CHAPTER

3

Breathing Systems

KEY CONCEPTS

1. Because insufflation avoids any direct patient contact, there is no rebreathing of exhaled gases if the flow is high enough. Ventilation cannot be controlled with this technique, however, and the inspired gas contains unpredictable amounts of entrained atmospheric air.
2. Long breathing tubes with high compliance increase the difference between the volume of gas delivered to a circuit by a reservoir bag or ventilator and the volume actually delivered to the patient.
3. The adjustable pressure-limiting (APL) valve should be fully open during spontaneous ventilation so that circuit pressure remains negligible throughout inspiration and expiration.
4. Because a fresh gas flow equal to minute ventilation is sufficient to prevent rebreathing, the Mapleson A design is the most efficient Mapleson circuit for spontaneous ventilation.
5. The Mapleson D circuit is efficient during controlled ventilation, because fresh gas flow forces alveolar air away from the patient and toward the APL valve.
6. The drier the soda lime, the more likely it will absorb and degrade volatile anesthetics.
7. Malfunction of either unidirectional valve in a circle system may allow rebreathing of carbon dioxide, resulting in hypercapnia.
8. With an absorber, the circle system prevents rebreathing of carbon dioxide at fresh gas flows that are considered low (fresh gas flow $\leq$ 1 L) or even fresh gas flows equal to the uptake of anesthetic gases and oxygen by the patient and the circuit itself (closed-system anesthesia).
9. Because of the unidirectional valves, apparatus dead space in a circle system is limited to the area distal to the point of inspiratory and expiratory gas mixing at the Y-piece. Unlike Mapleson circuits, the circle system tube length does not directly affect dead space.
10. The fraction of inspired oxygen (F_{IO_2}) delivered by a resuscitator breathing system to the patient is directly proportional to the oxygen concentration and flow rate of the gas mixture supplied to the resuscitator (usually 100% oxygen) and inversely proportional to the minute ventilation delivered to the patient.

Breathing *systems* provide the final conduit for the delivery of anesthetic gases to the patient. Breathing *circuits* link a patient to an anesthesia machine (**Figure 3–1**). Many different circuit designs have been developed, each with varying degrees of efficiency, convenience, and complexity. This chapter reviews the most important breathing systems: insufflation, draw-over, Mapleson circuits, the circle system, and resuscitation systems.

FIGURE 3–1 The relationship between the patient, the breathing system, and the anesthesia machine.

Most classifications of breathing systems artificially consolidate functional characteristics (eg, the extent of rebreathing) with physical characteristics (eg, the presence of unidirectional valves). Because these seemingly contradictory classifications (eg, open, closed, semiopen, semiclosed) often tend to confuse rather than aid understanding, they are avoided in this discussion.

INSUFFLATION

The term insufflation usually denotes the blowing of anesthetic gases across a patient's face. Although insufflation is categorized as a breathing system, it is perhaps better considered a technique that avoids direct connection between a breathing circuit and a patient's airway. Because children often resist the placement of a face mask (or an intravenous line), insufflation is particularly valuable during inductions with inhalation anesthetics in children (Figure 3–2). It is useful in other situations as well. Carbon dioxide accumulation under head and neck draping is a hazard of ophthalmic surgery performed with local anesthesia. Insufflation of air across the patient's face at a high flow rate (>10 L/min) avoids this problem, while not increasing the risk of fire from accumulation of oxygen

1 (Figure 3–3). Because insufflation avoids any direct patient contact, there is no rebreathing of exhaled gases if the flow is high enough. Ventilation cannot be controlled with this technique, however, and the inspired gas contains unpredictable amounts of entrained atmospheric air.

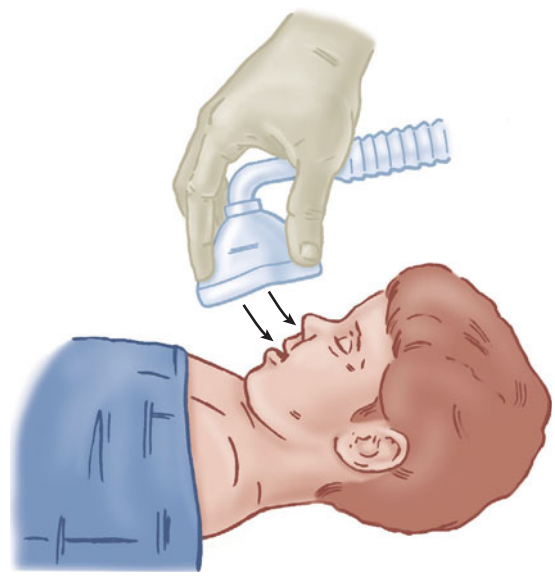


FIGURE 3–2 Insufflation of an anesthetic agent across a child's face during induction.

