Chapter 3: Monitoring, Breathing Systems, and Machines

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INTRODUCTION

FOCUS POINTS

1. Serious adverse events are more common in the pediatric population, so proper understanding and implementation of monitoring tools are essential to prevent adverse outcomes.
2. The American Society of Anesthesiology recommends that during all anesthetics the patient's oxygenation, ventilation, circulation, and temperature should be continually evaluated.
3. Due to the minimal dead space and resistance, Mapleson E and F are the circuit of choice for neonates and pediatric patients.
4. Pediatric breathing systems have the same components as standard adult circuits, but are modified to decrease resistance to breathing and minimize dead space. These modifications include short and narrow tubing, valves that require reduced pressure to open and close, smaller reservoir bag, shorter Y connection, and more compact carbon dioxide absorbers.
5. The primary resistance in a pediatric circuit is determined by the internal diameter of the endotracheal tube and by the length of the tube.[1] The unidirectional valves and carbon dioxide absorber also increase breathing resistance.

MONITORING

Serious adverse events occur in the pediatric population in about 1.4 per 1000 anesthetics and the incidence of cardiac arrest is approximately 0.3 per 1000 anesthetics. This is significantly higher than in the adult population. The incidence of adverse events is inversely related to age with the highest incidence of adverse effects and cardiac arrest occurring in neonates.[2] This data suggests that children are in a high-risk population for adverse events and need to be monitored closely during anesthetic procedures. The American Society of Anesthesiology (ASA) has developed a set of commonly used standards for basic monitoring that apply to both the adult and pediatric population. Qualified anesthesia personnel must be present during the entire anesthetic encounter, continually monitoring oxygenation, electrocardiography, temperature, and the adequacy of ventilation and circulation. Instruments that quantitatively measure oxygen levels should be employed, such as pulse oximeter and an oxygen analyzer to measure oxygen concentration in the breathing system. With regards to circulation, the arterial blood pressure needs to be monitored at least every 5 minutes and the electrocardiogram needs to be displayed from the beginning of every anesthetic until departing from the anesthetizing location. Tracheal intubation or laryngeal mask airway placement needs to be confirmed by clinical assessment and by qualitative detection of carbon dioxide in the exhaled gas. Finally, every patient receiving anesthesia should have their temperature monitored when clinically significant changes in body temperature are intended, anticipated, or suspected.[2]

Pulse Oximetry

Pulse oximetry has become the standard of care in measuring arterial oxygen saturation in the operating rooms and intensive care units. The oximetry probe contains two light-emitting diodes (LEDs) which produce both red and infrared light. The LEDs and the detectors should be transversely positioned to get the best readings. In neonates, this may require placing the probe across the palm of the hand or the foot. The pulse oximeter uses two wavelengths of light, so it can only accurately detect oxyhemoglobin and deoxyhemoglobin.[3] Deoxyhemoglobin absorbs more light in the red spectrum (660 nm), whereas oxyhemoglobin absorbs more light in the infrared spectrum (940 nm).

Fetal hemoglobin has minimal effect on pulse oximetry readings, so the pulse oximetry is equally accurate in both the adult and pediatric population. Polycythemia, anemia, and sickle cell hemoglobin do not affect the accuracy of pulse oximetry.[4]

The pulse oximeter is also useful to monitor preductal and postductal oxygen saturations in neonates whenever there is a persistence of fetal circulation. A 10% decrease in postductal oxygen saturations in relation to the preductal oxygen saturation signifies significant right to left shunting as a result of pulmonary hypertension.[5,6]

The pulse oximeter is also a valuable screening tool for detection of cyanotic congenital heart disease. Neonates who have oxygen saturation values less than or approximately 95% by day 2 of life suggest a cyanotic heart disease.[7]

There are, however, certain limitations of pulse oximetry that must be taken into consideration. For example, conditions that lead to hypothermia, vasoconstriction, and hypotension make the pulse oximeter less accurate. Dyes such as methylene blue, indocynanin green, and indigo carmine may also falsely lower pulse oximeter readings by absorbing light in the red spectrum (660 nm).

