Anesthesia for Pediatric Thoracic Surgery

50

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Key Points

- Pediatric patients present in varying stages of development, from the premature neonate to full-grown teenager. Appreciation of the unique physiologic states associated with the different stages of development will direct anesthetic management.
- Preoperative evaluation of the small child should include the neonatal history as this may indicate comorbid pulmonary and cardiac disease and linked syndromes which must be investigated.
- Lung isolation is not always necessary in pediatric thoracic surgery. Appropriate lung isolation techniques will depend on the age and size of the patient as there is no single technique that is suitable for all pediatric patients.
- Physiologic manifestation of one-lung ventilation may be more pronounced in children than in adults. The compliant rib cage, compressible lung parenchyma, reduced FRC under anesthesia, and higher oxygen consumption in the child contribute to aggravate hypoxemia during lung isolation.
- Adult thoracic surgery is often related to tumor excision, whereas pediatric thoracic disease encompasses a greater variety of pathology. Each specific disease state has its own particular anesthetic considerations and management strategy.
- Pain management in the pediatric population has evolved to include a greater use of regional and neuraxial techniques, even in the smallest of infants.
- Postoperative disposition will depend on the type and length of surgery, extent of resection or manipulation, and nature of the underlying condition. Many pediatric patients will require postoperative ventilation or close cardiorespiratory monitoring following the procedure.

Introduction

Pediatric and neonatal thoracic anesthesia begins with an understanding of the physiologic and anatomic differences that occur in this patient population. Pediatric patients will present in varying sizes and weights from less than 1 kg to greater than 100 kg and in varying stages of development from the extremely premature to the older teenage child. It is therefore the requirement of the pediatric anesthesiologist to understand the physiologic differences associated with these extremes and how they influence anesthetic management.

The determinants of these physiologic restraints and the practicality of securing ventilation and oxygenation will often dictate both the anesthetic management and the surgical approach. Unlike the adult population where one-lung isolation can almost universally be applied, in much of the neonatal population, this can be at best a harrowing challenge or even an impossibility. As well, securing invasive monitors such as arterial or central venous lines may be problematic in the pediatric population. This means that the pediatric anesthesiologist must appreciate the compromise that arises due to the nature of the patient and procedure and yet be flexible and knowledgeable enough to safely carry out the anesthetic management. Postoperative pain management

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and monitored postoperative disposition may differ significantly from that of the adult population and depend largely on the disease process, surgical intervention, and the physiologic maturity of the patient. Thoracoscopic procedures continue to be applied to smaller and younger patients with their own set of unique challenges and hazards.

The purpose of this chapter is to provide the anesthesiologist with the basic physiologic and anatomic characteristics associated with this patient population and how these differences are practically managed. A general discussion on the cardiopulmonary development of the pediatric patient will be presented; however, specialty texts should be sought for in-depth coverage of this topic. Case presentation and examples will be used where possible to provide the reader with a practical approach to common pediatric thoracic procedures. The understanding and practice of these techniques should then enable the pediatric anesthesiologist to apply this knowledge to more complicated and challenging cases.

Pediatric Growth and Development

Normal embryonic development begins at the time of conception and continues throughout the first 8 weeks of life. During this period of time, fetal cells will divide and begin the process of organogenesis. By the fourth week of embryonic development, the primitive heart and lungs appear. At this point neurulation also begins, a process that will see the eventual creation of the brain and spinal cord.

From this early lung, the trachea and bronchial tree will emerge, and by the eighth week of life, the segmental bronchi and diaphragm are complete. In the following months, the airways will canalize, and surfactant will be produced. Although lung maturation will continue post delivery, it is generally accepted that by the 27th week of gestation, fetal lung maturity is sufficient to sustain ex uterine life.