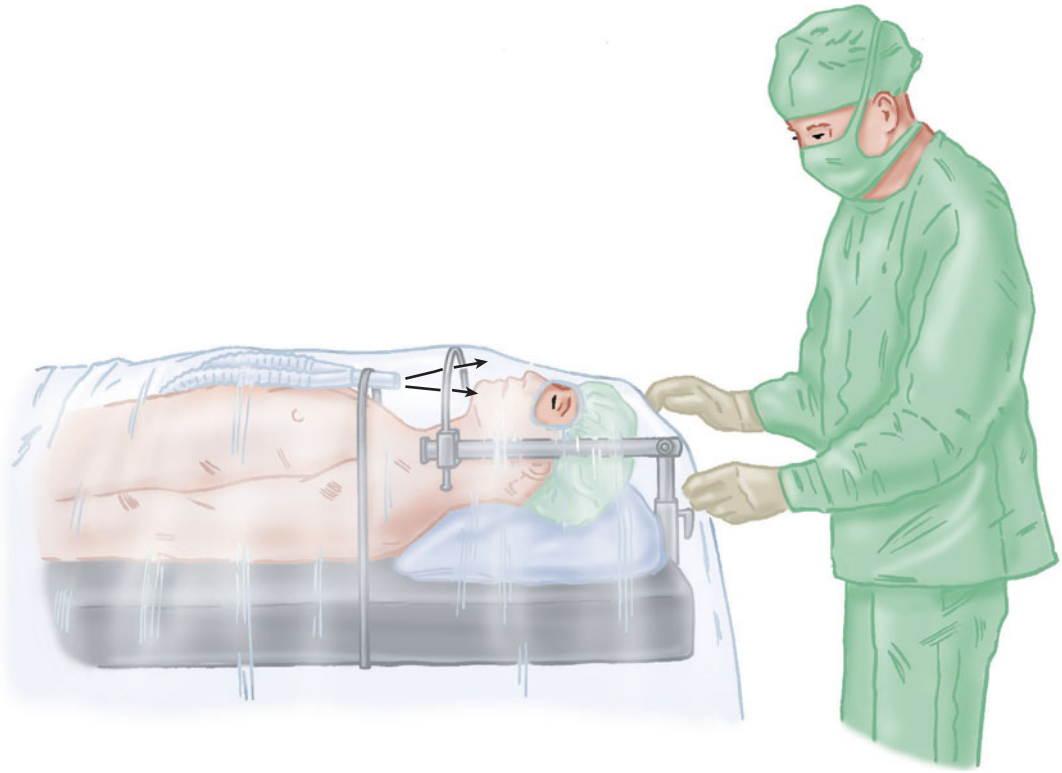


FIGURE 3–3 Insufflation of oxygen and air under a head drape.

Insufflation can also be used to maintain arterial oxygenation during brief periods of apnea (eg, during bronchoscopy). Instead of blowing gases across the face, oxygen is directed into the lungs through a device placed in the trachea.

OPEN-DROP ANESTHESIA

Although open-drop anesthesia is not used in modern medicine, its historic significance warrants a brief description here. A highly volatile anesthetic—historically, ether or chloroform—was dripped onto a gauze-covered mask (Schimmelbusch mask) applied to the patient's face. As the patient inhales, air passes through the gauze, vaporizing the liquid agent, and carrying high concentrations of anesthetic to the patient. The vaporization lowers mask temperature, resulting in moisture condensation and a drop in anesthetic vapor pressure (vapor pressure is proportional to temperature).

A modern derivative of open-drop anesthesia utilizes draw-over vaporizers that depend on the patient's inspiratory efforts to draw ambient air through a vaporization chamber. This technique may be used in locations or situations in which compressed medical gases are unavailable (eg, battlefields).

DRAW-OVER ANESTHESIA

Draw-over devices have nonrebreathing circuits that use ambient air as the carrier gas, although supplemental oxygen can be used, if available. The devices can be fitted with connections and equipment that allow intermittent positive-pressure ventilation (IPPV) and passive scavenging, as well as

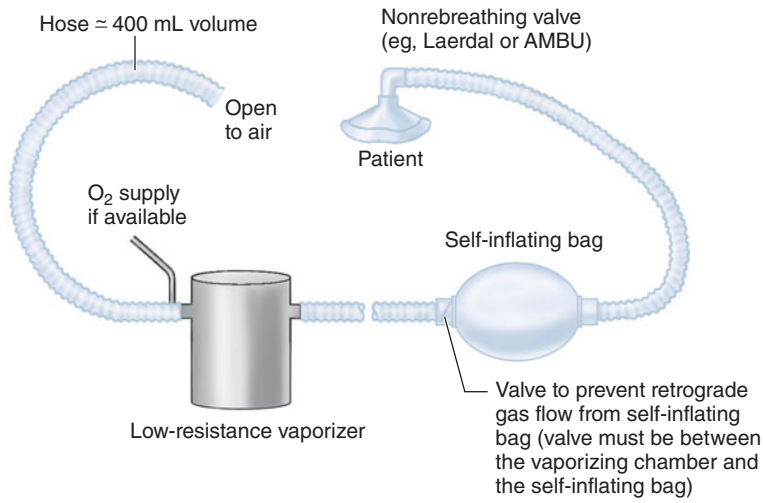


FIGURE 3–4 Schematic diagram of a draw-over anesthesia device/circuit.

continuous positive airway pressure (CPAP) and positive end-expiratory pressure (PEEP).

In its most basic application (Figure 3–4), air is drawn through a low-resistance vaporizer as the patient inspires. Patients spontaneously breathing room air and a potent halogenated agent often manifest an oxygen saturation (SpO_2) <90%, a situation treated with IPPV, supplemental oxygen, or both. The fraction of inspired oxygen (FIO_2) can be supplemented using an open-ended reservoir tube of about 400 mL, attached to a t-piece at the upstream side of the vaporizer. Across the clinical range of tidal volume and respiratory rate, an oxygen flow rate of 1 L/min gives an FIO_2 of 30% to 40%, or with 4 L/min, an FIO_2 of 60% to 80%. There are several commercial draw-over systems available that share common properties (Table 3–1).

The greatest advantage of draw-over systems is their simplicity and portability, making them useful in locations where compressed gases or ventilators are not available. The presence of the nonrebreathing valve, PEEP valve, and circuit filter close to the patient's head makes the technique awkward for head and neck surgery and pediatric cases. If the head is draped, the nonrebreathing valve is often covered as well.

The original design of a draw-over system has recently been modified to include a self-inflating bag, a ventilator, and/or a heat and moisture exchanger. The Ohmeda Universal Portable Anesthesia Complete (U-PAC) is one example of a draw-over anesthesia system.

TABLE 3–1 Properties of draw-over devices.

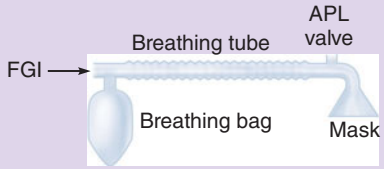
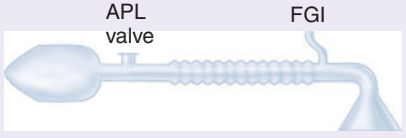
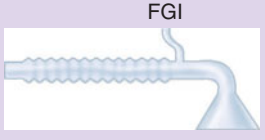
Portable
Low resistance to gas flow
Usable with any agent[1]
Controllable vapor output

[1]Halothane cannot be used with the Epstein Mackintosh Oxford device.

