or 30 mm OD, and the outlet can be of variable diameter (not 15 or 22 mm). Various interfaces are available (Fig. 17.62). An interface should provide positive-pressure relief to protect the patient from occlusions of the scavenging system, negative-pressure relief to limit the pressure effects of an active disposal system, and a reservoir for excess waste gas for use with active disposal systems. Interfaces may be opened or closed.[3]

The Disposal System

Disposal systems can be passive or active. Passive systems include non-recirculating ventilation systems, piping directly to the atmosphere, and absorption devices. Active systems include piped-vacuum and active duct systems. A non-recirculating ventilation system for the room allows the discharge of waste gases through an exhaust vent or grille. Discharging waste gases directly to the atmosphere is suitable for many veterinary hospitals because the distance from the gas-collecting assembly on the breathing system to the outside can be relatively short. Such systems can be affected by wind currents and should be designed so that water, wind, dust, and insects and other pests cannot enter the system from the outside.

Canisters containing activated charcoal (Fig. 17.63) will absorb halogenated hydrocarbon anesthetics with a varying degree of efficiency. The canisters are simple to use and portable. The effectiveness of absorption varies with different brands, styles of canisters, and rates of flow through the canisters. These devices must be changed regularly, making them rather expensive to use, and they do not absorb N_2O.[3] In general, other methods for scavenging waste gases are preferable, with absorption systems reserved for situations where more reliable methods are not accessible.

Central vacuum systems provide convenient anesthetic-gas disposal for hospitals with such systems already in place. The system should be able to create a flow of at least 30 L/min and functions best when the operator can manually adjust the flow.[3] The location for discharge of waste gases must be in an appropriate location and not situated where waste gases can reenter the ventilation system of the hospital. Ideally, a central vacuum system dedicated to scavenging, with another system to provide suction for other hospital needs (e.g., surgical suction), is most desirable.

An active duct system with a high volume of flow and a low negative pressure provides an excellent means of gas disposal (Fig. 17.64). Negative pressure is generated by a fan, pump, or other device in a large duct that is connected to smaller ducts that open into the room at the site of use. Such systems are effective, but regular maintenance is required to assure that the fan or pump is operational. This system is not affected by wind currents. With any disposal system, the ultimate elimination of gas must be at a point that prevents reentry of gases to any area of the hospital. The discharge site should be located away from any air-intake vents of the building, and the prevailing winds should not direct exhausted gases toward the air-intake vents of the building.

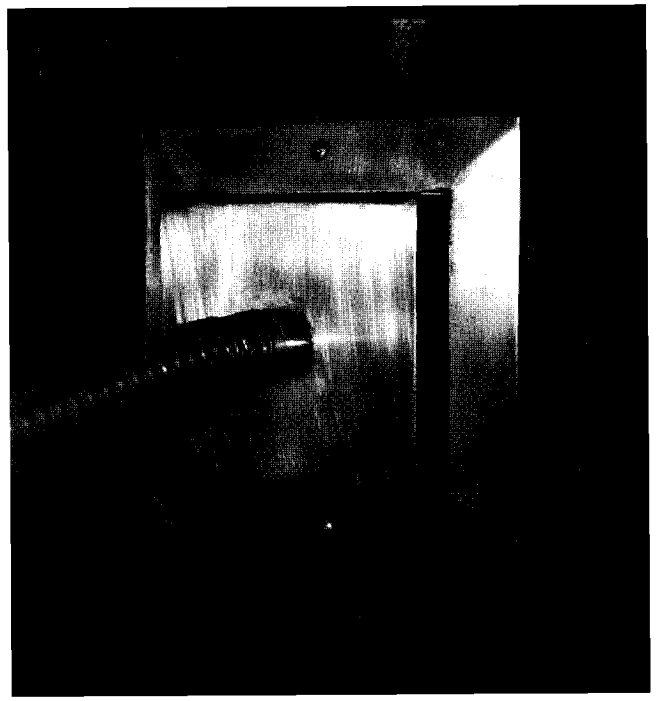

Fig. 17.64. Corrugated tubing from the pop-off valve of a circle breathing system attached to a high-volume, low-pressure scavenging system (an active duct system). Air is constantly entrained on each side of the stainless-steel plate, whereas waste gas from the breathing system enters the scavenging system through the corrugated tubing.

