Pediatric Thoracic Anesthesia

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24.1 Introduction

Pediatric patients undergoing thoracic surgery can present unique challenges to the anesthesiologist. Firstly, their unique anatomical and physiological characteristics render them at higher risk for hypoxemia during and after the procedure. Their size does not allow for the use of standard equipment often times requiring the anesthesiologist to get creative with the tools at hand. Their behavior will likely not allow them to cooperate despite the best laid anesthetic plan. And lastly, the large variety in pathology, some of which can be rare, adds more difficulty to the whole procedure. In this chapter we will discuss the above in more detail as well as go over the techniques that have been used successfully to take care of this patient population during thoracic surgery.

24.2 Pediatric Anatomy and Physiology

Pediatric patients have several key differences in anatomy and physiology compared to the adult which the anesthesiologists must be aware to successfully take care of these patients during thoracic surgery. The most prominent airway characteristics are listed below [1]:

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- Large head, short neck and a prominent occiput.
- Tongue is relatively large.
- Larynx is high and anterior, at the level of C3–C4.
- Epiglottis is long, stiff and U-shaped.
- Preferential nasal breathing
- Airway is funnel shaped and narrowest at the level of the cricoid cartilage.
- Airway is small and prone to develop edema resulting in airway obstruction.

In terms of respiratory physiology, the pediatric patients have a baseline limited respiratory reserve during normal two lung ventilation due to several reasons listed below [2]:

- Horizontal ribs prevent the 'bucket handle' action seen in adult breathing and limit an increase in tidal volume. Ventilation is primarily diaphragmatic.
- The chest wall is significantly more compliant than that of an adult. Subsequently, the Functional Residual Capacity (FRC) is relatively low. FRC decreases with apnea and anesthesia causing lung collapse.
- Minute ventilation is rate dependent as there is little means to increase tidal volume.
- The closing volume is larger than the FRC until 6–8 years of age. This causes an increased tendency for airway closure at end expiration. Thus, neonates and infants generally need intermittent positive pressure ventilation during anesthesia and would benefit from a higher respiratory rate and the use of positive and expiratory pressure (PEEP).
- Muscles of ventilation are easily subject to fatigue due to low percentage of Type I muscle fibers in the diaphragm. This number increases to the adult level over the first year of life.
- The alveoli are thick walled at birth. There is only 10% of the total number of alveoli found in adults. The alveoli clusters develop over the first 8 years of life.
- Apneas are common post operatively in premature infants.
- High O_2 consumption compared to adult.

24.2.1 Effects of the Lateral Decubitus Position and One Lung Ventilation (OLV) in Children

In children up to age 8 years, the chest wall compliance is high, the lungs are easily compressed by external pressures, the functional residual capacity is low and the oxygen consumption is high. All of these measures render children more vulnerable to the unwanted effects of the lateral decubitus position together with OLV, when compared to adults. The dependent lung is under pressure. Inhalational anesthetics inhibit hypoxic pulmonary vasoconstriction and blood flow to the operative lung cannot be reduced. Ventilation/perfusion is easily mismatched, atelectasis formation and hypoxemia are almost inevitable [10].

Unlike adults, oxygenation is higher in the nondependent lung rather than the dependent one (healthy lung), especially in neonates and infants. The reason for this is that children have easily compressible chest wall. FRC becomes equal to the residual volume in the dependent lung and small airways begin to close even in tidal volume values. Hydrostatic pressure between dependent and nondependent lungs is minimal because of the small size of the children. Therefore, the advantage of better oxygenation in the nondependent lung is heralded. As a result, compared to adults, children are at greater risk for developing hypoxemia or airway complications during thoracoscopic surgery or thoracotomy, even though one lung ventilation is not used [2].

24.3 Preoperative Evaluation

Preoperative evaluation and patient preparation are mandatory in order to reduce perioperative complications in thoracic surgery in children. The required fasting time and premedication recommendations are similar to other surgical patients. In summary, 2 h nil per os (NPO) for clear fluids, 4 h for breast milk, and at least 6 h for milk formula or light meal, is recommended per the American Society of Anesthesiology guidelines [3]. The most important task is the diagnosis and evaluation of the acute and chronic pulmonary and cardiac pathologies. Dyspnea and decreased tolerance to exercise are signs indicating decreased pulmonary reserve [2].

Lung auscultation must be performed in either supine or sitting position. Pathologic sounds such as rhonchus or wheezing should be evaluated. Blood gas analysis is not mandatory in children. It is usually sufficient to evaluate peripheral oxygen saturation and venous bicarbonate concentrations which is always elevated in children with chronic carbon dioxide (CO_2) retention [2]. Although respiratory function tests are not recommended in asymptomatic patients, they may be useful to determine the progression of disease [4, 5]. Radiologic appearance of the pathologies must be examined by the anesthesiologist. This examination may help the anesthesiologist to be ready for possible problems such as difficult intubation or blood loss.