MAPLESON CIRCUITS

The insufflation and draw-over systems have several disadvantages: poor control of inspired gas concentration (and, therefore, poor control of depth of anesthesia), mechanical drawbacks during head and neck surgery, and pollution of the operating room with large volumes of waste gas. The **Mapleson systems** solve some of these problems by incorporating additional components (breathing tubes, fresh gas inlets, adjustable pressure-limiting [APL] valves, and reservoir bags) into the breathing circuit. The relative location of these components determines circuit performance and is the basis of the Mapleson classification (Table 3–2).

TABLE 3–2 Classification and characteristics of Mapleson circuits.

Mapleson Class	Other Names	Configuration[1]	Required Fresh Gas Flows		Comments
			Spontaneous	Controlled	
A	Magill attachment		Equal to minute ventilation (≈80 mL/kg/min)	Very high and difficult to predict	Poor choice during cotrolled ventilaton. Enclosed Magill system is a modification that improves efficiency. Coaxial Mapleson A (Lack breathing system) provides waste gas scavenging.
B			2 × minute ventilation	2–2½ × minute ventilation	
C	Waters' to-and-fro		2 × minute ventilation	2–2½ × minute ventilation	
D	Bain circuit		2–3 × minute ventilation	1–2 × minute ventilation	Bain coaxial modification: fresh gas tube inside breathing tube (see Figure 3–7).
E	Ayre's T-piece		2–3 × minute ventilation	3 × minute ventilation (I:E-1:2)	Exhalation tubing should provide a larger volume than tidal volume to prevent rebreathing. Scavenging is difficult.
F	Jackson-Rees' modification		2–3 × minute ventilation	2 × minute ventilation	A Mapleson E with a breathing bag connected to the end of the breathing tube to allow controlled ventilation and scavenging.

[1]FGI, fresh gas inlet; APL, adjustable pressure-limiting (value).

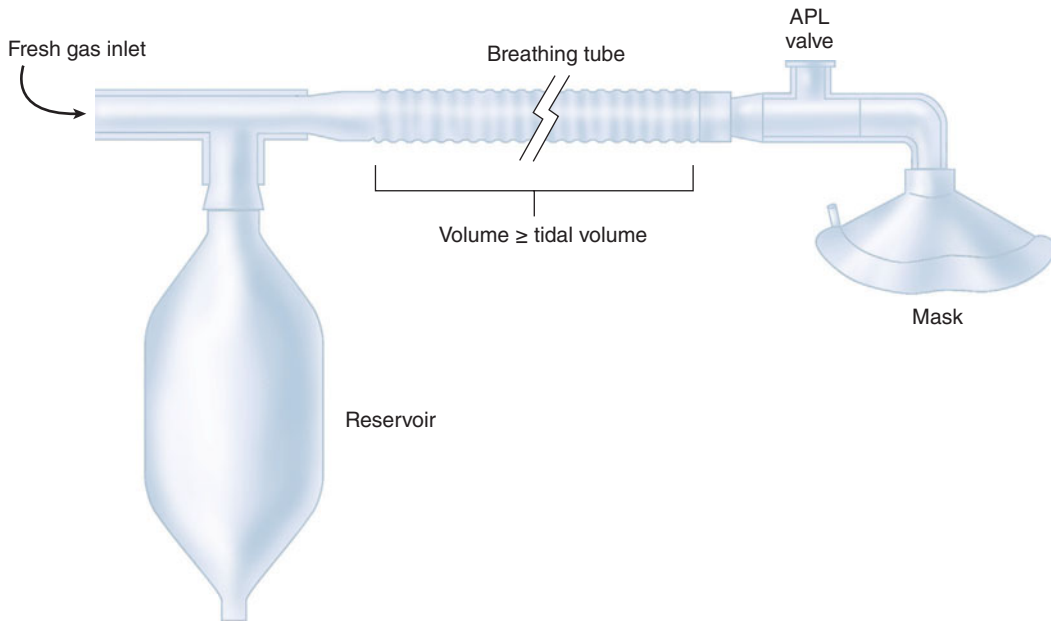


FIGURE 3–5 Components of a Mapleson circuit. APL, adjustable pressure-limiting (valve).

Components of Mapleson Circuits

A. Breathing Tubes

Corrugated tubes—made of rubber (reusable) or plastic (disposable)—connect the components of the Mapleson circuit to the patient (Figure 3–5). The large diameter of the tubes (22 mm) creates a low-resistance pathway and a potential reservoir for anesthetic gases. To minimize fresh gas flow requirements, the volume of gas within the breathing tubes in most Mapleson circuits should be at least as great as the patient's tidal volume.

The compliance of the breathing tubes largely determines the compliance of the circuit. (Compliance is defined as the change of volume produced by a change in pressure.) Long breathing tubes with high compliance increase the difference between the volume of gas delivered to a circuit by a reservoir bag or ventilator and the volume actually delivered to the patient. For example, if a breathing circuit with a compliance of 8 mL gas/cm H_2O is pressurized during delivery of a tidal volume to 20 cm H_2O, 160 mL of the tidal volume will be lost to the circuit. The 160 mL represent a combination of gas compression and breathing-tube expansion. This is an important consideration in any circuit delivering positive-pressure ventilation through breathing tubes (eg, circle systems).

B. Fresh Gas Inlet

Gases (anesthetics mixed with oxygen or air) from the anesthesia machine continuously enter the circuit through the fresh gas inlet. As discussed below, the relative position of the fresh gas inlet is a key differentiating factor in Mapleson circuit performance.

C. Adjustable Pressure-Limiting Valve (Pressure-Relief Valve, Pop-Off Valve)

As anesthetic gases enter the breathing circuit, pressure will rise if the gas inflow is greater than the combined uptake of the patient and the circuit. Gases may exit the circuit through an APL valve, controlling this pressure buildup. Exiting gases enter the operating room atmosphere or, preferably, a waste-gas scavenging system. All APL valves allow a variable pressure threshold for venting. The APL valve should be fully open during

spontaneous ventilation so that circuit pressure remains negligible throughout inspiration and expiration. Assisted and controlled ventilation require positive pressure during inspiration to expand the lungs. Partial closure of the APL valve limits gas exit, permitting positive circuit pressures during reservoir bag compressions.