Similarly the heart tube which began to beat at approximately day 22 will undergo a series of foldings and septate formation such that the four-chambered heart will be complete at the eighth week of gestation. Shortly thereafter, the valves separating these chambers will also form. Once the process of organogenesis is complete, the remainder of fetal development is devoted to an increase in cell numbers and the maturation of these organs. Intestinal rotation will proceed as well as a significant increase in overall size and weight. Interruption of this normal developmental pathway can have significant impact on the fetus. Teratogens acting at the time of organogenesis can impact organ formation. Abnormal morphogenesis may lead to cleft palate and congenital diaphragmatic hernia (CDH) among others. Chromosomal abnormalities, those that are not lethal, may have a cluster of symptoms that when grouped together form the basis of pediatric syndromes. As well the problems associated with premature infants (born <37 week GA) are almost entirely due to the immature nature of the fetal organ systems.

Lung and airway maturation continues until approximately the eighth year of life, during which time the number and size of alveoli steadily increase. Transition from intrauterine to the extrauterine environment will see the replacement of the previously fluid-filled alveoli with air as the first breaths are taken. The oxygen-Hb dissociation curve will begin to transition rightward as the alveolar oxygen partial pressure increases from that of intrauterine life.

The anatomic changes that the airway undergoes from that of the neonate to infant and onward to adulthood have been well described. The glottic opening is typically located at the level of the third cervical vertebra as opposed to C4–C5 in adults. In addition, the tongue is relatively large, and the epiglottis is long and floppy in infants up to 1 year in age. As a result the entire tongue of the neonate and infant is located in the oral cavity, whereas only the anterior two thirds of the tongue in older children and adults occupy the oral cavity. This accounts for the propensity to upper airway obstruction in neonates and infants who are sedated, have decreased level of consciousness, or during anesthetic induction. Until 7 or 8 years of age, the tracheal diameter at the level of the cricoid cartilage is narrower than that at the vocal cords, resulting in a conical larynx. A tracheal tube that passes through the vocal cords may not necessarily then pass through the cricoid ring. A relatively large head, short neck, and trachea mean that tracheal intubation, although not typically difficult, requires a subtly different technique than that used in the adult patient.

As the lungs fill with air during the first moments of extrauterine life, pulmonary vascular resistance (PVR) will fall and cause a dramatic increase in pulmonary blood flow. As PaO_2 rises, the ductus arteriosus will constrict and usually fully closes by the end of the first week of life. Left-sided cardiac pressures will rise and close the foramen ovale. The myocardium of the neonate is relatively noncompliant and cannot adjust contractility in response to changes in filling pressures. The cardiac output in the neonate is thus dependent on HR, and the normal heart rate is typically between 100 and 150 bpm.

Relative body composition changes also occur during the first year of life. The highest percent body fat is at 1 year of age (approximately 30%) and typically decreases throughout adult life. Total body water (as a percentage of body weight) is highest at birth (75%) and drops to adult (60%) levels by 1 year of age. The estimated blood volume (as a percent of body weight) also decreases. Term infants typically have an estimated blood volume of 95 mL/kg, whereas by 1 year of age, it has decreased to 65 mL/kg. In addition to this, the fluid, electrolyte composition, energy requirements, hematologic system, and vital signs all change significantly

throughout the various stages of growth. The pediatric anesthesiologist's understanding of these changes will necessarily guide the management of the patient as drug dosages, ventilation parameters, and equipment must be adjusted for the age and maturation of the patient.

Special Considerations

Prematurity

Premature infants have several unique features that will briefly be addressed here. In-depth coverage of this topic can be found in any neonatal or pediatric specific anesthesia text.

Fetal surfactant is produced by type II pneumocytes at approximately the 22nd week of gestation. Half of this production is usually complete by the 28th week, with the remainder by the 37th week. Steroid administration to the mother can speed up this process. Deficiency in surfactant production may result in respiratory distress syndrome (RDS) [1]. The constellation of tachypnea, indrawing, and oxygen desaturation results from collapse of alveoli caused by insufficient surfactant levels. This leads to decreased lung compliance, higher opening pressures, decreased FRC, and increased work of breathing. Arterial blood gas analysis will often reveal hypoxemia, hypercarbia, and acidosis.