Pediatric and adult thoracic surgeries differ in terms of indication. In adults, the indication is usually limited to infections, tumors, and lobe resections. Usual indications in younger children are congenital diseases, such as pulmonary sequestration, congenital diaphragmatic hernia, trachea-esophageal fistulas, congenital lobar emphysema, vascular rings and tracheal stenosis. Usual indications in older children and adolescents are infections, mediastinal masses and musculoskeletal deformities.

24.4 Anesthetic Techniques

24.4.1 Flexible Bronchoscopy

Flexible bronchoscopy is an endoscopic technique which enables to visualize and evaluate the trachea and bronchi mainly for diagnostic procedures. In pediatric anesthesia is it performed often times to evaluate the patency of the airway. In order to asses for dynamic obstructions spontaneous ventilation is necessary. Thus, sedation supplemented with topical anesthesia is usually satisfactory for this procedure. Optionally a laryngeal mask airway can be utilized while providing general anesthesia. If the flexible bronchoscopy is being done for other purposes, such as takin biopsy samples, general endotracheal anesthesia with or without paralysis is adequate.

24.4.2 Rigid Bronchoscopy (RB)

Rigid Bronchoscopy (RB) is mainly therapeutic in nature. It is used in the diagnosis and treatment of intraluminal obstructions or extra luminal mass effects. Due to the stimulating effects it is performed under general anesthesia. The indications of RB in pediatric patients are the same with the adult patients; but the most frequent indication is the tracheobronchial foreign body (FB) aspiration [6]. Broncho alveolar lavage, endobronchial biopsy, dilatation of the subglottic stenosis, tracheal stent application, laser surgery, cryotherapy and diagnostic procedures may also be performed under RB.

24.4.3 Thoracic Surgery

The goal of anesthesia during RB is to ensure adequate depth of anesthesia, provide effective analgesia, decrease airway secretions, restore hemodynamic stability, preserve airway patency at the end of the procedure. All stages of anesthesia including induction, maintenance, ventilation and emergence are critical and will be discussed next.

24.4.3.1 Preoperative Period

FB removal offers some differences with other bronchoscopic procedures. First, it is always performed under emergent conditions; second, the patient is usually totally healthy before FB aspiration. For this reason, pre-anesthetic evaluation of the routine laboratory tests is not beneficial and is time consuming. It is essential to inform parents about the perioperative risks of the procedure and to obtain a written consent. The fasting time should be in the recommended limits. If not (as in emergent cases), measures to reduce the aspiration risk should be taken. The decrease in the production of saliva and anxiety are the beneficial effects of premedication. Albuterol sulfate and budesonide inhalations are reported to be advantageous in reducing perioperative pulmonary complications [20]. The knowledge of the type, place and aspiration time of the FB is important. If it is above the carina, there is a total obstruction risk and face mask ventilation or ventilation after endotracheal intubation may be impossible. Penetrating objects may cause pneumomediastinum or subcutaneous emphysema. Organic materials may swell progressively and result in total obstruction. The anesthesiologist must know the aspiration time in order to predict the airway edema or granulation tissue formation [7].

24.4.3.2 Intraoperative Period

Performing general anesthesia in pediatric patients is always a challenging task, but the situation becomes more complicated in RB procedures, even in previously healthy children. RB indications usually include airway obstruction or respiratory system pathologies and children have limited pulmonary oxygen reserve and high oxygen consumption rate. Furthermore; the surgeon, the anesthesiologist and the nurse share the same space creating a risk of chaos [8].

The shaving chin position (with head extension by keeping a shoulder roll, chin pointing upwards) is given. This is the ideal position to restore airway continuity. Monitoring should include electrocardiography, oxygen saturation via pulse oximetry, noninvasive blood pressure and body temperature [9]. Monitoring of the end tidal CO_2 values is not possible. Transcutaneous CO_2 analysis may provide a continuous estimation of the arterial CO_2 values. Total intravenous anesthesia (TIVA) is commonly used during RB, therefore bispectral index monitor is recommended in order to assess the depth of anesthesia.

24.4.3.3 Ventilation Techniques

There are four ventilation techniques during RB [2]. The choice of the ventilation technique depends on the patient's condition and the anesthesiologist's preference.

