Mechanical Ventilation in the Operating Room

65

Joseph D. Tobias

During the provision of general anesthesia, some type of support of ventilatory function is generally necessary given the depressant effects of the various anesthetic and opioid agents that are administered to provide amnesia and analgesia. Furthermore, for major thoracic or abdominal procedures, neuromuscular blocking agents are frequently administered, thereby necessitating full control of ventilation. As with ventilation outside of the operating room (OR), variation options exist for respiratory support during the provision of general anesthesia including volume- or pressure-limited modalities or more recently the use of pressure support ventilation to augment spontaneous ventilation. Given the limitations of commercially available OR ventilators, critically ill patients may require the use of sophisticated ICU ventilators in the OR setting. In such instances, as the inhalational anesthetic agents cannot generally and easily be administered through such ventilators, general anesthesia is provided by intravenous anesthetic agents (total intravenous anesthesia or TIVA). This chapter reviews the basics of anesthesia breathing systems, options for ventilator support during anesthetic care, and special situations in the operating including the administration of adjunctive agents (helium, nitric oxide, nitrogen, and carbon dioxide) as well as the use of one-lung ventilation (OLV) during thoracic surgical procedures.

J.D. Tobias, MD
Department of Anesthesiology and Pain Medicine,
Nationwide Children's Hospital,
Columbus, OH, USA

Department of Anesthesiology and Pediatrics,
The Ohio State University, 700 Children's Drive,
Columbus, OH 43205, USA
e-mail: tobiasj@health.missouri.edu,
joseph.tobias@nationwidechildrens.org

65.1 Breathing Systems in the Operating Room

The general design of the anesthesia machine consists of a gas source for oxygen, air and nitrous oxide, flow meters, vaporizers, and a common gas outlet. The gas source is generally from a hospital-based system with wall outlets, although in remote areas of the hospital or in inauspicious surroundings, the source of gases can be standard tanks. The gases (oxygen, air, and nitrous oxide) are mixed using flow meters and then directed into the vaporizers for the delivery of various concentrations of the inhalational anesthetic agents. The inhalational anesthetic agents (sevoflurane, desflurane, and isoflurane) are volatile liquids, meaning that they have the potential to transform into a vapor. As the concentration on the vaporizer dial is increased, more of the gas flow is diverted through the vaporizer, thereby increasing the inspired concentration of the inhalational anesthetic agent. In today's clinical practice, there is a

P.C. Rimensberger (ed.), *Pediatric and Neonatal Mechanical Ventilation*,
DOI 10.1007/978-3-642-01219-8_65, © Springer-Verlag Berlin Heidelberg 2015

specific vaporizer calibrated for each of the various inhalational anesthetic agents as the vapor pressure varies from agent to agent. As the gas flow exits the vaporizer, it is directed toward the patient through the common gas outlet.

65.1.1 Open, Semi-open, Semi-closed, and Closed Breathing Systems

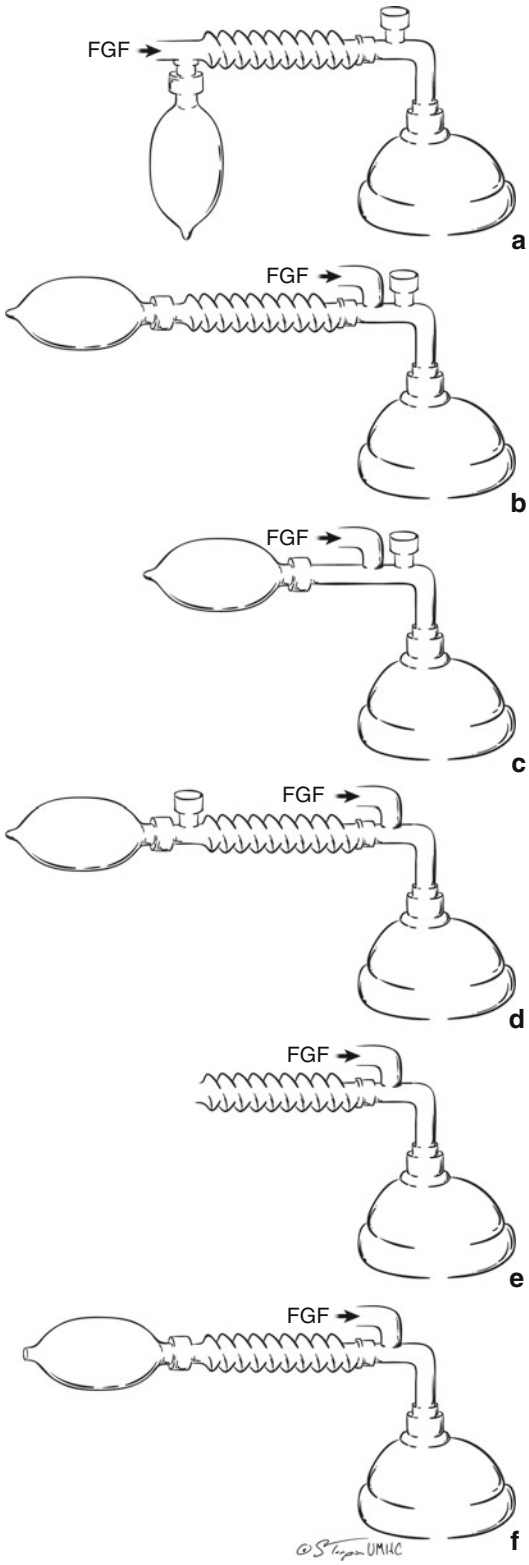
As the gas exits the anesthesia machine, it is delivered to the patient through the anesthesia circuit. The function of the circuit involves both the delivery and the removal of the exhaled gas from the patient. As the exhaled gas contains carbon dioxide, some means of its removal is mandatory to avoid rebreathing and the development of significant hypercarbia. This can be accomplished either by a high fresh gas flow (FGF) or the inclusion of a substance into the anesthesia system that will absorb the carbon dioxide (see below). The rebreathing of exhaled gases during general anesthesia is in marked distinction to what occurs in the ICU setting where the entire exhaled tidal breath is vented away from the patient, and therefore, no rebreathing occurs. Advantages of partial or complete rebreathing include conservation of gases (oxygen, air), heat, airway humidity, and inhalational anesthetic agents. Additionally, the semi-closed or closed systems reduce environmental pollution.

In general, anesthetic delivery systems are classified as open, semi-open, semi-closed, and closed. In current practice, open systems, which are exemplified by the administration of open-drop ether using a specialized mask wire frame mask developed by Dr. Schimmelbusch, are no longer in use. Although the semi-open, semi-closed, and closed designation is still in common use, a more appropriate terminology may be to divide systems into those where there is no rebreathing of exhaled gases (open and semi-open) and those in which there is rebreathing of exhaled gases (semi-closed and closed) (Conway 1985; Miller 1988). In systems with some or complete rebreathing, a CO_2 absorber is added in-line to remove CO_2 from the exhaled gases.

65.1.1.1 The Mapleson Breathing Systems

The era of modern-day anesthesia circuits was brought to anesthesia practice by the description and introduction into practice of the Mapleson systems (Mapleson 1954). The Mapleson systems includes five different configurations of the FGF, tubing, reservoir bag, and expiratory valve (Fig. 65.1). When compared with a standard circle system (see below), the Mapleson system does not have an inspiratory valve and was developed as such to limit the work of breathing in younger infants. The amount of rebreathing of exhaled gases that occurs with each system depends significantly on the patient's minute ventilation and the FGF rate. Modifications of the original Mapleson system include the addition of a sixth setup (the F system) and the Bain circuit. The F system is a modification of the E system (Ayre's t-piece) where a reservoir bag is placed at the end of the corrugated tubing (Willis et al. 1975). The reservoir bag is open at the distal end (away from the corrugated tubing) and can be occluded between the anesthesiologist's fingers or a clamp to allow for assisted or positive-pressure ventilation. When used in this fashion, it is commonly known as the Jackson-Rees modification of the Ayre's t-piece. An additional modification of the F system or Jackson-Rees modification of the Ayre's t-piece known as the Kuhn's circuit has a hole in the side of the reservoir bag instead of the end.