Anesthesia Apparatus: Checkout Recommendations

Evaluation of anesthesia machines and breathing systems is important to ensure safety for personnel and patients. For patients, delivery of appropriate concentrations and amounts of oxygen and anesthetics is essential. For personnel, the machine and breathing system should be maintained to prevent contamination of the workplace with anesthetics. The Food and Drug Administration has published "Anesthesia Apparatus Checkout Recommendations" for anesthesia-gas–delivery systems and recommends that this checkout or a reasonable equivalent be conducted before administering anesthesia. The intent is to improve patient safety.[58,59] Recommendations for checkout of veterinary machines have been published.[60]

The high-, intermediate-, and low-pressure areas of the anesthesia apparatus should be evaluated.[1–3] The high-pressure area includes gas cylinders, hanger yokes, yoke blocks, high-pressure hoses, pressure gauges, and regulators. These components are exposed to pressures up to 2200 psi for oxygen and up to 745 psi for N_2O. Testing should include inspection for loose connections and audible leakage, pressure checks (loss of pressure when cylinder valves are open and flowmeters are off), and use of soapy water solutions to "snoop" for leaks (creation of bubbles) especially at joints (Fig. 17.65). The intermediate-pressure area (approximately

Fig. 17.65. Searching for leaks in the gas piping system of an anesthesia machine. With the cylinder valve on and pressure on the system, soapy water is applied to areas with potential for leaks. Bubbles will form if leaks are present.

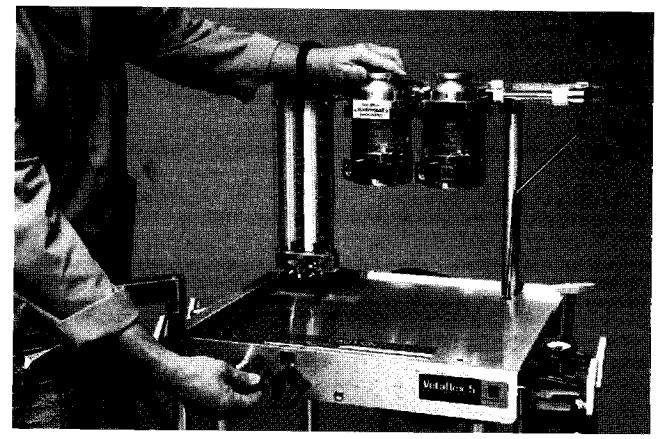

Fig. 17.66. Universal negative-pressure leak test. With all gases off and the vaporizer off, a compressed rubber bulb is attached to the common gas outlet of the anesthesia machine. The bulb should not reinflate in less than 10 s. The test should be repeated with the vaporizer control on. From Andrews.[16]

40 to 50 psi) includes pipeline inlets, conduits from pipeline inlets to flowmeters, and conduits from regulators to flowmeters, the flowmeter assembly, and the oxygen-flush apparatus. Tests include visual inspection, listening for leaks, and use of soapy water solutions. The low-pressure area includes the vaporizer(s), conduits from the flowmeters to the vaporizer, a conduit from the vaporizer to the common gas outlet, and a conduit from the common gas outlet to the breathing system. Pressures are slightly above atmospheric. Routing tests include visual inspection and pressure checks with the breathing system. In many anesthesia machines, pressure applied to the breathing system affects the low-pressure area of the machine. Some newer anesthesia machines have check valves near the common gas outlet.

A universal negative-pressure leak test has been proposed for contemporary anesthesia machines to evaluate the low-pressure area. The test requires a simple suction bulb.[16] The flowmeters and vaporizers are off during the test. The suction bulb is attached at the common gas outlet and squeezed until the bulb fully collapses, creating a vacuum in the low-pressure areas (Fig. 17.66). If the bulb reinflates in less than 10 s, a significant leak is present. The test is repeated with the control dial of the vaporizer on to detect any internal leaks that might not be found with the vaporizer off. This test differentiates between leaks in the low-pressure area of the machine (vaporizer) and the breathing system. The test can detect leaks as small as 30 mL/min and has been described as extremely reliable.