1. Apneic oxygenation: After preoxygenation, the patient is not ventilated until the periphery oxygen saturation begins to fall. This allows the surgeon a brief period of time to perform an intervention. At the end of this period, the patient is ventilated. This cycle is repeated during the procedure. The technique is not preferred in pediatric patients because of their limited oxygen reserves.
2. Spontaneous assisted ventilation: In this technique, the patient is ventilated with a bag and flexible tubing attached to the ventilation port of the RB, with high flow oxygen. Ventilation is spontaneously maintained by the patient and assisted by the anesthesiologist, when required. Generally, total intravenous anesthesia is administered, but despite the disadvantage of the environment air pollution, some centers use volatile anesthetics through the ventilation port of the bronchoscope. The advantages of this technique are the preservation of the patient's spontaneous ventilation during the procedure, decreased risk of migration of the FB to another site because of the absence of positive pressure. Nevertheless, spontaneous ventilation may be disrupted as a result of the increased airway resistance caused by the instruments inside the RB. Laryngospasm is another risk [10–12].
3. Positive pressure ventilation: This is the most commonly used technique. In this technique, anesthesia circuit is connected to the ventilation port of the RB. Positive pressure is created manually by the reservoir bag or by the anesthesia machine. Muscle relaxation is required. The advantages are the decrease of atelectasis risk, improvement in oxygenation and decrease in airway resistance. As the air leak through the outer part of the RB is inevitable, adequate tidal volume may not be delivered; this is the most frequent disadvantage of this ventila-

tion technique. Maintaining effective ventilation may only be possible by increasing flows and prolonging inspiratory times, bringing the risk of air trapping in airways distal to the stenotic areas. Another disadvantage is the dislocation of the FB by the effect of positive pressure. During positive pressure ventilation, the viewing port must be occluded in order to deliver an effective breath through the ventilation port of the RB [13]. It is advised to use spontaneous ventilation for the removal of proximally located FBs and positive pressure ventilation for the removal of distally located FBs [14].

4. Low-frequency jet ventilation (LFJV): This technique is preferred in order to prevent hypoventilation resulting from the air leak through the outside the RB. It can be applied via Sanders or Manujet III injector (VBM, Germany). High oxygen pressure created by the hospital medical gas system (wall piped oxygen) is applied to the ventilation port of the RB. This pressure is regulated and reduced by an adjustable valve, manually. It runs through the RB with a high flow, leading to a negative pressure within the airways. This creates an air corridor outside the RB and air is entrained to alveoli (Venturi effect). This technique allows the delivery of tidal volumes between 1 and 3 ml/kg. Ventilatory parameters used during LFJV vary with age group (Table 24.1). The resulting alveolar ventilation is the total of the volume delivered by the injector and the entrained air. Low-frequency jet ventilation offers the advantages of allowing bronchoscopic interventions to be performed without cessations. Complications include barotrauma, inability to predict FiO_2 and monitor $ETCO_2$, FB dislocation and blowing of blood and debris materials to distal airways resulting in inadequate gas exchange. LFJV should not be used in patients with tracheobronchial mucosa injury or low respiratory compliance [15]. In addition to standard monitoring, monitoring of chest wall rise, depth of anesthesia, SpO_2 and transcutaneous pressure of CO_2 (if available) is essential during LFJV.

Whatever the ventilation technique is, the key of an uncomplicated procedure is the cooperation of the surgeon and the anesthesiologist.

The choice of anesthesia method depends on the experience of the surgeon and the anesthesiologist. The major concern during anesthesia induction is to minimize airway reactivity. Concerning FB removal, face mask ventilation may cause a FB to move, resulting in complete obstruction. Inhalational or intravenous agents or both may be administered. During maintenance, short acting agents such as propofol, dexmedetomidine, remifentanil and short acting muscle relaxants are administered as the procedure is generally quite short. Nitrous oxide is not recommended, because many patients undergoing RB have air trapping to some extent.

Table 24.1 LFJV parameters according to age groups

Patient age group	Frequency/minute	Injection (driving) pressure
Neonate	40	0.5 bar
Infant	40	1 bar
Children	20–30	2 bar

Preservation of the spontaneous breathing during the procedure decreases the risk of FB dislocation, but unwanted motion, cough, retching, bronchospasm and laryngospasm are found to be more common compared to controlled ventilation. Nevertheless, there is still no consensus regarding the most effective ventilation method (spontaneous or controlled). In cases of spontaneous ventilation, anesthesia should be induced with sevoflurane, maintained with sevoflurane together with propofol infusion, together with topical lidocaine 1% (to diminish airway reflexes and anesthetic agent's doses) [25].

Severe complications can occur during RB [16]. These are closely related to the patient's condition, the severity of the pathology, the experience of the surgeon and the anesthesiologist.

Hypoxia-induced cardiac arrest is a major cause of death. Mortality is closely related to the general state of the children, at admission, the quality of anesthesia induction and the insertion success of the bronchoscopy.

The complications are as follows:

(a) Death (0.42%)
(b) Severe laryngeal edema
(c) Bronchospasm (Necessitating tracheostomy or endotracheal intubation)
(d) Pneumothorax and pneumomediastinum
(e) Hypoxic arrest during induction, maintenance or recovery period
(f) Hypoxic brain injury
(g) Tracheal or bronchial laceration
(h) FB dislocation
(i) Failure to perform RB (Necessitating thoracotomy or tracheostomy, depending of the pathology)

5. Ventilation during the postoperative period:

The choice of the ventilation technique after the procedure depends on the severity of the pathology, the patient's medical condition, the effectivity of the ventilation and the degree of edema in airways. In uncomplicated cases, spontaneous ventilation is assisted via a face mask; but endotracheal intubation should be preferred in patients having severe pathologies together with impotent airways and ineffective ventilation. After the recovery, hospital stay is strictly recommended [17]. If the patient has no previous respiratory failure and has completed the procedure without complication, he may be referred to the ward. Otherwise, follow up in intensive care is mandatory.