The Mapleson A circuit, also known as the Magill's circuit, has the FGF coming into a corrugated tube, a reservoir bag at the end of the corrugated tubing, and a one-way expiratory valve at the end of the corrugated tubing just proximal to the attachment to the patient (ETT, mask, or laryngeal mask airway). This arrangement is most efficient during spontaneous ventilation as rebreathing does not occur until the FGF is below 70 % of the patient's minute ventilation (Norman et al. 1967; Kain and Nunn 1967). However, the system is inefficient during positive-pressure ventilation as the expiratory valve must be closed to such a degree that there is limited venting of exhaled gases, thereby



resulting in rebreathing. As such, the device is not recommended for use during controlled ventilation (Kain and Nunn 1968; Sykes 1959). The Mapleson B differs from the Mapleson A in that the FGF is adjacent to the expiratory valve at the end of the corrugated tubing. Given the placement of the FGF, the system's efficiency is similar during spontaneous and controlled ventilation. The position of the FGF allows fresh gas and exhaled gases to accumulate in the corrugated tubing until the pressure increases to such a point that the gas is expelled through the expiratory valve. The gas that is expelled is a mixture of fresh gas and exhaled alveolar gas with the exact percentage of the two depending on the FGF rate. Rebreathing does not occur when the FGF rate is more than twice the minute ventilation during either controlled or spontaneous ventilation (Sykes 1968). The Mapleson C system, also known as the Waters' circuit without a CO_2 absorber, has a setup and design similar to that of the Mapleson B with a much shorter piece of tubing from the bag to elbow adaptor for attachment to the patient. As with the Mapleson B, the pop-off valve is located on the elbow adaptor. The elimination of the tubing or use of a shorter piece of tubing results in greater mixing of exhaled and inspired gases. An FGF of twice the minute ventilation is required to prevent rebreathing of exhaled CO_2. A similar device (Fig. 65.2) has been adapted for use during neonatal and pediatric resuscitation to provide preoxygenation and ventilation prior to endotracheal intubation. The modification of the Mapleson C device for resuscitation includes not only an inlet for the delivery of FGF, which is usually connected to a high-pressure oxygen source (wall outlet or standard E cylinder), but also a second attachment site which is hooked to a

Fig. 65.1 Arrangement of the various Mapleson circuits (**a**–**f**). The circuits vary based on the site of introduction of the fresh gas flow (*FGF*), pop-off or airway pressure relief valve, reservoir bag, and corrugated tubing. The arrangements vary significantly in their efficiency in carbon dioxide removal during either controlled or spontaneous ventilation

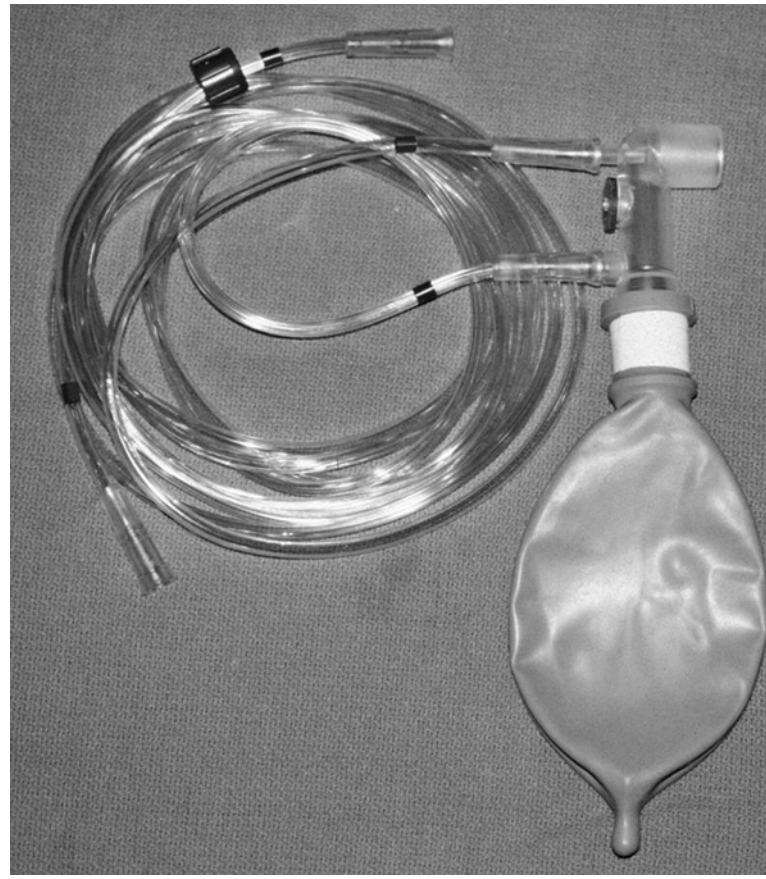


Fig. 65.2 Photograph of a Mapleson C circuit setup which is commonly used during resuscitation for positive-pressure or spontaneous ventilation through an anesthesia mask or an endotracheal tube. The tubing is connected to an oxygen source and a manometer. The adjustable pop-off valve lies between the two connection sites for the tubing

manometer to allow for pressure measurements during positive-pressure ventilation or the delivery of CPAP. When compared to a standard resuscitation bag (Ambu bag), advantages of the Mapleson C design include the ability to provide an FiO_2 of 1.0 for resuscitation, preoxygenation, transport, or positive-pressure ventilation; the ability to accurately assess and change the level of positive-pressure ventilation with the use of a manometer; the ability to deliver CPAP during spontaneous ventilation; and the ability to spontaneously ventilate with limited airway resistance. Additionally, when the modified Mapleson C is attached to an oxygen blender, the FiO_2 can be effectively and accurately adjusted for situations where positive-pressure ventilation with a varying FiO_2 may be indicated such as infants with single-ventricle physiology or during neonatal resuscitation. The Mapleson D system differs from the Mapleson B only in the location of the pop-off valve. With the Mapleson D, the pop-off valve is located near the reservoir bag instead of on the elbow adaptor. During exhalation, the exhaled gas travels down the corrugated tubing and mixes with the FGF. The composition of the inspired gas is therefore determined by the FGF rate, the exhaled tidal volume, and the expiratory time. A long expiratory time as will occur with a slow respiratory rate results in a longer time for the exhaled gas to flow down the corrugated tubing and be washed out of the circuit through the expiratory valve by the FGF. The system is most efficient during controlled ventilation with a requirement for an FGF rate less than that of the Mapleson A, B, or C system. During spontaneous ventilation, the FGF rate should be approximately twice the minute ventilation to prevent rebreathing (Bain and Spoerel 1973; Soliman and Laberge 1978). A modification of the Mapleson D circuit, known as the

Bain system, functions in a manner equivalent to that of the Mapleson D. The difference with the Bain system is that the FGF travels inside the corrugated tubing, therefore allowing the exhaled gas to warm the FGF prior to its administration to the patient. However, the disadvantage of the system is that the FGF line cannot be visualized in the event of its occlusion, disconnection, or kinking.

The Mapleson E and F systems are similar and differ only in the addition of a reservoir bag at the end of the corrugated tubing in the Mapleson F system. As opposed to the other Mapleson systems, neither of these systems has a pop-off valve incorporated into the elbow adaptor or the tubing system. The Mapleson E system was a modification of the Ayre's t-piece which was developed in the 1930s by Dr. Phillip Ayre for use during pediatric anesthesia (Ayre 1937). The Mapleson E system or some modification of its design is commonly used to administer oxygen during spontaneous ventilation through an ETT. It has no valves, thereby limiting resistance to breathing and hence the work of breathing and minimal dead space, and it permits the elimination of rebreathing with FGF rates of two to three times the minute ventilation. The reservoir space of the tubing prevents entrainment of room air provided that the tidal volume is less than the dead space of the tubing. As there is no reservoir bag on the Mapleson E, it cannot be used for positive-pressure ventilation. The modification of the Mapleson E by the addition of the reservoir B at the end of the corrugated tubing results in the Mapleson F system (more commonly known as the Jackson-Rees modification of the Ayre's t-piece). For use during positive-pressure ventilation, a pop-off value is incorporated into the reservoir bag. This opening in the bag can be occluded by the anesthesia provider to provide CPAP during spontaneous ventilation to allow for positive-pressure ventilation. Based on the FGF rate and the occlusion of the hole, the CPAP or peak inspiratory pressure can be altered. With the Mapleson F system (Jackson-Rees modification of the Ayre's t-piece), the hole is at the distal end of the reservoir bag and can be occluded between two fingers of the anesthesia provider or with a t-clamp. Alternatively, the hole in the reservoir bag can be on its side (Kuhn's circuit). FGF rates are similar to those described for the Mapleson D circuit.

Advantages of the Mapleson circuits which maintains their use in the practice of pediatric anesthesia include the ability to switch from controlled to spontaneous ventilation; limited inspiratory resistance and absence of valves, thereby decreasing work of breathing during spontaneous ventilation; and a long history of their use in the provision of pediatric anesthesia. Disadvantages include requirements for high FGF rates with the use of larger quantities of air/oxygen/nitrous oxide; no rebreathing, thereby increasing the requirements and cost of inhalational anesthesia; no humidification or heating of the inspired gas (this can be overcome by the inclusion of a heated humidifier to warm and humidify the FGF prior to its entry into the Mapleson system); and increased environmental pollution.