Significantly elevated levels of carboxyhemoglobin or methemoglobin will also drastically alter pulse oximetry readings. Methemoglobin absorbs red and infrared light in an equal 1:1 proportion, so the pulse oximeter will read approximately 85%. Falsely high readings may occur in the presence of carboxyhemoglobin because the pulse oximeter reads carboxyhemoglobin as 90% oxyhemoglobin and only 10% deoxyhemoglobin.[8]

Electrocardiography

Electrocardiography in the pediatric population is more commonly used to detect intraoperative arrhythmias such as supraventricular tachycardias or bradyarrythmias. It is less often used to detect ischemia because ischemia rarely occurs in the pediatric population. Lead II provides the best view of atrial activity, so it is recommended for intraoperative use and the detection of arrhythmias. Bradycardia is likely to be the first indicator of hypoxia in the pediatric patient and is likely to be picked up sooner than a decrease in oxygen saturation noted by pulse oximetry. Electrolyte abnormalities can also be visualized on electrocardiography. For example, hyperkalemia will reveal peaked T waves, progressive widening of the QRS complex, and low P-wave amplitude. Hypocalcemia would reveal a prolonged QT interval.

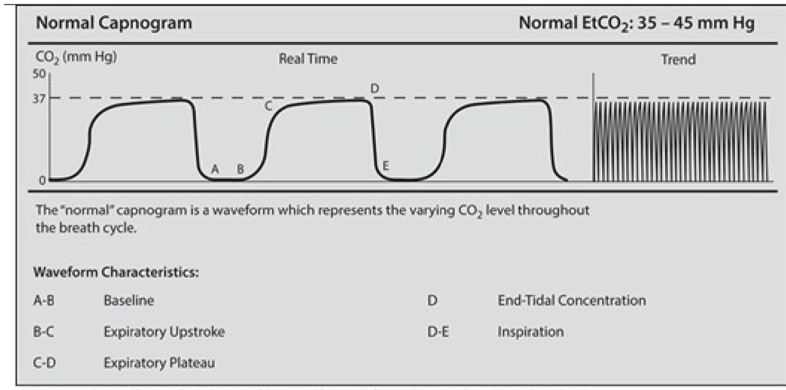
Capnography

Capnography is the monitoring of the concentration or partial pressure of carbon dioxide (CO_2) in the respiratory gases and is an indirect monitor of CO_2 partial pressure in the arterial blood. Its main development has been as a monitoring tool for use during anesthesia and for monitoring of critically ill patients in the intensive care unit. It has become the gold standard to detect correct placement of an endotracheal tube within the trachea. According to the ASA, “When an endotracheal tube or laryngeal mask is inserted, its correct positioning must be verified by clinical assessment and by identification of carbon dioxide in the expired gas. Continual end-tidal carbon dioxide analysis, in use from the time of endotracheal tube/laryngeal mask placement, until extubation/removal or initiating transfer to a postoperative care location, shall be performed using a quantitative method such as capnography, capnometry, or mass spectroscopy. When capnography or capnometry is utilized, the end tidal CO_2 alarm shall be audible to the anesthesiologist or the anesthesia care team personnel.”[3]

Changes in the shape of the capnograph can provide useful information on disease processes in an intubated patient. During ETT placement, the capnogram can readily alert the physician to endotracheal tube misplacement in the esophagus. Capnography has also long been used to determine the effectiveness of chest compressions (Figure 3-1).[9]

Figure 3-1

A capnogram illustrating both the inspiratory and expiratory phases of respiration. (Reproduced with permission, from Lerman J, ed. *Neonatal Anesthesia*. 2015. https://link.springer.com. Copyright © Springer-Verlag. All rights reserved.)