24.4.3.4 Sternotomy

In children, sternotomy is generally performed for the biopsy or removal of the mediastinal tumors. A detailed history and physical examination are extremely important. Anesthesiologists should focus on the respiratory system symptoms such as difficulty in breathing, cyanosis or stridor aggravated by motion, cough or straining. Wheezing unresponsive to the bronchodilators, recurrent pneumonia, persistent atelectasis, pericardial invasion, arrhythmias, pulsus paradoxus or signs of the superior vena cava syndrome are the warning pathologies for a complicated perioperative period. Echocardiographic examination is mandatory in children with mediastinal tumors in order to determine a possible mass effect. The riskiest period is the induction of anesthesia especially in previously symptomatic children. Decrease in the sympathetic tonus, loss of the spontaneous ventilation and physiologic changes related to patient position diminish compensatory mechanisms. Children with mediastinal mass are in increased risk of severe airway obstruction and hemodynamic instability. The pediatric surgeon must be ready to perform emergent rigid bronchoscopy (RB) during the anesthesia induction of children with a mediastinal mass, in cases of total obstruction as a result of a mass effect. During induction of anesthesia, preservation of the spontaneous ventilation to secure the airway continuity is recommended. In cases of superior vena cava obstruction symptoms, induction must be performed in the sitting position and intravenous lines must be inserted into the lower limb veins. If possible, biopsy must be taken under local anesthesia. Chemotherapy or radiotherapy must be done to shrink tumors before surgery. A cardiopulmonary bypass circuit on standby should be considered for extremely high-risk cases.

24.4.3.5 Two Lung Ventilation with Manual Retraction

Several thoracic procedures, for example patent ductus arteriosus ligation, vascular ring resection and tracheo-esophageal fistula repair, can be performed with a single lumen tube positioned in the trachea providing ventilation to both lungs with the surgeon retracting the lungs as necessary. This is typically for short procedures in small infants where the surgeon is operating in the chest cavity but not directly on the lungs. This technique is especially helpful in the management of emergencies such as acute hemorrhagic conditions or tension pneumothorax. Lung injury is a concern and thus retraction should be kept to the minimum necessary. It is also possible for the surgeon to insufflate carbon dioxide (CO_2) into the pleural space to displace the lung if a thoracoscopy is being performed.

24.4.3.6 Lung Isolation and OLV

OLV is a ventilation strategy which facilitates surgical exposure in thoracoscopy or thoracotomy [18]. Unlike adult patients, OLV is not easy in children, especially in neonates and infants, because of the equipment limitations. Nevertheless, technology is advancing daily and equipment available to help anesthesiologists in performing OLV has been developed. OLV has other advantages other than surgical exposure, they include:

- Decreasing the over distention of the pathologic lobe, in congenital lobar emphysema.
- Differentiating the normal lung tissue from the pathologic one.
- Decreasing the potential trauma to the lung tissue, caused by the retractors.
- Decreasing the risk of contamination of the healthy lung by secretions, blood or infected materials originating from the diseased lung.

We will discuss next different ways to achieve OLV in pediatric patients.

Selective Bronchial Intubation

Selective bronchial intubation with a regular single lumen tube can be achieved readily and is the simplest to achieve one lung ventilation. The endotracheal tube (ETT) is advanced while auscultating breath sounds until the sound is lost on the desired side. Confirmation can be obtained by noting an acute drop in end tidal CO_2 as the tube enters a mainstem bronchus. Being that the left bronchus has a more acute angle of separation from the trachea than the right bronchus (45° versus 25°) it is much more common for the tube to be advance into the right mainstem bronchus. Rotating the patient's head to the right side helps to decrease angle the left bronchus improving the chance of a left mainstem bronchus intubation. Also rotating the ETT 180° so the bevel is pointing to the left helps direct the tube to the left bronchus. Alternatively, and with higher first pass success rate, the tube can be guided with a fiber-optic bronchoscope. It should be noted that the bronchi have a smaller diameter than the trachea and thus a tube that is too big could cause trauma to the bronchus. If an uncuffed tube is being used there is chance of a leak which might not allow for full lung collapse. Cuffed tubes should not be placed too far into the bronchus since the cuff can occlude the upper lobe of the selected bronchus, especially when intubating the right mainstem bronchus [19]. It is recommended the cuff to partially remain in the trachea. A major downside to selective bronchial intubation is that it is not possible to ventilate, apply suction, or continuous airway pressure (CPAP) to the nondependent lung. Several variations of this technique have been described. Marraro described an endobronchial bilumen tube consisting of two uncuffed tube joined together with the bronchial tube being longer than the tracheal one. It is developed for children under 3 years old [20]. Tsujimoto et al., described a micro laryngeal ETT that can be advanced into the desired bronchus, through the intubating laryngeal mask airway, with the aid of flexible fiber-optic bronchoscopy (FOB) [21]. High frequency jet ventilation (HFJV) and high frequency oscillatory ventilation (HFOV) is another option and can be indicated in short procedures. They provide optimal surgical field while allowing blood gas exchange. There is inability to monitor end tidal CO_2 ($EtCO_2$) which might be overcome by transcutaneous CO_2 ($PtcCO_2$) monitoring (Table 24.2).