65.1.1.2 The Circle Anesthesia Breathing Systems

Given these concerns, there is increasing use of a standard circle system (Fig. 65.3) for the provision of anesthesia in the USA. The circle systems are semi-closed systems as rebreathing of the exhaled gases occurs depending on the FGF rate. As such, to prevent issues with the rebreathing of CO_2, some type of CO_2 absorber is required in these systems. Unidirectional values direct the FGF toward the patient and the expiratory gases toward the CO_2 absorber or the exhalation value, thereby limiting rebreathing when the FGF is decreased. With these systems, although the extent of rebreathing is determined primarily by the FGF, very low FGF rates (less than 500 mL/min in an adult) can be used since the CO_2 is eliminated from the exhaled gases and rebreathing serves to conserve heat, humidity, and anesthetic gases. The circle system serves to define and distinguish between the different types of anesthesia breathing systems as it can be used as a semi-open (no rebreathing), semi-closed (partial rebreathing), or closed (complete rebreathing) system based on the FGF rate (Moyers 1953). The circle system consists of several key

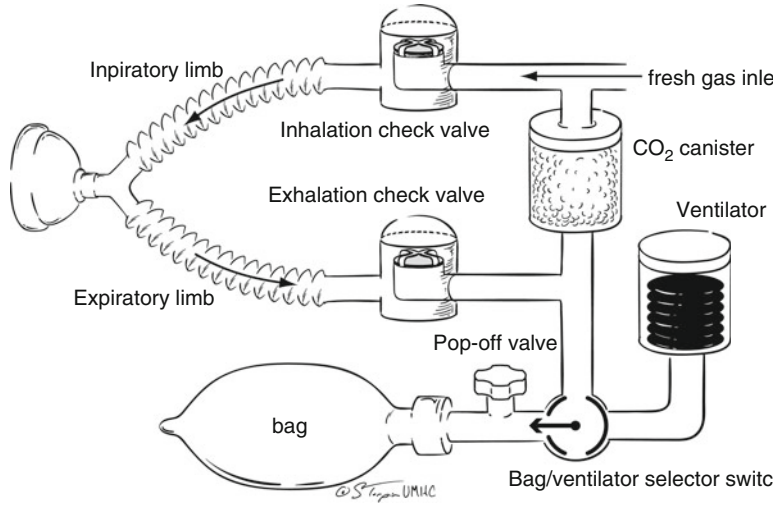


Fig. 65.3 Arrangement of the standard anesthesia circle system used in modern operating rooms for the delivery of anesthetic agents and gas mixtures (oxygen, air, and nitrogen)

elements including an FGF source, inspiratory and expiratory valves, inspiratory and expiratory corrugated tubing, a Y piece which connects with the standard 15 mm on the airway device (ETT, anesthesia mask, or laryngeal mask airway), a pop-off valve otherwise known as the airway pressure relief (APR) valve, a reservoir bag, and the CO_2 absorber cannister. The diameter of the corrugated tubing comes in various sizes to limit the dead space for pediatric patients. Additionally, specialized tubing is available which allows adjustment of the length of the inspiratory and expiratory limbs of the system to allow for the provision of general anesthesia in situations where the anesthesia machine must be placed some distance from the patient due to the presence of other personnel or apparatus such as the cardiac catheterization suite, radiology suite, or during magnetic resonance imaging. However, when the tubing is expanded, the dead space may increase, necessitating the increase of the FGF rate to prevent rebreathing from the dead space of the tubing. During the provision of anesthesia, the amount or presence of rebreathing can easily be assessed by using the end-tidal CO_2 monitor which provides not only expiratory CO_2 values (end tidal) but also inspiratory values which should be zero if there is adequate gas flow to wash out the CO_2 from the dead space of the circuit.

65.1.1.3 Carbon Dioxide Absorbers

As some rebreathing of exhaled gases generally occurs with the use of a circle system, a mechanism for scrubbing or removing the exhaled CO_2 must be in place. It has minimal dead space and no valves, thereby limiting resistance to breathing and hence the work of breathing. Additionally, it eliminates rebreathing with FGF rates of two to three times minute ventilation. In most circumstances, the rebreathing of exhaled gas is beneficial as it serves to conserve heat and humidity as the exhaled gases are already warmed and humidified as well as decreasing the cost of the care by limiting the need for the inhalational anesthetic agent. The latter is quite important as rebreathing of the exhaled gas and therefore the exhaled inhalational anesthetic agent allows for the decrease in the FGF rate to less than 1 L/min in some cases, thereby significantly decreasing the consumption of the inhalational anesthetic agent. However, whenever exhaled gases are rebreathed, hypercarbia will occur unless the carbon dioxide is removed or "scrubbed" from the exhaled gas. In clinical anesthesia, this is accomplished by passing the exhaled gas over a substance which removes the exhaled carbon dioxide. A similar process is used in other closed areas such as submarines to prevent the rebreathing of exhaled carbon dioxide.

In clinical anesthesia practice, one of three similar substances is used to remove the carbon dioxide from the exhaled gas: soda lime, baralyme, or calcium hydroxide lime (Amsorb). Soda lime, a mixture of chemicals in granular form, removes the carbon dioxide from the exhaled gases. Soda lime is produced by treating slaked lime with a concentrated sodium hydroxide solution. The main components of soda lime are calcium hydroxide or Ca $(OH)_2$ (75–70 %), water (15–20 %), sodium hydroxide or NaOH (3–4 %), and potassium hydroxide or KOH (1 %). The exothermic chemical reaction for the removal of carbon dioxide by soda lime can be summarized as $CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O +$ heat. Baralyme is a mixture of approximately 80 % calcium hydroxide and 20 % barium hydroxide. Calcium hydroxide lime (Amsorb) is the newest of the three agents available for carbon dioxide scrubbing. The impetus for the production of this agent was to provide an effective agent for carbon dioxide removal that does not contain either sodium or potassium hydroxides. The advantage of the elimination of these agents is that the new product (Amsorb) does not interact with the inhalational anesthetic agents to produce toxic by-products such as carbon monoxide or compound A (see below) (Versichelen et al. 2001).

The production of the carbon dioxide absorbers as a granular form has been studied by trial and error to produce granules which maximize the surface area for the absorption of carbon dioxide and minimize the resistance of the gas as it flows over these granules in the cannister (Hunt 1955). The granule size of soda lime and baralyme is measured in units known as mesh which refers to the number of openings per linear inch in a sieve through which the granules can pass. Soda lime and baralyme have granules that vary in size from 4 to 8 mesh which results in an adequate absorptive surface area for the removal of carbon dioxide with a minimal increase in the resistance to gas flow. In addition to the compounds which absorb carbon dioxide, an indicator is added to these agents to provide a warning that the agent is becoming exhausted or is no longer capable of removing carbon dioxide. As the carbon dioxide absorbing capacity becomes depleted, the pH of the granules decreases and the indicator (ethyl violet) turns from colorless to purple.

Although effective for the removal of carbon dioxide, recent evidence has suggested that the interaction of the carbon dioxide absorbent and various inhalational anesthetic agents may result in potentially deleterious effects including either the production of a toxic compound (compound A or carbon monoxide) or the production of excessive heat with the risk of thermal injury to the airway or production of a fire in the cannister (Fang et al. 1995; Baum et al. 1995). Only carbon dioxide absorbents that contain KOH or NaOH (soda lime and baralyme) can result in the production of carbon monoxide or compound A. No such interaction exists with the newer agent, Amsorb.

The potential interaction of inhalational anesthetic agents and the carbon dioxide absorbent is nothing new in the practice of clinical anesthesia. Such issues were first recognized in the 1950 and 1960s with the inhalational anesthetic agent, trichloroethylene which produces a neurotoxin, dichloroacetylene, and a respiratory toxin or irritant, phosgene. Such problems still potentially exist even with the use of the modern inhalational anesthetic agents. The vinyl ether, compound A, is produced during the metabolism of sevoflurane and its reaction with the soda lime or baralyme in the carbon dioxide absorber of the anesthesia machine (Morio et al. 1992; Frink et al. 1992). The safe concentration of compound A is unknown in humans as is the mechanism of the postulated renal injury (Mazze 1992). Compound A concentrations are increased by several factors including a high inspired concentration of sevoflurane, a low FGF through the system (less than 2 L/min), increasing temperatures of the soda lime cannister, the water content of the CO_2 absorbent, and high concentrations of potassium or sodium hydroxides in the CO_2 absorbent. Despite the demonstration of potentially nephrotoxic effects of compound A in laboratory animals, even in patients with preexisting renal

dysfunction, there are no data to suggest that sevoflurane and compound A lead result in clinical consequences on renal function even during prolonged anesthetics.