D. Reservoir Bag (Breathing Bag)

Reservoir bags function as a reservoir of anesthetic gas and a method of generating positive-pressure ventilation. They are designed to increase in compliance as their volume increases. Three distinct phases of reservoir bag filling are recognizable (Figure 3–6). After the nominal 3-L capacity of an adult reservoir bag is achieved (phase I), pressure rises rapidly to a peak (phase II). Further increases in volume result in a plateau or even a slight decrease in pressure (phase III). This ceiling effect provides some minimal protection of the patient's lungs against high airway pressures, if the APL valve is unintentionally left in the closed position while fresh gas continues to flow into the circuit.

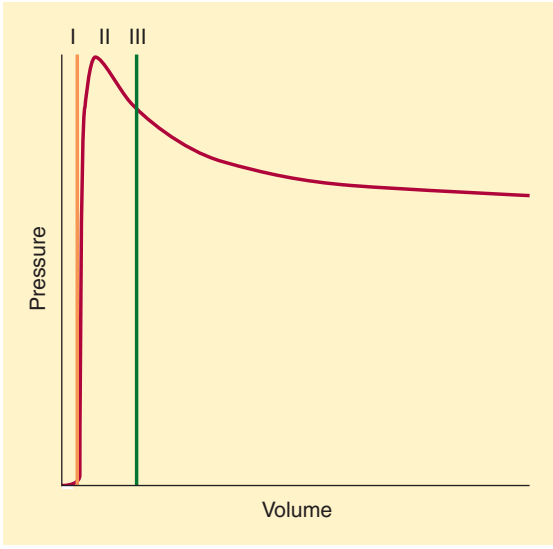


FIGURE 3–6 The increasing compliance and elasticity of breathing bags as demonstrated by three phases of filling (see text). (Reproduced, with permission, from Johnstone RE, Smith TC: Rebreathing bags as pressure limiting devices. Anesthesiology 1973;38:192.)

Performance Characteristics of Mapleson Circuits

Mapleson circuits are lightweight, inexpensive, and simple. Breathing-circuit efficiency is measured by the fresh gas flow required to reduce CO_2 rebreathing to a negligible value. Because there are no unidirectional valves or CO_2 absorption in Mapleson circuits, rebreathing is prevented by adequate fresh gas flow into the circuit and venting exhaled gas through the APL valve before inspiration. There is usually some rebreathing in any Mapleson circuit. The total fresh gas flow into the circuit controls the amount. To attenuate rebreathing, high fresh gas flows are required. The APL valve in Mapleson A, B, and C circuits is located near the face mask, and the reservoir bag is located at the opposite end of the circuit.

Reexamine the drawing of a Mapleson A circuit in Figure 3–5. During spontaneous ventilation, alveolar gas containing CO_2 will be exhaled into the breathing tube or directly vented through an open APL valve. Before inhalation occurs, if the fresh gas flow exceeds alveolar minute ventilation, the inflow of fresh gas will force the alveolar gas remaining in the breathing tube to exit from the APL valve. If the breathing-tube volume is equal to or greater than the patient's tidal volume, the next inspiration will contain only

4 fresh gas. Because a fresh gas flow equal to minute ventilation is sufficient to prevent rebreathing, the Mapleson A design is the most efficient Mapleson circuit for *spontaneous* ventilation.

Positive pressure during *controlled* ventilation, however, requires a partially closed APL valve. Although some alveolar and fresh gas exits through the valve during inspiration, no gas is vented during expiration, since the exhaled gas stagnates during the expiratory phase of positive pressure ventilation. As a result, very high fresh gas flows (greater than three times minute ventilation) are required to prevent rebreathing with a Mapleson A circuit during controlled ventilation. Fresh gas flows are conveniently available because the fresh gas inlet is in close proximity to the APL valve in a Mapleson B circuit.

Interchanging the position of the APL valve and the fresh gas inlet transforms a Mapleson A into a

5 **Mapleson D circuit** (Table 3–2). The Mapleson D circuit is efficient during controlled ventilation, since fresh gas flow forces alveolar air *away*

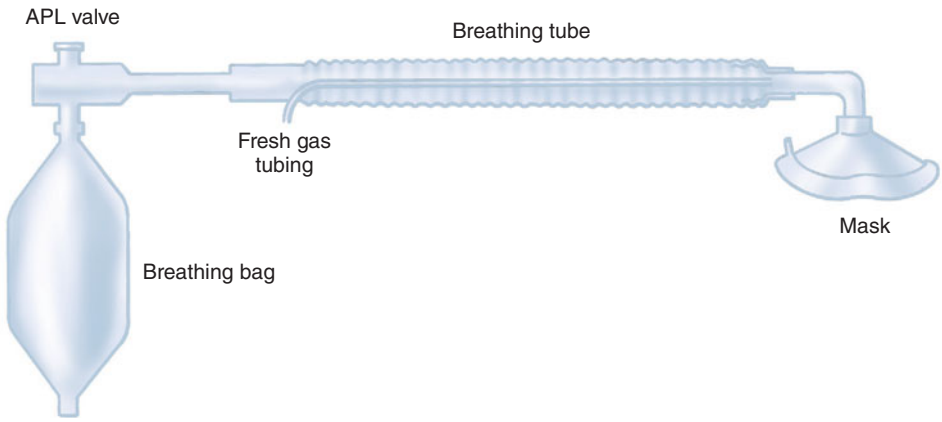


FIGURE 3–7 A Bain circuit is a Mapleson D circuit design with the fresh gas tubing inside the corrugated breathing tube. APL, adjustable pressure-limiting (valve). (Redrawn and reproduced, with permission, from Bain JA, Spoerel WE: Flow requirements for a modified Mapleson D system during controlled ventilation. Can Anaesth Soc J 1973;20:629.)

from the patient and *toward* the APL valve. Thus, simply moving components completely alters the fresh gas requirements of the Mapleson circuits.