Table 24.2 Approach to one lung ventilation by age

Age	ETT	Feasible one lung ventilation technique	Fiber-optic size
Newborn–2 years	3.0–4.5 mm	Endobronchial intubation/5F Parallel BB	<2.2 mm
2–8 years	4.5–6.0 mm	5F BB Coaxial/Endobronchial Intubation	2.2–2.8 mm
8–10 years	6.0–7.0 mm	5F BB coaxial/4.0 Univent Tube	2.8–4 mm
>10 years	7.0 mm plus	7F BB Coaxial/26 or higher Double Lumen Tube/4.0 or higher Univent Tube	2.8–4 mm

Bronchial Blocker

Another option for lung separation is the placement of a bronchial blocker (BB) in the operative side. A major advantage of this technique is the BB balloon can be deflated allowing quick ventilation to the operative lung if necessary. The smallest bronchial blockers in the market are the 5 French (F) Arndt blocker (Cook Medical, Indiana, USA) and the Uniblocker (Fuji System Corporation, Tokyo, Japan). They are both smaller versions of the 9F blockers from each company and are intended to be used in the same way, inside (also called coaxial) the ETT (Fig. 24.1) with the major difference to all the other blockers being that the 5F Uniblocker does not have a suction port. It should be noted that the 5F BB has a higher-pressure balloon than the 9F BB balloon used in adults and caution is warranted when inflating it [22]. Being that a fiber-optic bronchoscope is necessary for the placement of all bronchial blockers, placing them becomes a challenge when the ETT inner diameter is small. The most common pediatric fiber-optic bronchoscope size available is 2.2 mm in outer diameter. Since both the FOB (2.2 mm) and the 5F BB (1.67 mm) must fit inside the ETT plus some room for maneuvering them, the minimum recommended ETT inner diameter is 4.5 mm. Since there are many different models and sizes of fiber-optic bronchoscopes in the market it is best if the anesthesiologist checks that both the FOB being used and the BB fit inside the intended tube ex vivo. In small patients where the BB and the FOB do not fit inside the tube, i.e. ETT 4 mm or smaller, lung separation can still be achieved with a BB, however it must be placed outside (also referred as parallel) the ETT (Figs. 24.2a, b and 24.3). Our routine practice when doing this is, after assuring the patent is fully anesthetized and paralyzed, to perform a laryngoscopy with the adequate size blade, passing the 5F blocker through the glottis and advancing it gently until soft resistance is met, followed by intubation of the trachea with the desired ETT tube. Typically, we use cuffed ETT to minimize having to reintubate for leaks. After verifying the trachea has been properly intubated and end tidal CO_2 ($EtCO_2$) is confirmed, an FOB is placed inside the tube to visualize the carina and position the BB into the proper bronchus. The adapter included with BB can be used to ventilate while the FOB is being used. Most of the time the BB is in the right mainstem bronchus and needs to be pulled back. If collapse of the right lung is desired the balloon of the BB is placed

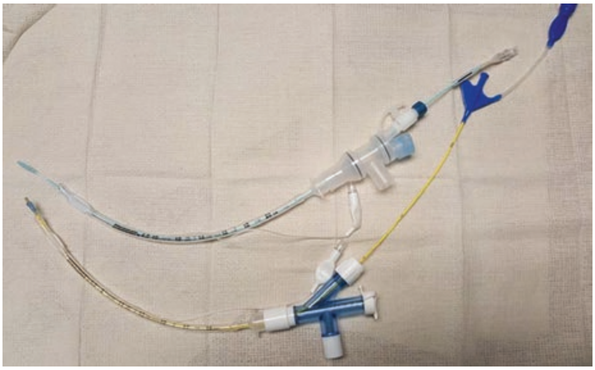

Fig. 24.1 5F Uniblocker and 5F Arndt blocker with its own ventilator adapter when used inside the tube (coaxially)