Another issue of potential concern regarding the interaction of the inhalational anesthetic agents and the carbon dioxide absorbents is the production of carbon monoxide. Clinically significant amounts of carbon monoxide are produced only when desiccated soda lime or baralyme is used in conjunction with desflurane or the older inhalational anesthetic agent, enflurane (Fang et al. 1995; Baum et al. 1995). The scenario of carbon monoxide toxicity related to such issues has most commonly reported with the first case on a Monday morning when the fresh gas has been left flowing through the anesthesia machine over the weekend resulting in the desiccation of the carbon dioxide absorbent (Berry et al. 1999). Although an extremely rare event, significant morbidity and mortality may occur as carboxyhemoglobin levels of up to 30 % have been reported (Berry et al. 1999). Factors which may increase the production of carbon monoxide include the inhalational anesthetic agent used (desflurane, enflurane) and its inspired concentration, the type of carbon dioxide absorbent, and the water content and temperature of the absorbent.

One final consequence of the use of carbon dioxide absorbents is the potential for an accelerated exothermic reaction with the subsequent generation of significant amounts of heat which, in rare circumstances, can result in the production of a fire. In 2004, Abbott laboratories released a dear healthcare provider letter, and warnings were published in the Anesthesia Patient Safety Foundation letter regarding the potential for an exothermic reaction leading to fires from the interaction of sevoflurane and the CO_2 absorbent, Baralyme®. To date, this has been an extremely rare occurrence with a limited number of reports in the literature (Castro et al. 2004; Wu et al. 2004; Fatheree and Leighton 2004). As was noted with the issues regarding the release of carbon monoxide from the interaction of the CO_2 absorbent and the inhalational anesthetic agents (see above), the exothermic reaction from the interaction of sevoflurane and Baralyme® occurs only under extreme circumstances when the CO_2 absorbent has been desiccated from prolonged high gas flows. Therefore, with proper care and attention, such issues should not be a concern during the routine provision of general anesthesia. However, the potential impact and danger of the extreme circumstances (desiccated CO_2 absorbent, high fresh gas flow, and high sevoflurane concentration) are demonstrated by the study of Laster et al. using a lung analogue model (Laster et al. 2004). Baralyme® was desiccated by a heated high oxygen flow for several hours. The CO_2 absorbent was then placed in a standard cannister on an anesthesia machine and a 6 L/min flow of oxygen directed through it with either 1.5 MAC of sevoflurane or both 1.5 and 3 MAC of desflurane and isoflurane. A 3-L resuscitation bag was used as a lung model and a minute ventilation of 10 L/min started. With either 1.5 or 3 MAC of isoflurane and desflurane, the temperature within the cannister increased to a peak of approximately 100 °C after 30–70 min. With 1.5 MAC of sevoflurane, the temperature increased to more than 200 °C, and in two of the five cases, flames were noted in the anesthesia circuit.

65.2 Intraoperative Mechanical Ventilation

There are several obvious differences between mechanical ventilation in the operating room and that performed in the ICU setting. In the operating room setting, airway control may be provided by an anesthesia mask, a supraglottic airway device such as the laryngeal mask airway, or an endotracheal tube. As opposed to the ICU setting, the operating room is unusual in that many patients who receive mechanical ventilation have relatively normal pulmonary function and receive endotracheal intubation and controlled ventilation only because of the requirements for the surgical procedure. However, other extremes exist in that patients may have preexisting pulmonary comorbidities which require meticulous intraoperative attention to

their requirements for mechanical ventilation. Alternatively, significant intraoperative or postoperative issues may develop (bronchospasm, acid aspiration, laryngospasm) which may require impact on respiratory function.

65.2.1 Controlled Ventilation

Although generally not as efficient as ICU ventilators, the newest generation of anesthesia ventilators allows various options for the mode of ventilation including pressure- or volume-limited ventilation as well as pressure support ventilation during spontaneous ventilation. As in the pediatric ICU, the goals of mechanical ventilation are to provide ventilation (removal of CO_2) and oxygenation. In many circumstances, anesthesia ventilators work in the IMV (intermittent mandatory ventilation) mode so that there is no synchronization with spontaneous ventilation. In fact, when potent inhalational anesthetic agents, high doses of propofol, or high doses of opioids are administered, they shift the CO_2 response curve to the right to such an extent that the patient's ventilatory drive is abolished. Additionally, for specific types of surgical procedures (thoracic or neurosurgery) when spontaneous ventilation may be undesirable or deleterious, neuromuscular blocking agents are added to the anesthetic regimen. Given these scenarios, CMV is used most commonly during the intraoperative period. As in the pediatric ICU, ventilation in the operating room is named by the limit variable (pressure or volume) or the parameter which is set to determine the magnitude of the tidal breath. In adult anesthesia practice, the limit variable is most frequently volume. A preset tidal volume is chosen (generally 6–8 mL/kg) and delivered at a rate per minute based on one's assessment of the patient's needs for minute ventilation. Alternatively, a pressure limit is used, and the tidal breath provided until a present pressure limit is achieved (pressure-limited ventilation). In general clinical practice, there are no data to demonstrate advantages of one mode over another; however, in specific clinical scenarios, there may be advantages to pressure-limited ventilation. Unzueta et al. randomized 58 adult patients with good preoperative pulmonary function scheduled for thoracic surgery requiring one-lung ventilation (OLV) into two groups (Unzueta et al. 2007). Patients received a tidal volume of 9 mL/kg delivered either by volume-limited ventilation for 30 min followed by pressure-limited ventilation for a similar period of time or by pressure-limited ventilation for 30 min followed by volume-limited ventilation for a similar duration. Although they noted no difference in the oxygenation during the two modes of ventilation, the peak airway pressure required to deliver the tidal volume of 9 mL/kg was lower with pressure-limited ventilation (24.43 ± 3.42 versus 34.16 ± 5.21 cmH_2O, $p < 0.001$).

In addition to choosing the mode of ventilation, the pressure or volume limit, and the rate, anesthesia ventilators allow the setting of an inspiratory time. Although an often forgotten parameter, the inspiratory time can impact on both CO_2 removal and oxygenation via its effects on tidal volume and mean airway pressure. With volume-limited ventilation, a specific tidal volume is set and an inspiratory time is chosen. The flow provided is then integrated based on the tidal volume and inspiratory time. For example, if a V_T of 500 mL with an inspiratory time of 1 s is chosen, 500 mL will be delivered over 1 s using a gas flow of 30 L/min (500 mL/1 s = 60 L/min). Therefore, during volume-limited ventilation, increasing the inspiratory time will result in a decrease in the flow rate and the delivery of that tidal volume with a lower peak inflating pressure. As such, lengthening of the inspiratory time during the provision of general anesthesia is most frequently performed in patients with altered resistance and compliance as a means of delivering the tidal volume with a lower peak inflating pressure. As most pressure ventilators actually time cycle (end inspiration based on the inspiratory time), increasing the inspiratory time will increase the mean airway pressure and hence the exhaled tidal volume. The increased mean airway pressure improves oxygenation, while the increased tidal volume increases minute ventilation.

With normal spontaneous ventilation, the *I*:*E* ratio is 1:3 or 1:4. Therefore, the use of longer

inspiratory times may be uncomfortable during spontaneous ventilation, generally not an issue in the operating room during the provision of general anesthesia. In our practice, we frequently use inspiratory times of 0.3–0.5 s for infants and up to 0.7–1.5 s in adolescents. The inspiratory time should also be adjusted based on the underlying disease process. Patients with bronchospasm and air trapping generally benefit from a shorter inspiratory time to allow for as much exhalation time as possible. Patients with alveolar space disease and poor compliance generally do better with longer inspiratory times to increase mean airway pressure and improve oxygenation. The inspiratory time can be increased up to 1.2–1.5 s as needed to increase mean airway pressure and recruit alveoli, but our practice generally restricts the inspiratory time to limit the *I*:*E* at 1:1. Reversal of the *I*:*E* ratio has been used in the management of patients with severe ARDS in attempts to augment oxygenation and allow weaning of the FiO_2 (Schuster et al. 1991). However, longer inspiratory times especially when combined with higher ventilator rates can result in reversal of the *I*:*E* ratio which may result in inadequate exhalation times. This may result in air trapping, the stacking of one breath on another (inspiration for the next breath starting before exhalation), thereby resulting auto-PEEP.

Various mechanisms are available for adjusting the inspiratory time, which vary depending on the make and model of the anesthesia ventilator. The inspiratory time may be set as a fixed time (seconds), by adjusting the inspiratory flow rate, as an *I*:*E* ratio or as a percentage of the respiratory cycle. If the inspiratory time is set as an *I*:*E* ratio or as a percentage of the respiratory cycle, adjusting the rate will affect the actual inspiratory time. For example, if the respiratory rate is set at 15 breaths/min with an inspiratory time of 25 % or an *I*:*E* ratio of 1:3, this results in an inspiratory time of 1 s. Changing the rate to 20 breaths/min with the same inspiratory time of 25 % or *I*:*E* ratio of 1:3 now results in an inspiratory time of 0.75 s. Such changes can result in changes in the peak airway pressure during volume-limited ventilation or tidal volume during pressure-limited ventilation.