The early management of RDS consists of oxygenation and assisted ventilation in the form of noninvasive CPAP/BIPAP [2–4]. Exposure to high oxygen concentrations may lead to retinopathy of prematurity (ROP) and other complications in these patients, although the role of anesthetic agents in causing ROP remains undefined. Balancing the need to avoid tissue hypoxemia and avoiding the toxic effects of oxygen can be challenging. Prudence would seem to suggest that using the lowest possible FiO_2 to maintain adequate tissue oxygenation is advisable. Oxygen therapy is often adjusted to achieve an oxygen saturation of 90–95% [5]; however, if there is evidence of hypoxia-induced hemodynamic instability or other end-organ failures, oxygen therapy should not be sacrificed in order to prevent ROP. Continued oxygen desaturation (below 90%) or persistent acidosis may require endotracheal intubation and mechanical ventilation be instituted. The goal of ventilation is to minimize baro- and volu-trauma while maintaining oxygen saturation between 90 and 95%. To this end, relative hypercapnia ($PaCO_2$ 45–60 mmHg) is often permitted. Much like the management of ARDS, the FiO_2 and PEEP ratio should be carefully adjusted to minimize both while achieving the above stated goals.

Exogenous surfactant can also be administered to these infants both at the time of birth and at regular intervals thereafter [6]. Surfactant acts to decrease alveolar surface tension and has been shown to decrease RDS-related morbidity and mortality [1, 7]. The long-term sequela from RDS is typically bronchopulmonary dysplasia (BPD). These children may continue to have respiratory difficulty secondary to decreased lung compliance and increased airway resistance with increased dead space.

Pulmonary Hypertension

Pulmonary hypertension is classically defined as mean pulmonary arterial pressure (PAP) >25 mmHg at rest or > 30 mmHg with activity [8]. In neonates, echocardiographic evidence of PVR greater than the half the systemic vascular resistance is commonly considered as evidence of pulmonary hypertension [9]. This state arises when PVR fails to decrease after the transition to extrauterine life occurs. Severely elevated pulmonary pressures will cause a decrease in blood flow through the lungs and encourage right-to-left shunting, resulting in cyanosis and hypoxemia. The causes of persistent pulmonary hypertension in the newborn are described in Table 50.1.

Management of pulmonary hypertension involves treating the underlying cause and reducing pulmonary vascular tone. To this end supplemental oxygen administration is employed as well as control of ventilation to avoid hypercapnia and acidosis. Pharmacologic pulmonary vasodilators such as intravenous prostacyclin, phosphodiesterase III inhibitors (e.g., milrinone), and/or inhaled nitric oxide may be administered if necessary [10]. Sildenafil has shown promise and is increasingly being used to treat responsive pulmonary hypertension in this patient population [11, 12]. Individual or combination therapies have

Table 50.1 Causes of persistent pulmonary hypertension in the newborn

Acute pulmonary vasoconstriction due to perinatal events
Meconium aspiration
Respiratory distress syndrome
Pneumonia
Hypoventilation/asphyxia
Hypothermia
Hypoglycemia
Sepsis
Idiopathic
Maternal NSAID or SSRI use
Pulmonary vascular hypoplasia
Congenital diaphragmatic hernia
Oligohydramnios
Congenital cystic adenomatoid malformation (CCAM)
Pulmonary sequestration
Cardiac lesions
Pulmonary atresia with intact ventricular septum
Transposition of the great arteries (TGA)
Total anomalous pulmonary venous drainage (TAPVD)
Tricuspid atresia

been used in neonatal and infant populations with some success [13–15]. Nitric oxide offers the theoretical advantage of improving V/Q matching by preferentially increasing blood flow to ventilated alveoli. Alternatively, extracorporeal membrane oxygenation (ECMO) has been utilized to temporize pulmonary hypertension or as a bridge to lung transplantation [9, 16, 17].

Cardiac Disease

Patent ductus arteriosus (PDA) is a common finding in the premature infant. Blood flow through the PDA is typically left to right, although this can reverse if pulmonary hypertension exists. Preoperative echocardiography should be performed to evaluate this. Depending on the reason for prematurity, these infants may also have other forms of congenital heart disease (CHD) that should be evaluated prior to undergoing any anesthetic. Although pharmacologic or surgical closure of the PDA is often indicated, if other cyanotic CHD exists, the closure of the PDA is delayed until the lesion is repaired or palliated via another form of surgical shunt. The anesthetic management of thoracic procedures in patients with unrepaired or palliated shunts is particularly challenging. Increased positive-pressure ventilation and compromised oxygenation may lead to worsening of right-to-left shunts.