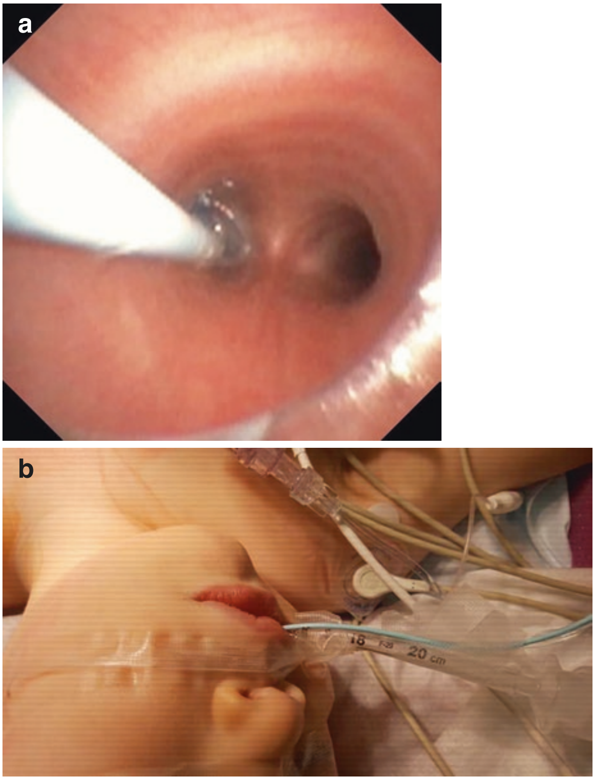

Fig. 24.2 (**a**) Uniblocker placed in left mainstem bronchus outside a 4.0 ETT visualized through a 2.2 fiber-optic scope. (**b**) Uniblocker placed outside a 4.0 mm ETT

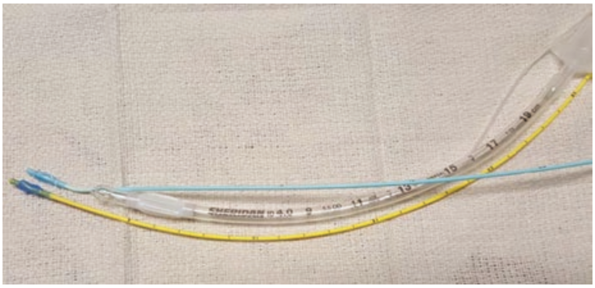

Fig. 24.3 5 French (F) Uniblocker and 5F Arndt blocker when used outside the tube (parallel)

very shallow in the right mainstem bronchus to avoid blocking the right upper lobe. Visualization of the cuff as it is being inflated is mandatory to avoid injuring the bronchus or herniation of the cuff into the trachea. If it is desired to block the left mainstem bronchus then the BB must be pulled above the carina and, taking advantage of the hockey stick design of the Uniblocker (or alternatively manually shaping the distal end of the Arndt blocker into a hockey stick, since we do not use the lasso with this technique), rotating it so that the hockey stick shape directs the BB into the left bronchus. As mentioned previously, rotating the head of the patient to the right side can help bring the left bronchus into a more direct angle. It must be recognized that when placing a BB outside the tube it can be much more difficult to manipulate the BB into the left bronchus compared to when placed inside the ETT, especially if it migrates out of the bronchus mid procedure. Care must be taken to ensure the ETT and BB are properly secured in place and not to allow any motion such as neck flexion or any undue pulling on the circuit that can displace the BB. Our preference is to advance the BB far into the desired bronchus while the patient is supine and, after the patient has been fully positioned, to pull the BB out into the correct distance into the bronchus after we are certain the patient will remain immobile. Alternatively, Fogarty catheters or Miller atrial septostomy balloons have been described when small BB have not been available but being that they have a high-pressure low volume balloons caution is recommended to avoid injuring the bronchus [2].

Univent Tube

The Univent tube (Fuji System Corporation, Tokyo, Japan) is a single lumen tube with a bronchial blocker balloon already integrated in the wall of the tube [13]. The blocker balloon has a hockey stick shape at the end and is advanced and rotated into position. Albeit narrow, the lumen of the second tube may be served to deliver oxygen, inhalational agents or suction the operated lung; but this property is only present in Univent tubes with an ID of 6 mm or greater. The Univent tube's blocker balloon has low-volume, high-pressure properties, so over distention or long-term use may cause damage of the tracheal mucosa [23]. Dislodgement of the balloon during surgery is quite difficult, because it is strictly connected to the main endotracheal tube [2]. Due to the simplicity of its design It would seem ideal for lung isolation in small pediatric patients. However, the outer diameter is much larger than a regular single lumen tube with the same inner diameter. For example, the smallest Univent tube in the market has a 3.5 mm inner diameter but an outer diameter of at least 7.5–8 mm per the manufacturer, which would compare to a regular 5.5 mm tube. Thus, it is useful for children older than 6 years of age, in which case it is likely preferable to use a regular single lumen tube with a BB inside, which provides a larger area to ventilate and less resistance to flow. In the scenario of a patient needing to remain intubated post procedure, the BB can be simply pulled out instead of requiring the Univent tube to be replaced a regular single lumen tube.