Anesthetic machines should be checked out each day before anesthetizing the first patient, and the breathing system should be evaluated before each patient. The operation manual for individual anesthesia machines gives specific guidelines for evaluation and checkout, and machines with special features require individualized attention. Ventilators on anesthesia machines and monitoring equipment should also be evaluated before beginning anesthesia. The following procedures are modified from the "Anesthesia Apparatus Checkout Recommendations" from the FDA's Center for Devices and Radiological Health[1] and are appropriate for evaluation of anesthesia machines and breathing systems before the first case of the day:

1. Check central oxygen and N_2O supplies for adequate quantities of gases and pipeline pressures.
2. Inspect the flowmeters, vaporizers, gauges, and supply hoses. Assure correct mounting of cylinders in the hanger yokes; the presence of a wrench for cylinder valve; and a complete, undamaged breathing system with adequate absorbent for carbon dioxide.
3. Assure that the waste-scavenging system is connected to the pop-off valve and is working properly. Leak tests for the scavenger system have been recommended.[3] If a charcoal canister is being used, confirm that it is not exhausted.
4. Turn off the flow-control valves for the flowmeters.
5. Assure that the vaporizer is properly filled, with the filler cap sealed and the control dial off.
6. Check oxygen cylinders on the machine. With the pipeline supply disconnected, oxygen cylinder valve off, and pressure gauge at zero, slowly open the valve to check the pressure (500 psi) and determine the presence of leaks (a slow drop in pressure on the gauge) (Figs. 17.67 and 17.68). With multiple oxygen cylinders, each cylinder should be checked.
7. Check the N_2O supply (if present) as in step 6. If they are present, test the fail-safe devices to assure that N_2O cannot be delivered without an adequate amount of oxygen.
8. Test the flowmeters for each gas. With the flow-control valve off, the float should rest at the bottom of the glass tube. Adjust flow through the full range to assure proper function (no sticking or erratic movements).
9. Test the central pipeline supplies of oxygen and N_2O. With small (E) cylinders off and pipeline inlets connected to the cen-

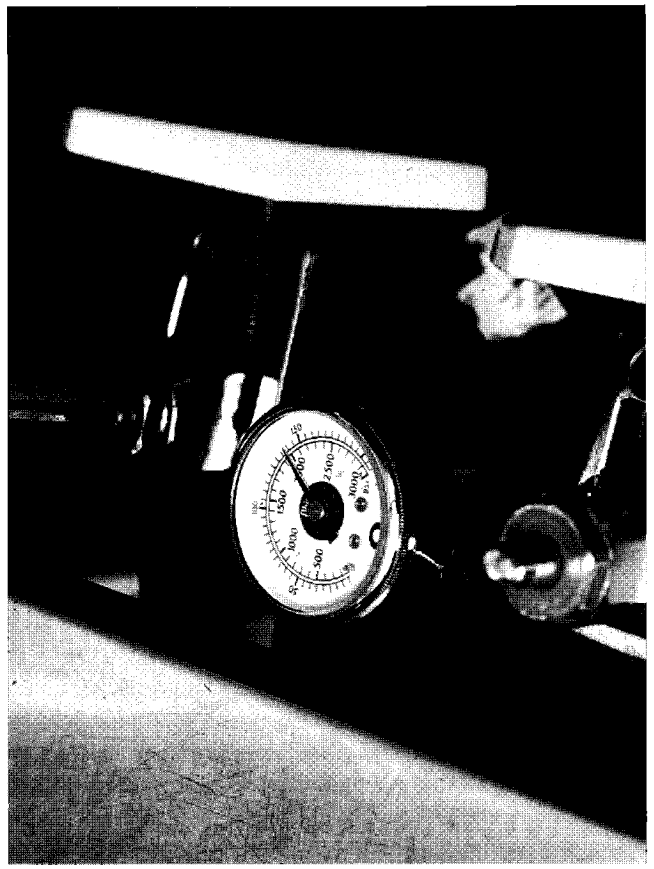

Fig. 17.67. Oxygen cylinder with the pressure gauge reading 2000 psi. An oxygen cylinder should have at least 500 psi before the cylinder and anesthesia machine are used with a patient. With oxygen flowmeters off, the cylinder valve should remain on to allow evaluation of the machine for slow leaks.

Fig. 17.68. Oxygen cylinder with the pressure gauge reading at 1700 psi after 15 min with the cylinder valve open. If the cylinder pressure was 2000 psi at the start of the test and the flowmeters were off, a significant leak is present and should be corrected before the anesthesia machine is used with a patient.