Another option on many anesthesia ventilators is the addition of an inspiratory pause. This time is added to the end of inspiration, thereby lengthening the inspiratory time, so its contribution to the total inspiratory time must be realized to avoid inadvertent reversal of the *I*:*E* ratio. This maneuver serves many of the same purposes as lengthening the inspiratory time including the recruitment of alveoli with long time constants (high resistance and low compliance), promotion of collateral ventilation via pores of Cohn and canals of Lambert, reversal of atelectasis, and improved matching of ventilation and perfusion. The inspiratory pause increases mean airway pressure, thereby improving oxygenation. Its effects on compliance result from the resolution of atelectasis and recruitment of lung units.

When considering mechanical ventilation in the operating room, the IMV mode is generally used based on the lack of spontaneous ventilation during many types of general anesthesia and the functioning parameters of operating room ventilators. However, other parameters are set very much in the same manner as they are in the pediatric ICU. The decisions to be made include (a) the limit variable (pressure or volume) which will control the tidal breath and its magnitude, (b) the inspiratory time, (c) the ventilator rate (breaths/min), (e) the FiO_2, and (f) the PEEP. The rate is set primarily based on the patient's age, the desired $PaCO_2$ level, and the V_T that is delivered. In patients with severe lung injury, poor resistance, or altered compliance, higher rates are used to compensate for lower tidal volumes, thereby limiting ventilator-induced lung injury. Guidelines for starting ranges of respiratory rates include 10–12 breaths/min for an adolescent, 12–16 breaths/min for an older child (6–10 years of age), 16–24 breaths/min for a toddler, and 24–30 breaths/min for a neonate. Higher rates may be needed in patients with more severe degrees of lung injury, when hyperventilation is used to treat increased intracranial pressure or pulmonary hypertension, or if endogenous CO_2 production is elevated. The actual rate can be further adjusted based on the $ETCO_2$ which is routinely used for every general anesthetic as part of the guidelines for intraoperative monitoring.

Oxygenation is controlled by mean airway pressure and the inspired oxygen concentration (FiO_2). As many factors including general anesthetic agents and neuromuscular blocking agents may decrease functional residual capacity (FRC) especially in infants and children, the anesthetized patient may be prone to develop hypoxemia due to the development of atelectasis and the resultant ventilation–perfusion inequalities. The latter can be prevented by strategies that maintain an effective mean airway pressure including the peak inflating pressure, PEEP, and the inspiratory time. The actual contribution and setting for each can be adjusted much the same way as in the ICU setting so that the desired mean airway pressure and oxygenation are achieved with a reasonable peak airway pressure and FiO_2. Further adjustments may be necessary in patients with acute lung injury, obesity, or other conditions that affect the ratio of the FRC to closing capacity. The latter may be particularly relevant during the performance of minimally invasive surgical procedures where abdominal insufflations may increase intra-abdominal pressure, thereby resulting in a cephalad shift of the diaphragm and a further decrease in FRC. The potential impact on such maneuvers in improving postoperative outcome has been demonstrated in the adult population (Talab et al. 2009).

Intraoperatively, the majority of patients receiving anesthesia will receive an FiO_2 that varies from 0.5 to 0.6. Although generally not necessary to maintain adequate oxygenation in patients devoid of pulmonary disease, the delivery of the volatile anesthetic agent from the vaporizer is accomplished using an FGF of 1–2 L/min which is usually equally provided by oxygen and air, both at a flow rate of 0.5–1 L/min and hence an FiO_2 of 0.5–0.6. In most scenarios, the brief exposure to such oxygen concentrations is neither helpful nor detrimental. Occasionally, provided that an acceptable oxygen saturation (93–95 %) can be maintained, the delivery of a lower oxygen concentration may be beneficial to the patient. Although there are no large, prospective trials to demonstrate such effects, it is generally accepted that the FiO_2 should be minimized in certain patient populations such as the preterm or term neonatal who may still be at risk for the development of retinopathy of prematurity or patients with oncologic diseases who have received irradiation to the chest or chemotherapeutic regimens containing bleomycin. In such circumstances, a high intraoperative F_i0_2 should be avoided if clinically feasible. Alternatively, although the data are not conclusive, in certain patient populations such as patients undergoing major orthopedic procedures or intra-abdominal surgery, a higher intraoperative FiO_2 may decrease postoperative wound infections which is postulated to result from an increase in tissue oxygenation and improvements in oxidative killing by neutrophils (Meyhoff et al. 2009; Maragakis et al. 2009).

65.2.2 Spontaneous Ventilation

As in the ICU setting, there may be many circumstances in which spontaneous ventilation is beneficial. In the operating room setting, spontaneous ventilation is feasible during many surgical procedures which do not require neuromuscular blocking agents. Examples of such include tonsillectomy, herniorrhaphy, and most peripheral extremity surgery. When spontaneous ventilation is used intraoperatively, the airway may be controlled by mask, a supraglottic device such as an LMA, or an endotracheal tube. Regardless of the airway device used, there are several advantages of spontaneous ventilation including avoidance of the need for reversal of neuromuscular blockade, thereby decreasing the incidence of postoperative nausea and vomiting from the use of neostigmine; the addition of an additional judge of the depth of anesthesia (respiratory rate), thereby allowing the appropriate titration of intraoperative opioid therapy, a decreased risk of intraoperative awareness; as well as improvements in respiratory function by a better matching of ventilation and perfusion. Additionally, there may be specific comorbid features which mandate the maintenance of spontaneous ventilation for a variable period of time including a potentially difficult airway or an anterior mediastinal mass.

During spontaneous ventilation and the administration of various anesthetic agents, the tidal volumes may decrease from baseline values related to the effects of the anesthetic agents on the central control of ventilation or due to alterations of resistance and/or compliance induced by the airway device. In such circumstances, the new generation of anesthesia machine ventilators allows the application of pressure support to augment tidal volume of spontaneous breaths. In this setting, the pressure support above PEEP, PEEP, and inspiratory time can be set and adjusted according to the patient's response. As in the ICU setting, pressure support is triggered by the patient's change in the pressure or flow in the anesthesia circuit. In smaller children and infants, the sensitivity of the ventilator may need to be adjusted to allow for sensing of the patient's spontaneous breaths. This may be done by adjusting the flow sensitivity or the flow that the patient must generate to initiate the spontaneous breath. Alternatively, if the sensitivity is set too low, auto-triggering (inadvertent triggering of inspiratory support) may be generated by cardiac oscillations or by loss of PEEP when an uncuffed ETT is used (Sheikh et al. 2009).

65.2.3 The ICU Ventilator in the OR Including High-Frequency Techniques

In specific circumstances including comorbid respiratory disease of the patient, it may not be feasible to use a conventional anesthesia machine ventilator. In such cases, the higher working pressures and efficiency of the ICU ventilator may be required in the operating room during the anesthetic care. Alternatively, sudden changes in the intraoperative respiratory status of the patient may mandate the intraoperative switch to an ICU ventilator. In many cases, the patient can be transported to the operating room using manual ventilation and then reattached to the ICU ventilator. However, our practice includes a trial of manual ventilation which is equivalent to the transport time to the operating room before leaving the ICU setting. To accomplish this, the ICU ventilator is disconnected, and an Ambu bag with a PEEP valve or a self-inflating resuscitation bag is used. The latter may be preferable as it allows the delivery of 100 % oxygen as well as variable levels of PEEP. Another option is to use an ICU transport ventilator, when available, as it will theoretically allow the use of the exact same pressure or volume settings as has been used in the ICU. These transport ventilators can also be used intraoperatively.