The **Bain circuit** is a coaxial version of the Mapleson D system that incorporates the fresh gas inlet tubing inside the breathing tube (Figure 3–7). This modification decreases the circuit's bulk and retains heat and humidity better than a conventional Mapleson D circuit as a result of partial warming of the inspiratory gas by countercurrent exchange with the warmer expired gases. A disadvantage of this coaxial circuit is the possibility of kinking or disconnection of the fresh gas inlet tubing. Periodic inspection of the inner tubing is mandatory to prevent this complication; if unrecognized, either of these mishaps could result in significant rebreathing of exhaled gas.

THE CIRCLE SYSTEM

Although Mapleson circuits overcome some of the disadvantages of the insufflation and draw-over systems, the high fresh gas flows required to prevent rebreathing of CO_2 result in waste of anesthetic agent, pollution of the operating room environment, and loss of patient heat and humidity (Table 3–3). In an attempt to avoid these problems, the **circle system** adds more components to the breathing system.

The components of a circle system include: (1) a CO_2 absorber containing CO_2 absorbent; (2) a fresh gas inlet; (3) an inspiratory unidirectional valve and inspiratory breathing tube; (4) a Y-connector; (5) an expiratory unidirectional valve and expiratory breathing tube; (6) an APL valve; and (7) a reservoir (Figure 3–8).

Components of the Circle System

A. Carbon Dioxide Absorber and the Absorbent

Rebreathing alveolar gas conserves heat and humidity. However, the CO_2 in exhaled gas must be eliminated to prevent hypercapnia. CO_2 chemically

TABLE 3–3 Characteristics of breathing circuits.

	Insufflation and Open Drop	Mapleson	Circle
Complexity	Very simple	Simple	Complex
Control of anesthetic depth	Poor	Variable	Good
Ability to scavenge	Very poor	Variable	Good
Conservation of heat and humidity	No	No	Yes[1]
Rebreathing of exhaled gases	No	No[1]	Yes[1]

[1]These properties depend on the rate of fresh gas flow.

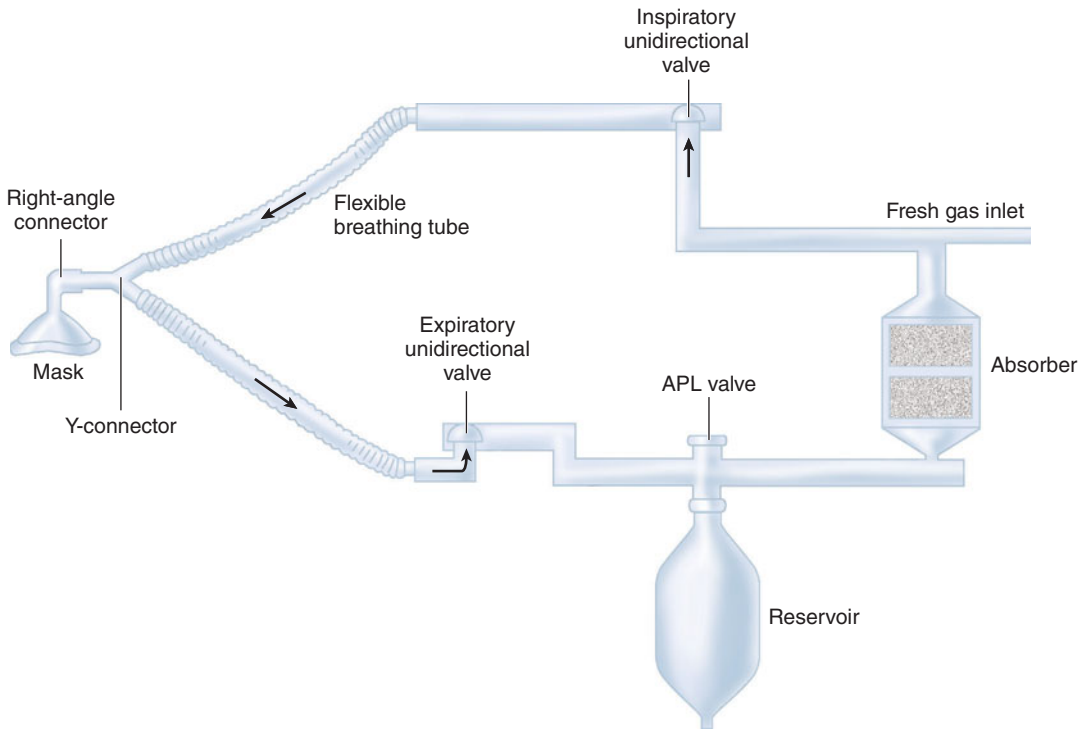


FIGURE 3–8 A circle system. APL, adjustable pressure-limiting (valve).

combines with water to form carbonic acid. CO_2 absorbents (eg, soda lime or calcium hydroxide lime) contain hydroxide salts that are capable of neutralizing carbonic acid (Table 3–4). Reaction end products include heat (the heat of neutralization), water, and calcium carbonate. **Soda lime** is the more common absorbent and is capable of absorbing up to 23 L of CO_2 per 100 g of absorbent. It consists primarily of calcium hydroxide (80%), along with sodium hydroxide, water, and a small amount of potassium hydroxide. Its reactions are as follows:

$$CO_2 + H_2O \rightarrow H_2CO_3$$

$$H_2CO_3 + 2NaOH \rightarrow Na_2CO_3 + 2H_2O + \text{Heat}$$

(a fast reaction)

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

(a slow reaction)

Note that the water and sodium hydroxide initially required are regenerated. Another absorbent, barium hydroxide lime, is no longer used due to the

TABLE 3–4 Comparison of soda lime and barium hydroxide lime.

	Soda Lime	Barium Hydroxide Lime
Mesh size[1]	4–8	4–8
Method of hardness	Silica added	Water of crystallization
Content	Calcium hydroxide Sodium hydroxide Potassium hydroxide	Barium hydroxide Calcium hydroxide
Usual indicator dye	Ethyl violet	Ethyl violet
Absorptive capacity (liters of CO_2/100 g granules)	14–23	9–18

[1]The number of openings per linear inch in a wire screen used to grade particle size.