Fig. 17.69. Checking the function of the expiratory one-way valve of a circle system. Wearing a surgical mask, the evaluator exhales through the Y piece and observes the expiratory one-way valve to ensure that the valve disk moves appropriately. The reservoir bag should expand as air moves through the valve.

tral gas supply, adjust flows to a midrange and assure that supply pressures remain near 50 psi.

10. With the vaporizer off, no odor of anesthetic should be present when the oxygen flowmeter is on.

11. For a circle system, test the function of the unidirectional valves. Wearing a surgical mask (Fig. 17.69), exhale through the exhalation limb to check the exhalation valve, and compress the reservoir bag (pop-off valve closed and Y piece open) to check the inhalation valve (Fig. 17.70). Valve disks should be present and should rise and fall appropriately.

12. Test for leaks in the circle breathing system and the anesthesia machine. Close the pop-off valve, occlude the Y piece, fill the system with oxygen, and turn the oxygen flow to 5 L/min. As the pressure in the system reaches 20 cm H_2O, reduce the flow until the pressure in the system (manometer) no longer rises. The oxygen flow should be negligible; a high leakage rate is unacceptable. Squeeze the reservoir bag to create a relatively high pressure (40 to 50 cm H_2O) and assure a tight system. In checking the circle system for leaks, one recommendation is to fill the circle (pop-off valve closed and Y piece occluded) to a pressure of 30 cm H_2O and assure that the leak rate is less than 250 mL/min[39] or that the pressure drop is less than 5 cm H_2O in 30 s or that the pressure remains at 30 cm H_2O for at least 10 s (Fig. 17.71).[3] Others have recommended similar testing procedures with slightly different values for testing pressures and acceptable leak rates.[61,62]

13. Open the pop-off valve slowly and observe the release of pressure. Occlude the Y piece and verify that only a negligible positive or negative pressure develops with an oxygen flow rate of zero or 5 L/min.

14. Assure that the pop-off valve provides relief of pressure when the flush valve is activated.

15. Similar to the circle system, non-rebreathing systems should be tested before use. For a complete system check of a Bain system, the patient port should be occluded, the relief valve closed, and the reservoir bag distended. The bag should remain fully distended, and pressure within the system should not decrease (Fig. 17.72). The complete system check does not assure a leak-free inner tube of the coaxial system. Therefore, the inner tube is evaluated by temporarily occluding the inner tube at the patient end with oxygen flowing at approximately 1 to 2 L/min (Fig. 17.73). During a short period of occlusion with an instrument such as the plunger of a syringe, the float in the oxygen flowmeter should fall (Fig. 17.74).[2,3] The complete system check will usually suffice for other non-rebreathing systems (e.g., Norman mask elbow and Ayre's T-piece systems).

Fig. 17.70. Checking the function of the inspiratory one-way valve of a circle system. With the pop-off valve closed, the reservoir bag is compressed, and the valve disk of the inspiratory one-way valve should move appropriately.

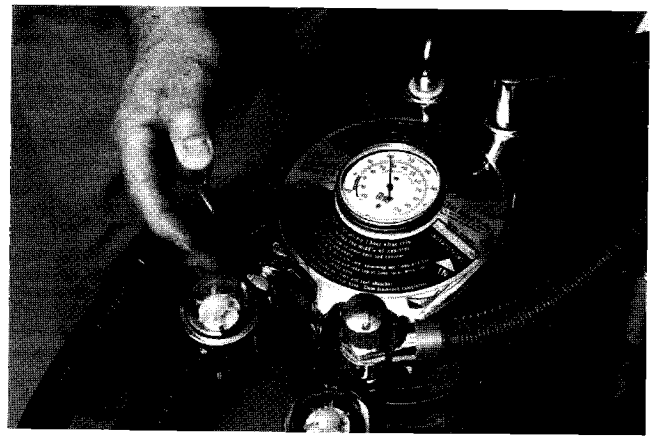

Fig. 17.71. Evaluation of the integrity of a circle breathing system. The pop-off valve is closed, the patient port is occluded, and the system is filled to a pressure of 30 cm H_2O for at least 10 s, or the leak as determined by use of the oxygen flowmeter should be less than 250 mL/min.