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Near-Infrared Spectroscopy

Near-infrared spectroscopy (NIRS) is a noninvasive technique that monitors regional tissue oxygenation and perfusion status. It measures tissue oxygenation through the use of near-infrared light at wavelengths between 700 and 1000 nm.[10] It is similar to pulse oximetry in some respects. Pulse oximetry, however, depends on pulsatile blood flow and measures only the oxyhemoglobin in the arterial blood. NIRS measures the difference between oxyhemoglobin and deoxyhemoglobin in regional tissues and reflects hemoglobin saturation in arterial, venous, as well as capillary blood. This difference between oxyhemoglobin and deoxyhemoglobin reflects oxygen uptake in those areas. This measurement is reported as regional oxygen saturation (rSO_2). This is most commonly measured in the brain, renal, and splanchnic systems. In the cerebral cortex, average tissue hemoglobin is distributed in a proportion of approximately 70% venous and 30% arterial. There can be some variation between individuals with regards to cerebral arterial/venous ratios. Therefore in clinical practice, the use of NIRS as a trend monitor minimizes confounding variables.[10] Cerebral uptake of oxygen is typically higher due to higher metabolic demands, while renal and splanchnic uptakes are slightly lower. Therefore, normal cerebral readings tend to be lower (60–80), while renal and splanchnic measurements are generally higher (65–90). Lower NIRS readings indicate increased oxygen extraction at the tissue level or decreased oxygen delivery to the tissue being recorded.[11]

In the pediatric setting, NIRS is being used for pediatric cardiac surgery and neurosurgery, as well as in the neonatal intensive care units. For infants undergoing cardiac surgery, perioperative cerebral and mesenteric NIRS monitoring has been shown to be beneficial in detecting changes from baseline, which represents possible hypoperfusion of tissue beds. During deep hypothermic circulatory arrest, there is little ability to monitor cerebral function, so cerebral NIRS has been used as a means of detecting cerebral ischemia.[11]

Blood Pressure Monitoring

Blood pressure can be monitored with basic noninvasive equipment such as a blood pressure cuff or through direct measurements using an arterial line.[12] The noninvasive blood pressure measurements are based on the principles of oscillometry. Systolic blood pressure is recognized by computer algorithms as the point where the rate of increase in the size of the oscillation is maximal. Diastolic blood pressure is recognized as the point of the maximal rate of decrease in the size of the oscillation. It is recommended that the blood pressure cuff width should be 40% of the circumference of the extremity.

Direct measurements of blood pressure can be used with the placement of an arterial line especially in critically ill children or in situations where noninvasive blood pressure cuff placement is not feasible. For example, in children with morbid obesity, the readings from a noninvasive blood pressure cuff may be inaccurate. In children with severe forms of osteogenesis imperfecta, the cycling of the blood pressure cuff may lead to fractures of their bones.[13]

Some common locations where arterial lines can be placed are in the radial artery, ulnar artery, brachial artery, femoral artery, posterior tibia artery, and umbilical artery. The umbilical artery is usually quite easy to access in the immediately neonatal period and is widely used in the neonatal intensive care units. Proper placement should be verified with radiographic films as improper positioning can lead to thrombotic complications which can ultimately affect organs, limbs, and even the spinal cord.[12,13]

The radial artery seems to have the lowest incidence of complications especially in the smaller pediatric patients. Axillary arterial cannulation is preferred over brachial artery cannulation as there is better collateral flow to the artery in the axillary artery. The brachial artery has poor collateral circulation, so limb ischemia is a concern with arterial line placement in this location. As with any arterial catheter, if there is evidence of impaired circulation to the extremities, the arterial catheter should be removed immediately and monitored closely.