TABLE 3–5 Indicator dye changes signaling absorbent exhaustion.

Indicator	Color when Fresh	Color when Exhausted
Ethyl violet	White	Purple
Phenolphthalein	White	Pink
Clayton yellow	Red	Yellow
Ethyl orange	Orange	Yellow
Mimosa 2	Red	White

possible increased hazard of fire in the breathing system.

A pH indicator dye (eg, ethyl violet) changes color from white to purple as a consequence of increasing hydrogen ion concentration and absorbent exhaustion (Table 3–5). Absorbent should be replaced when 50% to 70% has changed color. Although exhausted granules may revert to their original color if rested, no significant recovery of absorptive capacity occurs. Granule size is a compromise between the higher absorptive surface area of small granules and the lower resistance to gas flow of larger granules. The granules commonly used as CO_2 absorbent are between 4 and 8 mesh; the number of mesh corresponds to the number of holes per square inch of a screen. The hydroxide salts are irritating to the skin and mucous membranes. Increasing the hardness of soda lime by adding silica minimizes the risk of inhalation of sodium hydroxide dust and also decreases resistance of gas flow. Additional water is added to absorbent during packaging to provide optimal conditions for carbonic acid formation. Commercial soda lime has a water content of 14% to 19%.

Absorbent granules can absorb and later release medically important amounts of volatile anesthetic. This property can be responsible for modest delays of induction or emergence. The drier the soda lime, the more likely it will absorb and degrade volatile anesthetics. Volatile anesthetics can be broken down to carbon monoxide by dry absorbent (eg, sodium or potassium hydroxide) to such a degree that it is capable of causing clinically significant carbon monoxide poisoning. The formation of carbon monoxide is highest with desflurane; with sevoflurane, it occurs at a higher temperature.

Amsorb is a CO_2 absorbent consisting of calcium hydroxide and calcium chloride (with calcium sulfate and polyvinylpyrrolidone added to increase hardness). It possesses greater inertness than soda lime, resulting in less degradation of volatile anesthetics (eg, sevoflurane into compound A or desflurane into carbon monoxide).

Compound A is one of the by-products of degradation of sevoflurane by absorbent. Higher concentrations of sevoflurane, prolonged exposure, and low-flow anesthetic technique seem to increase the formation of Compound A. Compound A has been shown to produce nephrotoxicity in animals,

The granules of absorbent are contained within one or two canisters that fit snugly between a head and base plate. Together, this unit is called an absorber (Figure 3–9). Although bulky, double

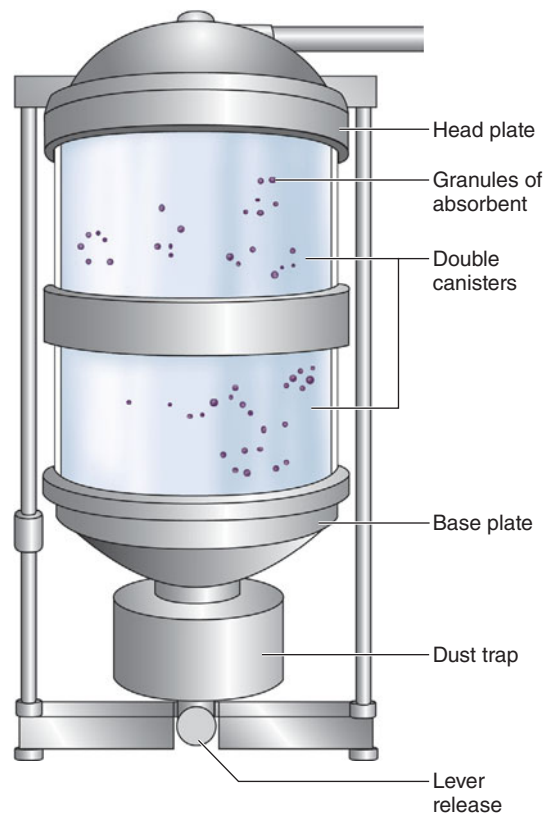


FIGURE 3–9 A carbon dioxide absorber.

canisters permit more complete CO_2 absorption, less frequent absorbent changes, and lower gas flow resistance. To ensure complete absorption, a patient's tidal volume should not exceed the air space between absorbent granules, which is roughly equal to 50% of the absorber's capacity. Indicator dye color is monitored through the absorber's transparent walls. Absorbent exhaustion typically occurs first where exhaled gas enters the absorber and along the canister's smooth inner walls. Channeling through areas of loosely packed granules is minimized by a baffle system, which directs gas flow through the center, thereby allowing greater utilization of the absorbent. A trap at the base of the absorber collects dust and moisture. Newer absorbers are used until CO_2 is found in the inhaled gas on the anesthetic-gas monitor, at which time the canister(s) are replaced.

B. Unidirectional Valves

Unidirectional valves, which function as check valves, contain a ceramic or mica disk resting horizontally on an annular valve seat (**Figure 3–10**). Forward flow displaces the disk upward, permitting the gas to proceed through the circuit. Reverse flow pushes the disk against its seat, preventing reflux. Valve incompetence is usually due to a warped disk or seat irregularities. The expiratory valve is exposed to the humidity of alveolar gas. Condensation and resultant moisture formation may prevent upward displacement of the disks, resulting in incomplete escape of expired gases and rebreathing.

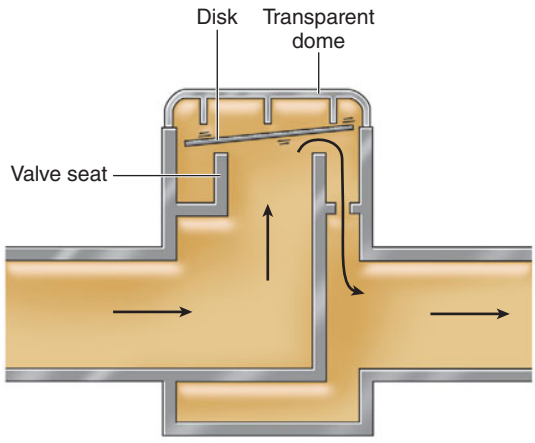


FIGURE 3–10 A unidirectional valve.