Fig. 17.72. Evaluation of a Bain breathing system (Kendall, Boston, MA) with a complete system check. With all gas flows off, the overflow valve is closed and the patient port is occluded. The bag is filled with the flush valve to a pressure of 30 cm H_2O, and a leak-free system should maintain this pressure for at least 10 s. If a leak is present, it can be quantified with the oxygen flowmeter and should not exceed 300 mL/min. From Dorsch and Dorsch.[3]

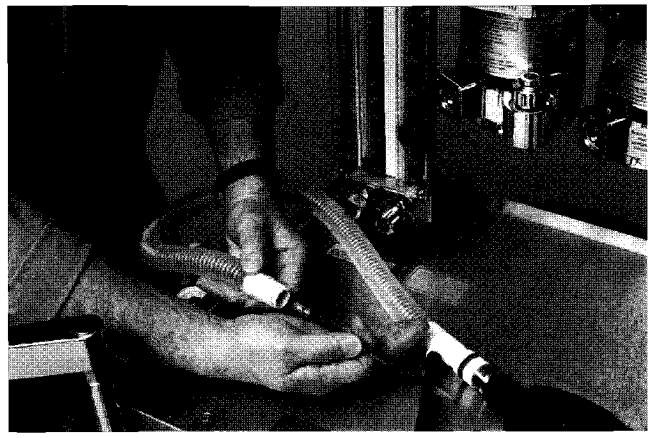

Fig. 17.73. Evaluation of the inner tube of a Bain breathing system. The first step is to turn on the oxygen flowmeter. In this example, the flow of oxygen was set at 1 L/min.

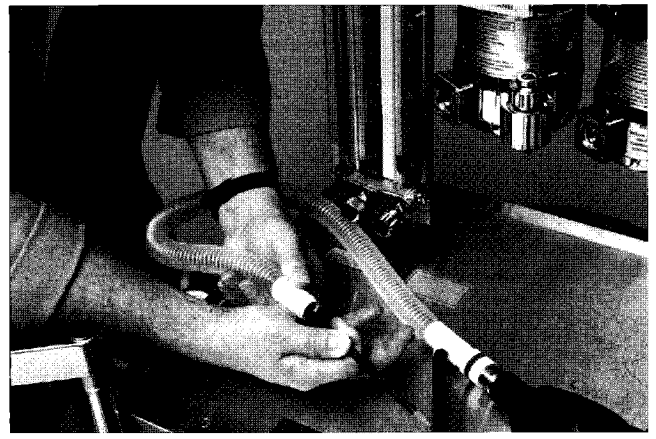

Fig. 17.74. Evaluation of the inner tube of a Bain breathing system. The second step is to occlude the patient end of the inner tube. If the inner tube is intact, the oxygen flowmeter's indicator (e.g., ball or bobbin) should fall (stop flow). From Dorsch and Dorsch.[3]

The tests mentioned here should be considered the minimum. The operation manual for a specific anesthesia machine usually provides appropriate per-use checkout procedures, and numerous other tests have been described to evaluate anesthesia apparatus.[3] Depending on the type of anesthesia machine, breathing system, ventilator (manual or mechanical), and monitoring equipment, other tests may be indicated. Veterinarians should familiarize themselves with the evaluation procedures that are most appropriate for their specific anesthesia apparatus.