Body Temperature Monitoring

The ASA recommends continuous temperature monitoring during anesthetic procedures. There are different sites that can be used to achieve these readings. The most commonly used sites are the axilla, rectum, bladder, skin, and esophagus. Rectal temperature is often considered the gold standard of temperature monitoring. The younger the pediatric patient, the more challenging it is to monitor and regulate their temperature in the operating theater. Neonates are especially vulnerable to heat loss and temperature regulation. They have larger surface area to body weight ratio, a thin subcutaneous fat layer, and are unable to shiver, so they depend on non-shivering thermogenesis (NST) from brown fat for heat production. NST is triggered by a surge of catecholamines, released from the sympathetic nervous system during times of cold stress.[14] With continued cold stress, the stores of brown fat become depleted and this eventually leads to hypoxia and hypoglycemia. During general anesthesia, neonates lose the ability to perform NST and so they are unable to respond effectively to even mild intraoperative hypothermia.

BREATHING SYSTEMS AND MACHINES

The breathing system is essentially an extension of the patient's lung and upper airway connecting it to the anesthesia machine.

Characteristics of an ideal breathing system include:

1. Efficient delivery of intended inspired gas mixture. This means the system should be able to deliver target concentration of gas mixture in a timely manner. Also, it should be able to adjust to rapid changes in delivery of concentration.
2. Effective elimination of CO_2 and easy removal of waste gas.
3. Minimizing dead space.
4. Minimal amount of resistance.
5. Preservation of heat and humidity in expired gases.
6. Versatility in modes of ventilation in all age groups.
7. Efficient and allows low fresh gas flow (FGF).
8. Light weight and compact while being safe and inexpensive.

Breathing systems are classified as open, semi-open, semi-closed, and closed. The classification is dependent on the presence or absence of a reservoir bag, rebreathing of exhaled gases, CO2 absorption, and unidirectional valves (Table 3-1).

Table 3-1

Breathing System Classification

Breathing Systems	Types	Reservoir Bag	CO_2 Absorption	Rebreathing of Gases	Unidirectional Valves
Open	Insufflation, open-drop anesthesia	–	–	–	–
Semi-open	Mapleson circuits	+	–	–	1 valve
Semi-closed	Circle system (FGF < MV)	+	+	Partial	3 valves
Closed	Circle system where FGF equals patient's basal oxygen requirements (FGF = uptake)	+	+	Total	3 valves

FGF, fresh gas flow; MV, minute ventilation.

Open Breathing System

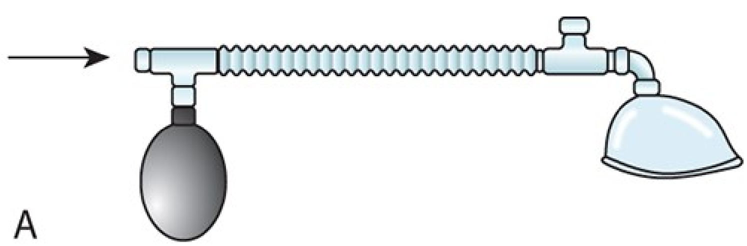
The open breathing system does not include a circuit; therefore, the patient has access to atmospheric gases. Examples of the open system include insufflation and open-drop anesthesia. Presently, insufflation is not used as a breathing system, but more as a method to administer passive oxygen during periods of apnea (eg, bronchoscopy) or as a technique for inhalational induction for pediatric patients. Similarly, open-drop anesthesia is no longer used in the United States. It consists of dripping an anesthetic (eg, ether) on a gauze, covered mask and applying it over the patient's mouth and nose. As long as flows are high there is no rebreathing of exhaled gases in the open breathing. Disadvantages of the open system include lack of conservation of humidity and heat in exhaled gases, difficult airway management, pollution of the operating room, poor control of depth of anesthesia, and inability to control ventilation.