Double Lumen Tube

Double lumen tubes are the preferred method for lung separation in older children. Just as with adults, it provides true lung isolation, it allows for suction, and application of CPAP. The smallest in the market is 26F Rusch (Teleflex, North Carolina, USA). Both right and left sided tubes are available. Its outer diameter is 8.67 mm which is close to the outer diameter of a 6.5 mm regular single tube (8.9 mm). Other pediatric sizes available in the market are 28F and 32F, both made by Rusch and Mallinckrodt (United Kingdom). Thus, they are recommended for children older than 8 years of age [24]. A small pediatric FOB is required to be able to enter each lumen. In adults, the correct length of the tube is directly proportionate to the height of the patient, but there is not a clear proportion in children. The use of right DLTs is not preferred in small children because of the high risk of occluding the right upper lobe. This is an anatomical disadvantage of the children and the tube manipulation does not overcome it. A similar disadvantage is present in left-sided DLTs such as occluding the left upper lobe bronchus by the advanced bronchial tip. The technique for placement is the same as in adults and will not be described here.

Hypoxemia Management During OLV

Hypoxemia during OLV is almost inevitable, especially in small children. As in adults, CPAP use or intermittent ventilation of the nondependent lung, PEEP application to the dependent lung may improve oxygenation [10].

24.4.3.7 Monitoring

Standard monitoring including electrocardiogram, pulse oximeter, blood pressure measurement, end tidal CO_2 monitoring ($EtCO_2$), and temperature are the minimum requirement for any thoracic procedure involving general anesthesia. Invasive arterial blood pressure monitoring is usually not required unless there is expectation of a long or complicated procedure, poor cardiopulmonary status, or possibility of large blood loss. If in doubt it is probably best to err on the side of caution and obtain arterial access. In terms of venous access most cases can be done with two large bore, for age, peripheral intravenous catheter. Central venous access is rarely required, but if there is poor peripheral venous access or any comorbidity that might require the patient to need any vasoactive infusions, it is reasonable to obtain. Transcutaneous CO_2 ($PtcCO_2$) is recommended when the operative procedure does not allow for end tidal CO_2 monitoring.

24.4.3.8 Pain Management

Pain management after thoracic surgery in pediatric patients presents unique challenges. In young patients that may not be able communicate properly the identification and assessment of pain presents a challenge in itself. Even when pain has been properly identified and assessed, providing adequate analgesia without risking over sedation and respiratory depression can be difficult. Pain is a very complex experience involving a multitude of factors, the most obvious being the tissue trauma, but also just as important, the anxiety and coping mechanisms of the child along with the parents [25]. Left untreated, pain can have physical consequences such as hyperglycemia, protein catabolism, increased oxygen consumption, increased blood pressure, diaphragmatic splinting, decreased cough, decreased tidal volume, decreased Functional Residual capacity (FRC), and decreased bowel motility [26].

Chronic pain after thoracotomy, also referred to as post thoracotomy pain syndrome, is defined by the International Association for the Study of Pain as pain along the thoracotomy incision that persist after 2 months following the surgical procedure [27]. Its incidence is estimated around 50% in adults but appears to be lower in 20% children [28, 29]. Preemptive analgesia, particularly regional anesthesia, may help to reduce its incidence [30, 31].

Regional Modalities

The most basic form of regional anesthesia is surgical wound infiltration with local anesthetic. It has low risk and can be easily performed by the surgeon. Care must be taken not to exceed the toxic amount of local anesthetic. Doses of bupivacaine of up to 3 mg/kg, and lidocaine up to 5 mg/kg have been found to be below the toxic range [32, 33]. It should be noted that clearance and protein binding for local anesthetic agents are reduced in infants below 6 months of age thus the dose is recommended to be halved in these patients. Preemptive local anesthetic infiltration prior to incision for thoracotomy did not reduce postoperative pain in a study by Cerfolio et al. [34].

Thoracic epidural catheters are the most common modality for pain management in adult thoracic anesthesia [35]. It seems obvious that local anesthetic delivered at the corresponding thoracic level will provide superior pain control. The administration of local anesthetics at the thoracic level is easily titratable, and provides the additional advantage of sympathetic blockade and superior blunting of stress response otherwise not achieved by other techniques. In pediatric patients, epidural catheter placement is performed in the same manner and following the same safety guidelines as for adults with the major difference being that both, the American Society of Regional Anesthesia and the and the European Society of Regional Anesthesia, recommend that all regional anesthesia in children should be performed during general anesthesia or deep sedation [36, 37]. Also, in infants less than 1 year it is common practice to thread the epidural catheter from the caudal space to the desired thoracic location [38]. Ultrasound imaging has been found to be helpful in guiding the catheter to the proper location [39]. Maximum infusion rates for lidocaine of 1 mg/kg per h, and for bupivacaine of 0.2–0.3 mg/kg per h have been recommended for young infants [33, 40]. Again, the dose should be halved for infants younger than 6 months. The concomitant use of opioids allows the use of lower concentrations of local anesthetics and decreases the risk of local anesthetic toxicity.