Inhalation opens the inspiratory valve, allowing the patient to breathe a mixture of fresh and exhaled gas that has passed through the CO_2 absorber. Simultaneously, the expiratory valve closes to prevent rebreathing of exhaled gas that still contains CO_2. The subsequent flow of gas away from the patient during exhalation opens the expiratory valve. This gas is vented through the APL valve or rebreathed by the patient after passing through the absorber. Closure of the inspiratory valve during exhalation prevents expiratory gas from mixing with fresh gas in the inspiratory limb. Malfunction of either unidirectional valve may allow rebreathing of CO_2, resulting in hypercapnia.

Optimization of Circle System Design

Although the major components of the circle system (unidirectional valves, fresh gas inlet, APL valve, CO_2 absorber, and a reservoir bag) can be placed in several configurations, the following arrangement is preferred (Figure 3–8):

- Unidirectional valves are relatively close to the patient to prevent backflow into the inspiratory limb if a circuit leak develops. However, unidirectional valves are not placed in the Y-piece, as that makes it difficult to confirm proper orientation and intraoperative function.
- The fresh gas inlet is placed between the absorber and the inspiratory valve. Positioning it downstream from the inspiratory valve would allow fresh gas to bypass the patient during exhalation and be wasted. Fresh gas introduced between the expiratory valve and the absorber would be diluted by recirculating gas. Furthermore, inhalation anesthetics may be absorbed or released by soda lime granules, thus slowing induction and emergence.
- The APL valve is usually placed between the absorber and the expiratory valve and close to the reservoir bag. Positioning of the APL valve in this location (ie, before the absorber) helps to conserve absorption capacity and minimizes the venting of fresh gas.

- Resistance to exhalation is decreased by locating the reservoir bag in the expiratory limb. Bag compression during controlled ventilation will vent expired gas through the APL valve, conserving absorbent.

Performance Characteristics of the Circle System

A. Fresh Gas Requirement

8 With an absorber, the circle system prevents rebreathing of CO_2 at reduced fresh gas flows (≤1 L) or even fresh gas flows equal to the uptake of anesthetic gases and oxygen by the patient and the circuit itself (closed-system anesthesia). At fresh gas flows greater than 5 L/min, rebreathing is so minimal that a CO_2 absorber is usually unnecessary.

With low fresh gas flows, concentrations of oxygen and inhalation anesthetics can vary markedly between fresh gas (ie, gas in the fresh gas inlet) and inspired gas (ie, gas in the inspiratory limb of the breathing tubes). The latter is a mixture of fresh gas and exhaled gas that has passed through the absorber. The greater the fresh gas flow rate, the less time it will take for a change in fresh gas anesthetic concentration to be reflected in a change in inspired gas anesthetic concentration. Higher flows speed induction and recovery, compensate for leaks in the circuit, and decrease the risks of unanticipated gas mixtures.

B. Dead Space

That part of a tidal volume that does not undergo alveolar ventilation is referred to as dead space. Thus, any increase in dead space must be accompanied by a corresponding increase in tidal volume, if alveolar ventilation is to remain unchanged.

9 Because of the unidirectional valves, apparatus dead space in a circle system is limited to the area distal to the point of inspiratory and expiratory gas mixing at the Y-piece. Unlike Mapleson circuits, the circle system tube length does not affect dead space. Like Mapleson circuits, length does affect circuit compliance and thus the amount of tidal volume lost to the circuit during positive-pressure ventilation. Pediatric circle systems may have both a septum dividing the inspiratory and expiratory gas in the Y-piece and low-compliance breathing tubes to further reduce dead space, and are lighter in weight.

C. Resistance

The unidirectional valves and absorber increase circle system resistance, especially at high respiratory rates and large tidal volumes. Nonetheless, even premature neonates can be successfully ventilated using a circle system.

D. Humidity and Heat Conservation

Medical gas delivery systems supply dehumidified gases to the anesthesia circuit at room temperature. Exhaled gas, on the other hand, is saturated with water at body temperature. Therefore, the heat and humidity of inspired gas depend on the relative proportion of rebreathed gas to fresh gas. High flows are accompanied by low relative humidity, whereas low flows allow greater water saturation. Absorbent granules provide a significant source of heat and moisture in the circle system.

E. Bacterial Contamination

The minimal risk of microorganism retention in circle system components could theoretically lead to respiratory infections in subsequent patients. For this reason, bacterial filters are sometimes incorporated into the inspiratory or expiratory breathing tubes or at the Y-piece.

Disadvantages of the Circle System

Although most of the problems of Mapleson circuits are solved by the circle system, the improvements have led to other disadvantages: greater size and less portability; increased complexity, resulting in a higher risk of disconnection or malfunction; complications related to use of absorbent; and the difficulty of predicting inspired gas concentrations during low fresh gas flows.

RESUSCITATION BREATHING SYSTEMS

Resuscitation bags (AMBU bags or bag-mask units) are commonly used for emergency ventilation because of their simplicity, portability, and ability to deliver almost 100% oxygen (Figure 3–11). A

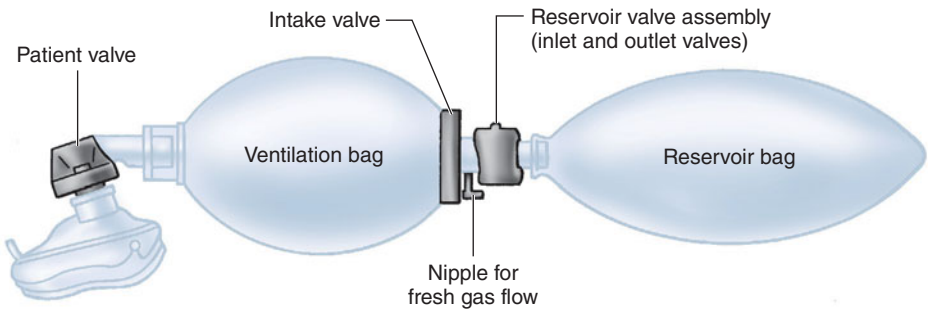


FIGURE 3–11 The Laerdal resuscitator. (Reproduced, with permission, from Laerdal Medical Corp.)

resuscitator is unlike a Mapleson circuit or a circle system because it contains a **nonrebreathing valve**. (Remember that a Mapleson system is considered valveless even though it contains an APL valve, whereas a circle system contains unidirectional valves that direct flow through an absorber but allow rebreathing of exhaled gases.)