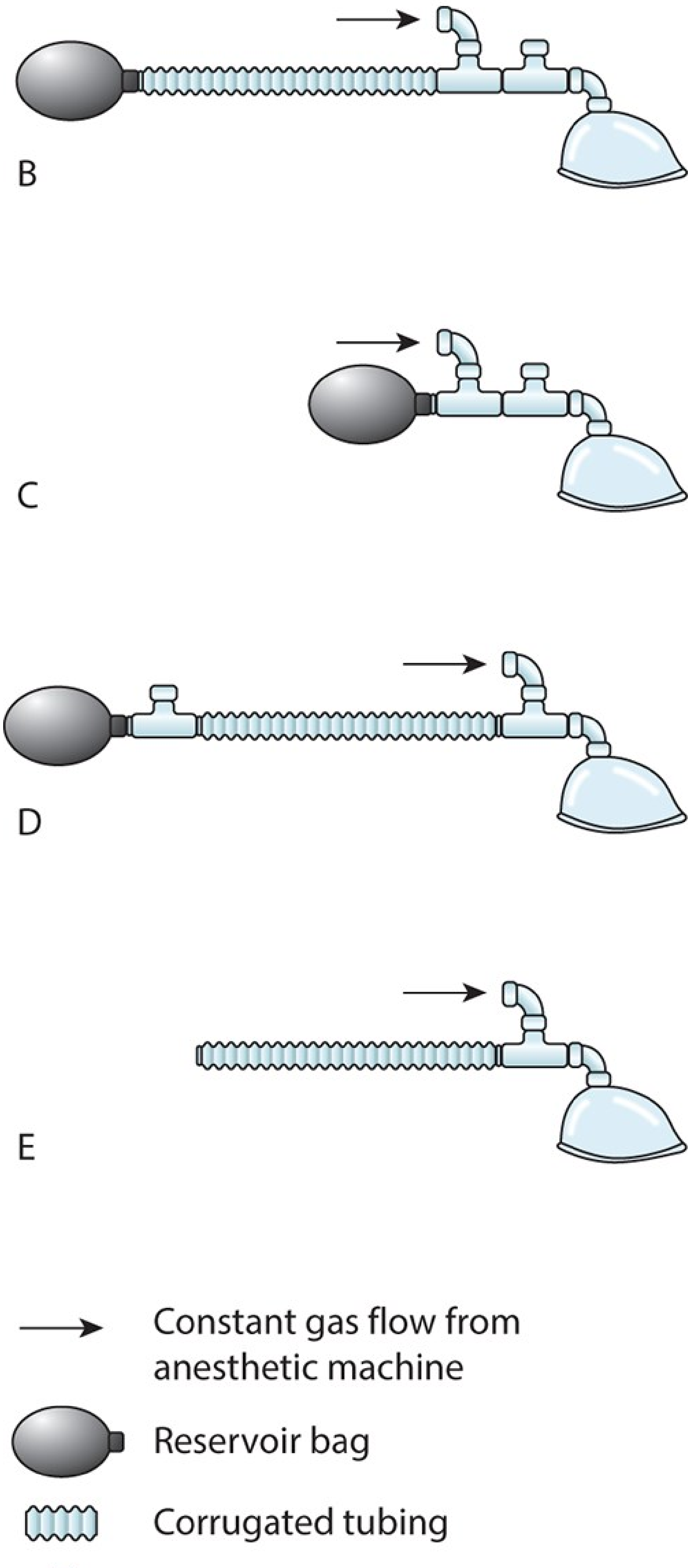
Semi-Open Breathing System

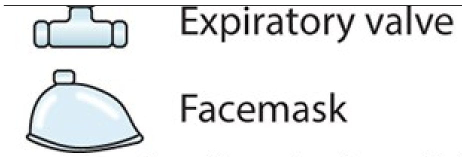
The most common semi-open breathing system is the Mapleson system (Figure 3-2). The Mapleson system helps some of the above problems by including additional components into the breathing system. Those components include adjustable pressure limiting (APL) valves, reservoir bag, and breathing tube. Depending on the relative location of these components, Mapleson system is classified into five basic types (Mapleson A, B, C, D, and E). Mapleson F was added later, which is a Jackson-Rees modification of Mapleson E (T-piece). The Bain circuit is a modification of the Mapleson D system.