References

1. American Society for Testing and Materials. Minimum Performance and Safety Requirements for Components and Systems of Anesthesia Gas Machines (ASTM F1161-99). Philadelphia: American Society for Testing and Materials, 1989.
2. Dorsch JA, Dorsch SE. Understanding Anesthesia Equipment: Construction, Care, and Complications, 2nd ed. Baltimore: Williams and Wilkins, 1984.
3. Dorsch JA, Dorsch SE. Understanding Anesthesia Equipment: Construction, Care, and Complications, 3rd ed. Baltimore: Williams and Wilkins, 1994.
4. Ehrenwerth J, Eisenkraft JB, eds. Anesthesia Equipment: Principles and Application. St Louis: CV Mosby, 1993.
5. Hartsfield SM. Machines and breathing systems for administration of inhalation anesthetics. In: Short CE, ed. Principles and Practice of Veterinary Anesthesia. Baltimore: Williams and Wilkins, 1987:395.
6. Andrews JJ. Inhaled anesthetic delivery systems. In: Miller RD, ed. Anesthesia, 3rd ed. New York: Churchill Livingstone, 1990:171.
7. Fox JWC, Fox EJ. An unusual occurrence with a cycloproprane cylinder. Anesth Analg 47:624, 1968.
8. Webb AI, Warren RG. Hazards and precautions associated with the use of compressed gases. J Am Vet Med Assoc 181:1491, 1982.
9. Stoelting RK, Miller RD. Basics of Anesthesia. New York: Churchill Livingstone, 1984.
10. Haskins SC, Sansome AL. A timetable for exhaustion of nitrous oxide cylinders using cylinder pressure. Vet Anesth 6:6, 1979.
11. Grant WJ. Medical Gases: Their Properties and Uses. Chicago: Year Book, 1978.
12. Schreiber P. Anesthesia Equipment: Performance, Classification and Safety. New York: Springer-Verlag, 1972.
13. Mazzia VDB. Oxygen and the anesthesia machine. NY State J Med 62:2845, 1962.
14. Gray PR. Anesthetic machine leak. J Am Vet Med Assoc 179:1348, 1981.
15. Hartsfield SM. Practical problems with veterinary anesthesia machines. In: Proceedings of the Fifth International Congress of Veterinary Anesthesia, Guelph, Ontario, 1994:21.
16. Andrews JJ. Understanding your anesthesia machine. In: Annual Refresher Course Lecture 163:1. Washington, DC: American Society of Anesthesiologists, 1993.
17. Hartsfield SM, Thurmon JC. Reduced anesthetic vapor concentration in a breathing circuit related to a leak in the oxygen flush apparatus. Vet Anesth 5:35, 1978.
18. Bednarski RM, Gaynor JS, Muir WW III. Vaporizer in circle for delivery of isoflurane to dogs. J Am Vet Med Assoc 202:943, 1993.
19. Gallagher LV, Klavano PA. Scavenging waste anesthetic gases from obsolescent anesthetic machines. J Am Vet Med Assoc 179:1393, 1981.
20. Schreiber PJ. Effects of barometric pressure on anesthetic equipment. Audio Digest (Anesthesiol) 17:14, 1975.
21. Munson WM. Cardiac arrest: Hazard of tipping a vaporizer. Anesthesiology 26:235, 1965.
22. Ludders JW. Vaporizers used in veterinary anesthesia. Semin Vet Med Small Anim 8:72, 1993.
23. Orkin FK. Anesthetic systems. In: Miller RD, ed. Anesthesia, 2nd ed. New York: Churchill Livingstone, 1986:117.
24. Wagner AE, Bednarski RM. Use of low-flow and closed-system anesthesia. J Am Vet Med Assoc 200:1005, 1992.
25. Lin C. Assessment of vaporizer performance in low-flow and closed-circuit anesthesia. Anesth Analg 59:359, 1980.
26. Hill DW, Lowe HJ. Comparison of concentration of halothane in closed and semiclosed circuits during controlled ventilation. Anesthesiology 23:291, 1962.