Although relatively uncommon, surgical procedures may be required on patients receiving high-frequency ventilation. As transport on these ventilators is not feasible, one of two options exists. It may be feasible to transport the patient to the operating room with usual manual ventilation and then reconnect the patient to the high-frequency ventilator. Alternatively, if the patient's condition does not permit such transport, the surgical procedure may need to be performed at the bedside in the ICU setting. Given their effects on lung movement and gas exchange, there are additional circumstances, most commonly thoracic surgical procedures, in which the use of high-frequency techniques may facilitate the surgical procedure. Both high-frequency oscillatory and jet ventilation have been used intraoperatively. Tobias and Burd reported the intraoperative use of high-frequency oscillatory ventilation (HFOV) in a cohort of 3 infants requiring surgical intervention (Tobias and Burd 2001). HFOV was used in three different clinical scenarios including its elective use to limit lung motion and facilitate thoracotomy and ligation of a patent ductus arteriosus in a preterm infant, an intraoperative switch due to progressive alterations in lung resistance and compliance leading to ineffective ventilation and oxygenation with conventional ventilation, and a neonate requiring a surgical procedure who was already receiving HFOV due to comorbid lung disease. In all cases, HFOV provided effective intraoperative ventilation and oxygenation. The intraoperative use of HFOV has also been reported to stabilize patients during surgical procedures for diaphragmatic hernia repair or the excision of thoracic lesions (bullae or congenital cystic adenomatoid malformations) (Miguet et al. 1994; Aubin et al. 1999; Nakano

et al. 1991). Likewise, there is anecdotal experience for case reports and small cases series regarding the use of intraoperative high-frequency jet ventilation (HFJV) (Cotter et al. 2004; Davis et al. 1994; Meliones et al. 1991; Schur et al. 1988; Obara et al. 1988). In a crossover trial, where nine term infants undergoing Blalock–Taussig shunt received both conventional positive-pressure ventilation and HFJV, there was a lower mean airway pressure, higher PaO_2, and lower $PaCO_2$ with HFJV (Davis et al. 1994). Additionally, as assessed by an independent observer, lung movement and the amount of surgical retraction needed were less with HFJV. In patients with Fontan physiology, HFJV resulted in a 50 % decrease in mean airway pressure, 59 % reduction in pulmonary vascular resistance, and a 25 % increase in cardiac output while providing the same ventilation and oxygenation as conventional ventilation (Meliones et al. 1991). Other authors have anecdotally reported the successful use of intraoperative jet ventilation during aortic arch surgery (coarctation repair) and resection of tracheal stenosis (Cotter et al. 2004; Schur et al. 1988; Obara et al. 1988).

The primary disadvantages to such techniques are limited availability of equipment and the unfamiliarity of pediatric anesthesia personnel with such techniques. In such circumstances, consultation with respiratory therapy staff and pediatric ICU physicians may be helpful in the successful applications of these modes of ventilation. Additionally, as these modes of ventilation eliminate the use of the anesthesia machine, the use of inhalational anesthetic agents is not feasible, thereby mandating the use of total intravenous anesthesia.

65.3 Special Situations and Adjunctive Agents in the OR

In the majority of cases in the operating room, mechanical ventilation remains straightforward with the anesthesia provider using the standard anesthesia machine and its ventilator and easily providing effective ventilation and oxygenation. In addition to issues presented by alterations in the patient's pulmonary function, there are several other special circumstances in the operating room which may necessitate the use of specialized endotracheal tubes (one-lung ventilation) or adjunctive gases (helium, nitrogen, carbon dioxide, and nitric oxide).

65.3.1 One-Lung Ventilation

The purpose of one-lung ventilation (OLV) is to separate the two lungs, thereby allowing for the maintenance of oxygenation and ventilation through one lung while leaving the other lung deflated and motionless. The technique is used during thoracotomy and thoracoscopy to provide adequate surgical access to the lung and limit movement, thereby facilitating the surgical procedure. Occasionally the technique is used in the ICU setting in patients with unilateral lung disease to allow for selective and differential ventilation of the two lungs. For the OR setting when collapse of one lung is required, there are several options for OLV depending on the age and size of the patient. Options include a double-lumen ETT, a bronchial blocker or balloon-tipped catheter which is placed in the main stem bronchus to occlude the lung, and selective main stem intubation. As a full review of this subject matter is beyond the scope of this chapter, the reader is referred to references Hammer (2004) and Tobias (2001) for a full description of the techniques available for OLV.

In older patients, there are several manufacturer-made sizes of double-lumen ETT which can be used in patients as young as 8–10 years of age and body weight ranging from 30 to 40 kg (Fig. 65.4). Advantages of a standard double-lumen ETT are their relative ease of use, and once placed successfully, they effectively separate the two lungs, thereby preventing spillage of contents from one lung to the other. The latter is highly beneficial when dealing with empyema and infectious processes and mandatory when performing bronchoalveolar lavage. Additionally, a double-lumen ETT allows the easy and rapid switch from two-lung to one-lung ventilation as well as provides a means of differential ventilation of the two lungs. When anatomic or size constraints preclude the

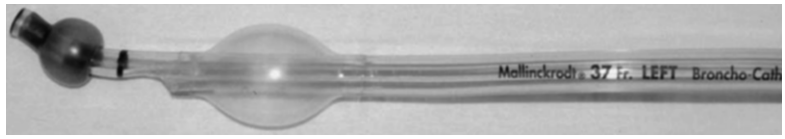


Fig. 65.4 Distal (tracheal end) or a standard double-lumen endotracheal tube used for one-lung ventilation during thoracic surgery. The tube has two lumens with balloons which allow separation of the two lungs. The distal opening of the far tube is placed into the left main stem bronchus while the proximal opening lies in the trachea

use of a double-lumen ETT, the other two choices for OLV are selective main stem intubation or the use of a bronchial blocker. The major disadvantage of selective main stem intubation is that it is not possible to quickly change from OLV to two-lung ventilation without repositioning the ETT from the main stem bronchus into the trachea. With movement of the ETT, inadvertent extubation may occur which may be particularly problematic for the patient in the lateral decubitus position. For main stem intubation, the ETT should be 0.5 mm smaller than what would normally be used based on the patient's age (usually a 3.0–3.5 ETT in neonates). Using conventional direct laryngoscopy, the ETT is placed into the midportion of the trachea and bilateral breath sounds verified. The depth of insertion of the ETT at the alveolar ridge is noted. The ETT is then advanced into the main stem bronchus, and when there is disappearance of breath sounds on the left, the depth of insertion is noted again. This documents the depth of insertion for mid-tracheal placement and main stem bronchus placement of the ETT. The ETT is advanced only until there is a disappearance of breath sounds on the left. Placement too deep into the main stem bronchus may occlude the bronchus to the right upper lobe and prevent ventilation of that lobe. Although blind placement into the right main stem bronchus is generally feasible, left main stem intubation may be more problematic. For left-sided placement, the author recommends reversing the usual orientation of the bevel at the distal end of the ETT, using a stylet so that the concave segment is now convex. When this is done, the angle of the bevel at the distal end of the ETT will face the patient's right side with the Murphy's eye along the left lateral wall of the trachea. Once the ETT is positioned in the midportion of the trachea, the stylet is removed to prevent tracheal trauma and the ETT advanced. Other maneuvers suggested to aid the successful placement in the left main stem bronchus include elevating the contralateral shoulder or turning the head to the opposite side. The author's preference, and perhaps the easiest technique, is to use bronchoscopic guidance by placement of the fiber-optic bronchoscope through the ETT, into the bronchus to be occluded, followed by advancement of the ETT over the bronchoscope. Advancement of the ETT using fluoroscopic guidance is also feasible if a suitable-sized bronchoscope is not available.

Alternatively, the bronchus on the operative side can be occluded with a bronchial blocker, thereby eliminating the need for manipulation of the ETT during the procedure. Several different devices can be used as bronchial blockers including the Univent endotracheal tube (Fuji Systems, Tokyo, Japan) which has a bronchial blocker incorporated into the shaft of the ETT or any balloon-tipped catheter such as a Fogarty embolectomy catheter, atrio-septostomy catheter, pulmonary artery catheter, or the Arndt endobronchial blocker (Cook Critical Care, Birmingham, In). These devices have a balloon at the end that is inflated to occlude the bronchus of the operative lung. Those with a central channel (pulmonary artery catheter, Arndt endobronchial blocker, Univent blocker) provide the advantage of allowing some degree of suctioning through the channel, not to clear the lung of secretions as the channel is too small for that purpose but rather to deflate the operative lung and improve surgical visualization. The central channel can also be used for the insufflation of oxygen and the application of CPAP should that become necessary to maintain arterial oxygenation. When devices without a central channel are used, air or gas

cannot exit from the lung once the balloon is inflated; therefore, the lung may not deflate totally and may obscure surgical visualization. Regardless of which catheter and technique of placement are chosen, there remains a risk of displacement of the bronchial blocker during the surgical procedure or with repositioning of the patient. If this occurs, the bronchial blocker may occlude the tracheal lumen just beyond the ETT, resulting in inadequate ventilation. Continuous auscultation of breath sounds on the nonoperative side and monitoring of airway pressures should identify this problem rapidly. Clinical experience suggests that inflating the balloon of the bronchial blocker with saline as opposed to air may limit movement and dislodgement during surgical manipulation.