Figure 3-2

Depending on the relative location of expiratory valve, reservoir bag, and corrugated tubing, Mapleson system is classified into five basic types (Mapleson A, B, C, D, and E). (Adapted with permission, from Mapleson WW. The elimination of rebreathing in various semi-closed anaesthetic systems. *Br J Anaesth.* 1954;26(5):323–332. https://bjanaesthesia.org.)




B
C
D
E
Constant gas flow from anesthetic machine
Reservoir bag
Corrugated tubing



The Mapleson system lacks expiratory and inspiratory valves and carbon dioxide absorption, which reduces the resistance of the circuit; therefore, work of breathing is low. However, the lack of separation between the inspired and expired gases causes rebreathing to occur when inspiratory flow exceeds FGF. Therefore, the amount of rebreathing is highly dependent on FGF. Rebreathing can help conserve heat, humidity, and anesthetic gases. However, if CO_2 is not monitored correctly, the risk of hypercarbia and acidosis is high. Monitoring end-tidal CO_2 is the best way to determine the ideal amount of FGF.[15]

Historically, pediatric patients less than 10 kg were anesthetized with either the Mapleson D or F breathing system. Mapleson circuits are infrequently used because most hospitals have converted to the circle system due to cost containment and cost of newer anesthetic agents. Currently, the most commonly used Mapleson systems are the Jackson-Rees and Bain circuit. The B and C systems are rarely used today. For adults, Mapleson A is the circuit of choice for spontaneous respiration because there is no rebreathing during spontaneous ventilation when the FGF is greater than 75% of the minute ventilation.[16] Although Mapleson D and its Bain modification require a little more FGF during spontaneous ventilation to eliminate rebreathing, it is the most efficient circuit for controlled ventilation for adults.[1]

Due to the minimal dead space and resistance, Mapleson E and F are the circuit of choice for neonates and pediatric patients.[15] They both allow for observation of ventilation during spontaneous breathing, as well as positive pressure ventilation by applying pressure to the bag. Hence, Mapleson F is commonly used to transport a child post-anesthesia to the recovery room or other parts of the hospital.

An important clinical consideration of the Mapleson system is that any anesthetic concentration changes made to the vaporizer will have immediate effects on the concentration reaching the patient. This can be advantageous for a more rapid induction; however, it also increases the risk of possible anesthetic overdose compared to the circle system. Although the Mapleson system is able to address some of the problematic issues with the open system, it shares others.[17] This includes the need for high gas flow to prevent rebreathing which causes more operating room pollution, loss of conservation of humidity and heat in exhaled gases, and waste of anesthetic gases increasing cost.

Circle System

The circle absorber may be used as a closed or semi-closed system. A semi-closed circle absorber is the most commonly used breathing system. In a semi-closed system, the pressure relief valve is opened, allowing excess gas to escape. This allows higher FGF rates to be used to reduce rebreathing of gases. This system is more stable since excess gas can escape if the system fills up to capacity.[15] High FGF also allows the ability to rapidly change concentration of anesthetic gases delivered. Disadvantages of the semi-open circle system are increased anesthetic and oxygen usage and atmospheric pollution.

In a closed system, the pressure-relief valve is closed so that no gas escapes. The FGF equals the patient's basal oxygen requirements. This system is less stable because if inflow gas does not exactly match oxygen consumption, the patient will have difficulty breathing.[15] Also, low FGF prevents rapid changes in concentration of anesthetic gases. The advantage of the closed system is that anesthetic and oxygen usage is optimized and atmospheric pollution is minimized.