27. Hill DW. The design and calibration of vaporizers for volatile anesthetic agents. In: Scurr C, Feldman S, eds. Scientific Foundations of Anesthesia. Chicago: Year Book, 1974:71.
28. Thurmon JC, Benson GJ. Inhalation anesthetic delivery equipment and its maintenance. Vet Clin North Am Large Anim Pract 3:73, 1981
29. Mulroy M, Ham J, Eger EI II. Inflowing gas leak, potential source of hypoxia. Anesthesiology 45:102, 1976.
30. Operation and Maintenance Manual for the Metomatic Model 980 Veterinary Anesthesia Machine. Madison, WI: Ohio Medical Products.
31. Lumb WV, Jones EW. Veterinary Anesthesia, 2nd ed. Philadelphia: Lea and Febiger, 1984.
32. Muir WW III, Hubbell JAE. Handbook of Veterinary Anesthesia, 2nd ed. St Louis: Mosby, 1995.
33. Steffey EP, Woliner MJ, Howland D. Accuracy of isoflurane delivery by halothane-specific vaporizers. Am J Vet Res 44:1072, 1983.
34. Hamilton WK. Nomenclature of inhalation anesthetic systems. Anesthesiology 25:3, 1964.
35. Dunlop CI. The case for rebreathing circuits for very small animals. Vet Clin North Am Small Anim Pract 22:400, 1992.
36. Bednarski RM. Anesthetic breathing systems. Semin Vet Med Surg (Small Anim) 8:82, 1993.
37. Menhusen MJ. Anesthetic machine malfunctions resulting in soda lime bypass and hypercarbia. J Am Anim Hosp Assoc 15:507, 1979.
38. Jorgensen B, Jorgensen S. Carbon dioxide elimination from circle systems. Acta Anaesthesiol Scand Suppl 53:86, 1973.
39. Bednarski RM. Anesthetic equipment. In: Muir WW III, Hubbell JAE, eds. Equine Anesthesia, Monitoring and Emergency Therapy. St Louis: Mosby Year Book, 1991:325.
40. Tevik A, Nelson AW, Berkley WE, Lumb WV. Effect of nitrogen in a closed-circle system with low oxygen flows for equine anesthesia. J Am Vet Med Assoc 154:166, 1969.
41. Muir WW III, Hubbell JAE. Handbook of Veterinary Anesthesia. St Louis: CV Mosby, 1989.
42. Klide AM. The case for low gas flows. Vet Clin North Am Small Anim Pract 22:384, 1992.
43. Hartsfield SM, Sawyer DC. Cardiopulmonary effects of rebreathing and nonrebreathing systems during halothane anesthesia in the cat. Am J Vet Res 37:1461, 1976.
44. Suter CM, Pascoe PJ, McDonell WN, Wilson B. Resistance and work of breathing in the anesthetized cat: Comparison of a circle breathing circuit and a coaxial breathing system. In: Proceedings of the Annual Meeting of the American College of Veterinary Anesthesiologists, 1989.
45. Hodgson DS, McMurphy RM. Resistance to flow in large animal anesthetic machine breathing circuits. In: Proceedings of the Annual Meeting of the American College of Veterinary Anesthesiologists, Washington, DC, 1993.
46. Soma LR, ed. Textbook of Veterinary Anesthesiology. Baltimore: Williams and Wilkins, 1971.
47. Manley SV, McDonnell WN. Clinical evaluation of the Bain breathing circuit in small animal anesthesia. J Am Anim Hosp Assoc 15:67, 1979.
48. Hodgson DS. The case for nonrebreathing circuits for very small animals. Vet Clin North Am Small Anim Pract 22:397, 1992.
49. Haskins SC. Monitoring the anesthetized patient. In: Short CE, ed. Principles and Practice of Veterinary Anesthesia. Baltimore: Williams and Wilkins, 1987:455.
50. Manley SV, McDonnell WN. A new circuit for small animal anesthesia: The Bain coaxial circuit. J Am Anim Hosp Assoc 15:61, 1979.
51. Sawyer DC. The practice of small animal anesthesia. Philadelphia: WB Saunders, 1982.
52. Anesthetic gases. AVMA Professional Liability Insurance Trust Saf Bull 1(1):1, 1992.
53. Occupational Safety and Health Administration (OSHA). DVM Issues. Austin: Texas Veterinary Medical Association, May 1991.
54. Quick BA, Fountain BL. OSHA and the veterinary practice establishment. J Am Vet Med Assoc 195:302, 1989.
55. National Institute for Occupational Safety and Health (NIOSH). Criteria for a Recommended Standard Occupational Exposure to Waste Anesthetic Gases and Vapors. HEW Publ N105H. Washington, DC: US Government Printing Office, 1977.
56. Milligan JE. Anesthetic gas hazards. In: Heidelbaugh ND, Murnane TG, Rosser WW, eds. Health Hazards in Veterinary Practice, 2nd ed. Austin: Texas Department of Health, 1989:101.
57. Smith JA. Anesthetic pollution and waste anesthetic gas scavenging. Semin Vet Med Surg Small Anim 8:90, 1993.
58. Food and Drug Administration (FDA). Anesthesia apparatus checkout recommendations: Availability. Federal Register 52:5583, 1987.
59. March MG, Crowley JJ. An evaluation of anesthesiologists' present checkout methods and the validity of the FDA checklist. Anesthesiology 75:724, 1991.
60. Mason DE. Anesthesia machine checkout and troubleshooting. Semin Vet Med Surg Small Anim 8:104, 1993.
61. Paddleford RR. Exposure of veterinary personnel to waste anesthetic gases. Semin Vet Med Surg 1:249, 1986.
62. Manley SV, McDonell WN. Recommendations for reduction of anesthetic gas pollution. J Am Vet Med Assoc 176:519, 1980.
63. Haskins SC. Opinions in small animal anesthesia. Vet Clin North Am Small Anim Pract 22:245, 1992.
64. Rayburn RL. Pediatric anesthesia circuits. In: Annual Refresher Course Lecture 117. Washington, DC: American Society of Anesthesiologists, 1981.