High concentrations of oxygen can be delivered to a mask or tracheal tube during spontaneous or controlled ventilation if a source of high fresh gas flow is connected to the inlet nipple. The patient valve opens during controlled or spontaneous inspiration to allow gas flow from the ventilation bag to the patient. Rebreathing is prevented by venting exhaled gas to the atmosphere through exhalation ports in this valve. The compressible, self-refilling ventilation bag also contains an intake valve. This valve closes during bag compression, permitting positive-pressure ventilation. The bag is refilled by flow through the fresh gas inlet and across the intake valve. Connecting a reservoir to the intake valve helps prevent the entrainment of room air. The reservoir valve assembly is really two unidirectional valves: the inlet valve and the outlet valve. The inlet valve allows ambient air to enter the ventilation bag if fresh gas flow is inadequate to maintain reservoir filling. Positive pressure in the reservoir bag opens the outlet valve, which vents oxygen if fresh gas flow is excessive.

There are several disadvantages to resuscitator breathing systems. First, they require high fresh gas flows to achieve a high F_{IO_2}. F_{IO_2} is directly proportional to the oxygen concentration and flow rate of the gas mixture supplied to the resuscitator (usually 100% oxygen) and inversely proportional to the minute ventilation delivered to the patient. For example, a Laerdal resuscitator equipped with a reservoir requires a flow of 10 L/min to achieve an inspired oxygen concentration approaching 100% if a patient with a tidal volume of 750 mL is ventilated at a rate of 12 breaths/min. The maximum achievable tidal volumes are less than those that can be achieved with a system that uses a 3-L breathing bag. In fact, most adult resuscitators have a maximum tidal volume of 1000 mL, which is sufficient for the lower tidal volumes generally employed in patient management. Finally, although a normally functioning patient valve has low resistance to inspiration and expiration, exhaled moisture can cause valve sticking.

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CASE DISCUSSION

Unexplained Light Anesthesia

An extremely obese but otherwise healthy 5-year-old girl presents for inguinal hernia repair. After uneventful induction of general anesthesia and tracheal intubation, the patient is placed on a ventilator set to deliver a tidal volume of 7 mL/kg at a rate of 16 breaths/min. Despite delivery of high concentrations of sevoflurane in 50% nitrous oxide, tachycardia (145 beats/min) and mild hypertension (144/94 mm Hg) are noted. To increase anesthetic depth, fentanyl (3 mcg/kg) is administered. Heart rate and blood pressure continue to rise and are accompanied by frequent premature ventricular contractions.

What should be considered in the differential diagnosis of this patient's cardiovascular changes?

The combination of tachycardia and hypertension during general anesthesia should always alert the anesthesiologist to the possibility of hypercapnia or hypoxia, both of which produce signs of increased sympathetic activity. These life-threatening conditions should be quickly and immediately ruled out by end-tidal CO_2 monitoring, pulse oximetry, or arterial blood gas analysis.

A common cause of intraoperative tachycardia and hypertension is an inadequate level of anesthesia. Normally, this is confirmed by movement. If the patient is paralyzed, however, there are few reliable indicators of light anesthesia. The lack of a response to a dose of an opioid should alert the anesthesiologist to the possibility of other, perhaps more serious, causes.

Malignant hyperthermia is rare but must be considered in cases of unexplained tachycardia, especially if accompanied by premature contractions. Certain drugs used in anesthesia (eg, pancuronium, ketamine, ephedrine) stimulate the sympathetic nervous system and can produce or exacerbate tachycardia and hypertension. Diabetic patients who become hypoglycemic from administration of insulin or long-acting oral hypoglycemic agents can have similar cardiovascular changes. Other endocrine abnormalities (eg, pheochromocytoma, thyroid storm, carcinoid) should also be considered.

Could any of these problems be related to an equipment malfunction?

Gas analysis can confirm the delivery of anesthetic gases to the patient.

A misconnection of the ventilator could result in hypoxia or hypercapnia. In addition, a malfunctioning unidirectional valve will increase circuit dead space and allow rebreathing of expired CO_2. Soda lime exhaustion could also lead to rebreathing in the presence of a low fresh gas flow. Rebreathing of CO_2 can be detected during the inspiratory phase on a capnograph. If rebreathing appears to be due to an equipment malfunction, the patient should be disconnected from the anesthesia machine and ventilated with a resuscitation bag until repairs are possible.

What are some other consequences of hypercapnia?

Hypercapnia has a multitude of effects, most of them masked by general anesthesia. Cerebral blood flow increases proportionately with arterial CO_2. This effect is dangerous in patients with increased intracranial pressure (eg, from brain tumor). Extremely high levels of CO_2 (>80 mm Hg) can cause unconsciousness related to a fall in cerebrospinal fluid pH. CO_2 depresses the myocardium, but this direct effect is usually overshadowed by activation of the sympathetic nervous system. During general anesthesia, hypercapnia usually results in an increased cardiac output, an elevation in arterial blood pressure, and a propensity toward arrhythmias.

Elevated serum CO_2 concentrations can overwhelm the blood's buffering capacity, leading to respiratory acidosis. This causes other cations such as Ca^{2+} and K^+ to shift extracellularly. Acidosis also shifts the oxyhemoglobin dissociation curve to the right.

Carbon dioxide is a powerful respiratory stimulant. In fact, for each mm Hg rise of $PaCO_2$ above baseline, normal awake subjects increase their minute ventilation by about 2–3 L/min. General anesthesia markedly decreases this response, and paralysis eliminates it. Finally, severe hypercapnia can produce hypoxia by displacement of oxygen from alveoli.

SUGGESTED READING

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