Components of the circle include a gas inlet, unidirectional inspiratory and expiratory valves, corrugated tubing, CO_2 absorber canister, adjustable pressure-limiting (APL) valve, reservoir bag, and a Y piece connector. The most efficient configuration of the components diagrammed in Figure 3-3 includes a unidirectional valve on either side of the reservoir bag, the APL valve should be positioned before the absorber in the expiratory limb, FGF should enter between the absorber and inspiratory valves, and the reservoir bag is located in the expiratory limb.[15]

Figure 3-3

The most efficient configuration of circle system. (Reproduced with permission, from Butterworth IV JF, Mackey DC, Wasnick JD. eds. *Morgan &*

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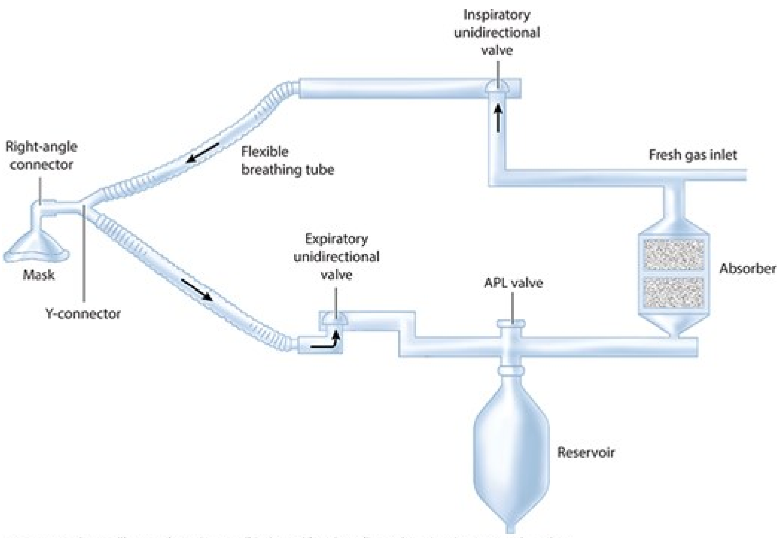

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Dead space in the circuit is located distal to where inspiratory gases mix with exhaled gases located at the Y piece. The goal for pediatric patients is to reduce dead space as much as possible especially for younger patients. Unlike the Mapleson system, the tubing length does not affect dead space.[18] The primary resistance in a pediatric circuit is determined by the internal diameter of the endotracheal tube and by the length of the tube.[1] The unidirectional valves and carbon dioxide absorber also increase breathing resistance.

Pediatric breathing systems have the same components as standard adult circuits, but are modified to decrease resistance to breathing and minimize dead space. These modifications include short and narrow tubing, valves that require reduced pressure to open and close, smaller reservoir bag, shorter Y connection, and more compact carbon dioxide absorbers.[17] This helps decrease compliance of the circuit and allows rapid changes in concentration of anesthetic gases.

Most of the issues associated with the Mapleson system are solved with the circle system. Some disadvantages include bulkiness and less portability, increased resistance to breathing due to the addition of valves and CO_2 absorbent, and increased possibility for disconnection and failure due to different components.

Anesthesia Machines

Currently, there are no anesthesia machines designed only for pediatric use. Standard adult breathing machines can be used as long as the user understands how to compensate for their limitations. Advanced ventilators are the biggest difference between newer and older anesthesia machines.[19] In the past, anesthesia ventilators were unable to accurately deliver small tidal volumes for neonates, accommodate the high respiratory rate required for neonatal ventilation, and offer other modes of ventilation other than volume control.[20] Anesthesiologists resorted to using the ICU ventilators in the operating room. Newer anesthesia machines are able to provide different modes of ventilation and also estimate and compensate for circuit compliance. This feature is called circuit compliance compensation.[19] The compensation consists of delivering slightly more than the set tidal volume to compensate for volume lost to the circuit. Low compliance is desirable to minimize the amount of volume lost to expanding and contracting the circuit during ventilation. Ideally the circuit should be stiff and not distensible. Newer machines also have FGF decoupling, which means there is no change in tidal volume regardless of changes in fresh gas flow. Fresh gas flow decoupling and compliance compensation have increased the safety profile of ventilators and anesthesia machines in the pediatric population.

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