After separation of the nonoperative from the operative lung using one of the above described techniques, general anesthesia is maintained with a combination of intravenous and inhalational anesthetic agents. Hypoxic pulmonary vasoconstriction (HPV) is a normal physiologic response that occurs in poorly ventilated alveoli to preferentially shunt pulmonary blood flow to ventilated alveoli. Any nonspecific vasodilator (terbutaline, albuterol, isoproterenol, dobutamine, nicardipine, nitroglycerin, sodium nitroprusside, inhalational anesthetic agent) can impair HPV and affect oxygenation. The anesthetic technique can also affect HPV and thereby arterial saturation. Isoflurane, sevoflurane, or desflurane has less of an effect on HPV than either halothane or enflurane (Benumof et al. 1987; Wang et al. 2000). During the procedure and OLV, ventilation is maintained with tidal volumes of 6–8 mL/kg, provided that the peak inflating pressure can be maintained at $\leq$30 cmH_2O and the respiratory rate adjusted as needed to maintain normocarbia as hypocarbia interferes with HPV. In the adult population, tidal volumes are better maintained with lower peak inflating pressures with pressure-limited rather than volume-limited ventilation. Although ventilation is generally easily maintained, given the large area of lung that is excluded for gas exchange, oxygenation may be problematic especially in patients with comorbid respiratory problems. If adequate oxygenation cannot be maintained during OLV with an FiO_2 of 1.0 to the nonoperative side, CPAP of 4–5 cmH_2O can be applied to the operative lung provided that a DLT, Univent, or bronchial blocker with a central channel has been used. Although this will improve oxygenation, it may also distend the operative lung to some degree and impair surgical visualization. If the above measures fail, it may be necessary to provide two-lung ventilation intermittently. Alternatively, oxygenation can be improved by the administration of nitric oxide or a direct acting, α-adrenergic agonist (Moutafis et al. 1999; Dietrich and Tobias 2003). The latter is thought to act by its augmentation of HPV.

65.3.2 Helium

The therapeutic benefits and clinical applications of helium–oxygen gas mixtures were first reported over 70 years ago (Barach and Eckman 1935, 1936). In current clinical practice, a helium–oxygen combination is most commonly used to improve gas exchange in patients with upper airway obstruction of various etiologies, including infectious and post-intubation croup (Tobias 1997; Berkenbosch et al. 2004; Duncan 1979). The beneficial effects of helium have also been noted and reported in patients with obstructive processes more distally along the tracheobronchial tree such as those who require mechanical ventilation for asthma and other respiratory disorders (Manthous et al. 1997; Michael et al. 1999). Additionally, there are anecdotal reports of helium being used successfully in the operating room to treat respiratory compromise related to an anterior mediastinal mass, bronchospasm, and tracheal stenosis.

There are several potential benefits of helium in patients with obstructive diseases at various points along the airway. Helium's primary effects are the result of its lower density, thereby providing decreased resistance during turbulent gas flow. Resistance during turbulent gas flow, as described by the Hagen–Poiseuille law, is directly related to the density of the gas. Helium may also increase gas flow by converting turbulent flow to laminar flow by lowering the Reynolds number.

The Reynolds number is the ratio of kinetic and viscous forces. It predicts whether flow will be laminar or turbulent (turbulent flow occurs with a Reynolds number ≥2,000). Helium also enhances the diffusion effect on the elimination of CO_2. Through a mixture of helium–oxygen, carbon dioxide diffuses four- to fivefold faster than nitrogen–oxygen. Therefore, for the equivalent partial pressure of CO_2, a greater amount of CO_2 is eliminated per unit of time. In the perioperative setting, helium is used most commonly for the induction of anesthesia in patients with upper airway obstruction such as croup or epiglottitis who are presenting to the operating room for direct laryngoscopy under general anesthesia. In this scenario, a mixture of helium and oxygen is used to deliver increasing concentrations of sevoflurane while maintaining spontaneous ventilation. As one of the factors that determine the rapidity of anesthetic induction is minute ventilation, the addition of helium may augment minute ventilation especially in the presence of upper airway obstruction. Additionally, helium may be used intraoperatively during airway laser surgery to decrease the risk of airway fire as helium has a higher conductivity of heat than a nitrogen–oxygen mixture.

In the pediatric ICU setting, helium is generally delivered using a high flow gas system to eliminate the entrainment of room air. Alternatively, there are also mechanisms to allow its delivery through an ICU ventilator. In the OR setting, helium can be delivered with an anesthesia machine that is commercially available with a helium flow meter in addition to the standard anesthesia gases (oxygen, air, and nitrous oxide). These machines allow the administration of helium from an E cylinder (generally one containing 80 % helium and 20 % oxygen) prior to the gas flowing through the vaporizers. Therefore, no specialized setup or preparation is required for the delivery of helium. Of importance is the fact that the helium flow meter does not participate in the ratio control (proportioning system) that is present with the use of nitrous oxide and oxygen. Therefore, when helium is in use, the delivery of a hypoxic mixture is possible. Therefore, it is mandatory to use a separate in-line oxygen and anesthesia gas monitor as well as standard ASA monitors.

65.3.3 Nitric Oxide, Carbon Dioxide, and Nitrogen

In patients with congenital heart disease or pulmonary hypertension, supplemental gases such as nitric oxide (NO), carbon dioxide, or nitrogen may be added to the inspiratory gas mixture to manipulate the pulmonary artery pressure. NO is used primarily in the treatment of pulmonary hypertension. Its mechanism of action resides in its ability to stimulate guanylate cyclase, thereby increasing the concentration of cGMP. As it is delivered via the lungs, its effect is limited to the pulmonary vasculature as it is inactivated after interaction with hemoglobin. In the perioperative care of infants with single-ventricle anatomy, the ratio of system to pulmonary vascular resistance is a key factor in the regulation of systemic blood flow and oxygen delivery (Norwood 1991). In addition to pharmacologic therapy, the control of the partial pressure of oxygen and/or carbon dioxide in the blood has been shown to be an effective means of altering the ratio of pulmonary to systemic vascular resistance and thereby controlling systemic oxygen delivery (Jobes et al. 1992). Methods to control the partial pressure of oxygen and carbon dioxide in the blood include the either use of a subatmospheric concentration of oxygen or the addition of carbon dioxide to induce hypercapnia. Although there are proponents to both therapies, it has been demonstrated that hypercapnia increases cerebral oxygenation, mean arterial pressure, and systemic oxygen delivery, while lowering the fraction of inspired oxygen has no effect (Ramamoorthy et al. 2002).

In clinical ICU care, these adjunct gases are frequently added to the inspiratory limb of the respiratory circuit with the flow rates adjusted to achieve the desired concentration. In distinction to mechanical ventilation in the ICU setting, in the OR, there is generally at least partial rebreathing of the exhaled gases (see above) during the use of a circle system. This rebreathing can result in the administration of a higher concentration of

one of the adjunct gases (nitric oxide, carbon dioxide, or nitrogen) than is intended (Tobias and Grueber 2000). One means of eliminating such concerns is to use an ICU ventilator for such cases. However, if the anesthesia machine ventilator is used, the FGF rate should equal at least and preferably twice the minute ventilation (Tobias and Grueber 2000). This will eliminate rebreathing and the issues outlined above.

65.4 Summary

As in the ICU setting, ventilatory support is frequently required in the operating room during the provision of general anesthesia. In distinction to the ICU setting, many patients who receive endotracheal intubation and mechanical ventilation in the operating room have relatively normal pulmonary function and thereby require minimal support. In many of these patients, mechanical ventilation is required due to the requirements for the surgical procedure, the depressant effects of the anesthetic agents, or the use of neuromuscular blocking agents. However, significant respiratory comorbidities may exist in patients requiring general anesthesia which mandate significant expertise in mechanical ventilation to provide adequate intraoperative oxygenation and ventilation. In the majority of cases, mechanical ventilation is provided by the use of the anesthesia machine and its ventilator. As in the ICU setting, the basic settings for mechanical ventilation include the provision of adequate minute ventilation (respiratory rate and tidal volume) and the maintenance of oxygenation through manipulations of the mean airway pressure (PEEP, PIP, and inspiratory time) and FiO_2. Ventilation may be provided by pressure- or volume-limited modes with manipulations of the inspiratory time to compensate for changes in respiratory compliance and resistance. Additionally, during many surgical procedures, spontaneous ventilation is maintained and supported by pressure support which is now available on modern-day anesthesia machines. Rarely, patient comorbidities or specific requirements for the surgical procedure preclude the use of the anesthesia machine ventilator and mandate the use of an ICU ventilator. In such circumstances, anesthesia is provided by the use of intravenous agents. Additionally, other modes of respiratory support such as high-frequency ventilation may be required during anesthetic care, and with appropriate preparation, such techniques can be used intraoperatively. In special circumstances, adjunctive agents such as helium, nitric oxide, nitrogen, or carbon dioxide may be used based on the patient's status. Regardless of the technique chosen, a thorough preoperative evaluation which includes an investigation into the patient's current respiratory status is mandatory to ensure the appropriate intraoperative care of respiratory function and to ensure adequate oxygenation and ventilation.