Paravertebral catheters have emerged as an alternative to the epidural catheter route for management of post thoracotomy pain. When performed unilaterally they have been found to provide comparable pain control with fewer side-effects such as nausea, vomiting, and hypotension, when compared to an epidural catheter technique [41].

Single shot epidural techniques are typically administered in younger children at the caudal epidural space. Since administering a local anesthetic at the caudal or even lumbar epidural level will not reach adequate thoracic levels, single shot caudal techniques are mostly limited to the use of hydrophilic opioids and in particular preservative free morphine. Morphine, easily administered via the caudal space in younger children (typically but not limited to children <5 years of age) will provide a long-lasting analgesic effect. Its peak analgesic effect is 4–7 h [42], and its duration of action has been reported up to 24 h [43]. Even though neuraxial opioids don't offer the potential advantages of a sympathetic thoracic epidural block achieved with local anesthetic agents, epidurally administered opioids have been shown to provide excellent analgesia, pulmonary function, and early ambulation [44]. Side effects related to neuraxial opioids include nausea and vomiting, pruritus, somnolence, respiratory depression, and urinary retention. Close post-operative monitoring for 24 h is mandatory when neuraxial opioids are utilized. Alternative drugs such as the alpha 2 receptor agonist clonidine, ketamine, and magnesium have been used in the epidural space to minimize undesirable side effects of opioids such as respiratory depression, and to prolong analgesic effects [45–47].

Insertion of an epidural catheter can lead to several complications such as misplacement, knotting, and migration, especially if advanced too far, rupture, infection, leakage, epidural hematoma, and neurologic injury. The true incidence of neuraxial anesthesia complications is not known. Severe complications of epidural catheters, defined as infection, local anesthetic toxicity, cardiac arrest, drug error causing harm, or neurologic injury, in pediatric patients have been estimated around 1 in 2000 patients in one study, with permanent neurologic injury at 1 in 10,000 patients [48]. Whereas another reported zero neurologic complications in 150,000 single shot caudal anesthetics [49]. At the moment it does not appear children are at higher from neuraxial techniques risk than adults [50].

Intravenous Modalities

Intravenous opioids although highly effective for pain management, have the downside of having periods of heavy sedation early after being administered, transitioning into periods of low analgesic effect when wearing off. In addition, nausea, pruritus, urinary retention, and constipation are common side effects. Long acting opioids such as morphine, hydromorphone, and even methadone provide a steadier pain control than short acting opioids such as fentanyl.

Acetaminophen is a non-opioid, centrally acting analgesic. Acetaminophen used in combination with opioids leads to improved analgesia and a decrease in opioid dosing and their side effects [51]. Non-Steroidal Anti-inflammatory Drugs (NSAIDS), particularly ketorolac, have been shown to reduce postoperative opioid requirements in pediatric surgical patients, including neonates and premature babies [52].

Dexmedetomidine is a sedative agent that confers sedation by selectively binding to central alpha 2 adrenoceptors. Although at this point it is only approved by the FDA for use in adults for up to 24 h, it has been widely used in children even for prolonged periods of time [53]. It has become popular in pediatric anesthesia since it is associated with a lower incidence of emergence delirium after inhalational anesthesia in children [54, 55]. Preemptive use of intravenous dexmedetomidine was reported to reduce the incidence of post thoracotomy pain syndrome in adults undergoing coronary artery bypass grafting [56]. However, in another study, when administered via a paravertebral catheter even though it was associated with lower post-operative pain and opioid consumption, it had no effect in the incidence of post thoracotomy pain syndrome. It must be noted that pre-operative teaching also plays a role in anxiety reduction [57].

Ketamine, an N-methyl D-aspartic acid (NMDA) receptor antagonist, is a dissociative hypnotic with analgesic properties when used in low doses. It has been shown to reduce in lower pain scores in the postoperative period in adults [58].

Taking it all together, a complete multimodal approach to pain management covers different factors involved in the experience of pain. Local anesthetic to block the transition of the nociceptive signal, and anti-inflammatory to reduce tissue trauma, an NMDA receptor antagonist to prevent central sensitization to pain, opioids to enhance inhibitory pathways, and a preoperative teaching and/or a sedative for anxiolysis.

24.5 Conclusion

Anesthesia for pediatric thoracic surgery is quite challenging. It is essential to perform a detailed preoperative evaluation, have a knowledge of characteristics of different age groups and applicable two-lung or OLV strategies, and also have a full anesthetic plan that includes pain management strategies. Furthermore, it must be stressed that communication between the surgeon and the anesthesiologist, such as sharing the surgical plan, any acute changes in ventilation parameters, heart rate or blood pressure, and the post-operative plan, is extremely important in order to reduce complications.

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