References

Aubin P, Vischoff D, Haig M et al (1999) Management of an infant with diffuse bullous pulmonary lesions using high frequency oscillatory ventilation. Can J Anaesth 46:970–974

Ayre P (1937) Endotracheal anesthesia for babies with special reference to hare-lip and cleft palate operations. Anesth Analg 16:330–333

Bain JA, Spoerel WE (1973) Flow requirements for a modified Mapleson D system during controlled ventilation. Can Anaesth Soc J 20:629–636

Barach A, Eckman M (1935) The use of helium as a new therapeutic gas. Anesth Analg 14:210–215

Barach A, Eckman M (1936) The effects of inhalation of helium mixed with oxygen on the mechanics of respiration. J Clin Invest 15:47–61

Baum J, Sachs G, Driesch C et al (1995) Carbon monoxide generation in carbon dioxide absorbents. Anesth Analg 81:144–146

Benumof JF, Augustine SD, Gibbons JA (1987) Halothane and isoflurane only slightly impair arterial oxygenation during one-lung ventilation in patients undergoing thoracotomy. Anesthesiology 67:910–914

Berkenbosch JW, Grueber RE, Graff GR, Tobias JD (2004) Patterns of helium-oxygen (heliox) use in the critical care environment. J Intensive Care Med 19:335–344

Berry PD, Sessler DI, Larsen MD (1999) Severe carbon monoxide poisoning during desflurane anesthesia. Anesthesiology 90:613–615

Castro BA, Freedman A, Craig WL et al (2004) Explosion within an anesthesia machine: Baralyme®, high fresh gas flows, and sevoflurane concentration. Anesthesiology 101:537–539

Conway CM (1985) Anaesthetic breathing systems. Br J Anaesth 57:649–657

Cotter T, Russo P, Tobias JD (2004) Intraoperative jet ventilation during aortic coarctation repair in an infant. J Intensive Care Med 18:207–209

Davis DA, Russo PA, Greenspan JS et al (1994) High-frequency jet ventilation versus conventional ventilation in infants undergoing Blalock-Taussig shunts. Ann Thorac Surg 57:846–849

Dietrich CC, Tobias JD (2003) Intraoperative administration of nitric oxide. J Intensive Care Med 18:146–149

Duncan PG (1979) Efficacy of helium-oxygen mixtures in the management of severe viral and post-intubation croup. Can Anaesth Soc J 26:206–221

Fang ZX, Eger EI II, Laster MJ et al (1995) Carbon monoxide production from degradation of desflurane, enflurane, isoflurane, halo-thane, and sevoflurane by soda lime and Baralyme®. Anesth Analg 80:1187–1193

Fatheree RS, Leighton BL (2004) Acute respiratory distress syndrome after an exothermic Baralyme®-sevoflurane reaction. Anesthesiology 101:531–533

Frink EJ Jr, Malan TP, Morgan SE et al (1992) Quantification of the degradation products of sevoflurane in two CO2 absorbents during low-flow anesthesia in surgical patients. Anesthesiology 77:1064–1069

Hammer GB (2004) Single lung ventilation in infants and children. Pediatr Anesth 14:98–102

Hunt HE (1955) Resistance in respiratory valves and canisters. Anesthesiology 16:190–194

Jobes D, Nicolson S, Steven J et al (1992) Carbon dioxide prevents pulmonary overcirculation in hypoplastic left heart syndrome. Ann Thorac Surg 54:150–151

Kain ML, Nunn JF (1967) Fresh gas flow and rebreathing in the Magill circuit with spontaneous respiration. Proc R Soc Med 60:749–750

Kain ML, Nunn JF (1968) Fresh gas economics of the Magill system. Anesthesiology 29:964–974

Laster M, Roth P, Eger EI II (2004) Fires from the interaction of anesthetics with desiccated absorbent. Anesth Analg 99:769–774

Manthous CA, Morgan S, Pohlman A, Hall JB (1997) Heliox in the treatment of airflow obstruction: a critical review of the literature. Respir Care 42:1034–1042

Mapleson WW (1954) The elimination of rebreathing in various semi-closed anesthetic systems. Br J Anaesth 26:323–332

Maragakis LL, Cosgrove SE, Martinez EA et al (2009) Intraoperative fraction of inspired oxygen is a modifiable risk factor for surgical site infection after spinal surgery. Anesthesiology 110:556–562

Mazze RI (1992) The safety of sevoflurane in humans. Anesthesiology 77:1062–1066

Meliones JN, Bove E, Dekeon MK et al (1991) High-frequency jet ventilation improves cardiac function after the Fontan procedure. Circulation 84:364–368

Meyhoff CS, Wetterslev J, Jorgensen LN et al (2009) Effect of high perioperative oxygen fraction on surgical site infection and pulmonary complications after abdominal surgery: the PROXI randomized clinical trial. JAMA 302:1543–1550

Michael JG, Bocklage T, Tobias JD (1999) Helium administration during mechanical ventilation in children with respiratory failure. J Intensive Care Med 14:140–147

Miguet D, Claris O, Lapillonne A et al (1994) Preoperative stabilization using high frequency oscillatory ventilation in the management of congenital diaphragmatic hernia. Crit Care Med 22:S77–S82

Miller DM (1988) Breathing systems for use in anaesthesia. Evaluation using a physical lung model and classification. Br J Anaesth 60:555–564

Morio M, Fujii K, Satoh N et al (1992) Reaction of sevoflurane and its degradation products with soda lime. Toxicity of the byproducts. Anesthesiology 77:1155–1164

Moutafis M, Dalibon N, Colchem A, Fischler M (1999) Improving oxygenation during bronchopulmonary lavage using nitric oxide inhalation and almitrine infusion. Anesth Analg 89:302–304

Moyers J (1953) A nomenclature for methods of inhalation anesthesia. Anesthesiology 14:609–611

Nakano S, Tashiro C, Nishimura M et al (1991) Perioperative use of high-frequency oscillation immediately after birth in two neonates with congenital cystic adenomatoid malformation. Anesthesiology 74:939–941

Norman J, Adams AP, Freedman S, Sykes MK (1967) Rebreathing with the Magill circuit. Br J Anaesth 39:517–520

Norwood WI (1991) Hypoplastic left heart syndrome. Ann Thorac Surg 52:688–695

Obara H, Maekawa N, Iwai S et al (1988) Reconstruction of the trachea in children with tracheal stenosis by using jet ventilation. Anesthesiology 68:441–443

Ramamoorthy C, Tabbutt S, Kurth D et al (2002) Effects of inspired hypoxic and hypercapnic gas mixtures on cerebral oxygen saturation in neonates with univentricular heart defects. Anesthesiology 96:283–288

Schur MS, Maccioli GA, Azizkhan RG et al (1988) High frequency ventilation in the management of congenital tracheal stenosis. Anesthesiology 68:441–443

Schuster S, Weilemann LS, Kelbel C, Schinzel H, Meyer J (1991) Inverse ration ventilation improves pulmonary gas exchange and systemic oxygen transport in patients with congestive heart failure. Clin Intensive Care 2:148–153

Sheikh E, Maguire DP, Gratch D (2009) Autotriggering during pressure support ventilation due to cardiogenic oscillations. Anesth Analg 109:470–472

Soliman MG, Laberge R (1978) The use of the Bain circuit in spontaneously breathing paediatric patients. Can Anaesth Soc J 25:276–281

Sykes MK (1959) Rebreathing during controlled respiration with the Magill attachment. Br J Anaesth 31:247–257

Sykes MK (1968) Rebreathing circuits. Br J Anaesth 40:666–674

Talab HF, Zabani IA, Abdelrahman HS et al (2009) Intraoperative ventilatory strategies for prevention of pulmonary atelectasis in obese patients undergoing laparoscopic bariatric surgery. Anesth Analg 109:1511–1516

Tobias JD (1997) Helium: applications in the practice of anesthesia and critical care. Am J Anesthesiol 24:194–200

Tobias JD (2001) Thoracic surgery in children. Curr Opin Anaesthesiol 14:77–85

Tobias JD, Burd RS (2001) Anaesthetic management and high frequency oscillatory ventilation. Paediatr Anaesth 11:483–487

Tobias JD, Grueber RE (2000) Nitric oxide administration using an operating room ventilator. Am J Anesth 27:137–139

Unzueta MC, Casas JI, Moral MV (2007) Pressure controlled versus volume controlled ventilation during one-lung ventilation for thoracic surgery. Anesth Analg 104:1029–1033

Versichelen LF, Bouche MP, Rolly G et al (2001) Only carbon dioxide absorbents free of both NaOH and KOH do not generate compound A during in vitro closed system sevoflurane: evaluation of five absorbents. Anesthesiology 95:750–755

Wang JYY, Russell GN, Page RD et al (2000) A comparison of the effects of desflurane and isoflurane on arterial oxygenation during one-lung ventilation. Anaesthesia 55:163–183

Willis BA, Pender JW, Mapleson WW (1975) Rebreathing in a T-piece: volunteer and theoretical studies of the Jackson-Rees modification of the Ayre's t-piece during spontaneous respiration. Br J Anaesth 47:1239–1246

Wu J, Previte JP, Adler E et al (2004) Spontaneous ignition, explosion, and fire with sevoflurane and barium hydroxide lime. Anesthesiology 101:534–537