Immature organ function and depleted metabolic reserves predispose the premature infant to several other age-related disorders. Lack of glycogen stores in the premature neonatal liver places these patients at risk for hypoglycemia. The implications of untreated hypoglycemia can be quite severe and include seizures and developmental delay. The normal stress response of surgery is to increase plasma glucose levels secondary to catecholamine and cortisol production. This may not occur, however, in the very sick child. Five or ten percent dextrose solution should be used as maintenance fluid in the pediatric population, although at what age this practice should cease is not clear [18]. To avoid hyperglycemia a balanced salt solution should be used for fluid bolus administration [19].

Apnea of prematurity is common, and its incidence is inversely proportional to the gestational age and weight of the child. Apnea (airflow cessation lasting more than 15 s) may be accompanied by bradycardia and hypoxia. The presumptive mechanism is due to immature neuronal control at the level of the brainstem and peripheral chemoreceptors [20]. An obstructive component to the apnea is often present as well. Other risk factors include a hemoglobin <100 or Hct < 30. Management may include minimizing narcotic use, stimulation and airway support, and pharmacology (e.g., caffeine). Postoperative observation and monitoring for apnea are mandatory in premature and ex-premature infants less than 50–60 weeks postconceptual age.

Preoperative Evaluation

As in adults the preoperative evaluation of the pediatric patient focuses on the history, physical exam, and laboratory investigations, although an age-appropriate evaluation is necessary. The pediatric practitioner must be aware that certain congenital anomalies do not occur in isolation. For example, tracheoesophageal fistula may be associated with other significant anomalies as part of the VACTERL syndrome (vertebral, anal, cardiac, TE fistula, renal, radial, and limb anomalies). The presence and severity of the associated anomalies should be identified as they may affect anesthetic management.

The evaluation of the neonate or infant typically begins with a history of the pregnancy, labor, and delivery. Apgar scores and resuscitation efforts at delivery are important as they may provide diagnostic clues. For example, prolonged tracheal intubation early in life may predict the presence of subglottic stenosis. RDS leading to BPD may affect children many years after their NICU discharge. Both these examples may lead the anesthesiologist to modify his approach to airway management or ventilation strategy.

As this may be the first anesthetic the child is to receive, the biological parents must be questioned with regard to prior familial anesthetic complications. Malignant hyperthermia and pseudocholinesterase deficiency (among others) have a genetic transmission and may present with the first anesthetic. If a prior anesthetic record is available, it should be reviewed. As in adults particular attention should be focused on the ease of bag-mask ventilation and intubation. In the pediatric population, one must also look for evidence of difficulty with intravenous access and the disposition of the child prior to induction. Endotracheal tube (ETT) size and the presence of a leak around the tracheal tube should also be noted.

Functional capacity should be assessed keeping in mind the patient's age. An infant's inability to take full feeds, sweating, and/or cyanosis during feeds may be an indicator of heart failure. In toddlers and older children, activity level or ability to run or play is a better measure of cardiothoracic functional capacity. A helpful indicator is whether the child is able to keep up with his peers when at play. A child who takes more frequent naps or must stop and sit while his peers continue to play is a clear indication of decreased functional capacity. Height- and weight-based growth analysis will also provide evidence of failure to thrive which can be caused by or exacerbate a decreased functional capacity.

The physical exam can be challenging in the pediatric patient. Noncompliance and occasionally combativeness will prevent thorough examination. Most adult markers for difficult bag-mask ventilation and intubation are not appropriate for infants and children. Assessing Mallampati score in a newborn may be impossible and futile. In its place many

pediatric anesthesiologists assess the craniofacial silhouette or profile, focusing on evidence of retro- or micrognathia. A gloved finger can also be used to feel for the presence of a high arched and/or cleft palate, which may be associated with difficult laryngoscopy.

Respiratory compromise or distress will manifest not only as tachypnea but perhaps also as indrawing, nasal flaring, grunting, accessory muscle use, or paradoxical breathing. All are easily identifiable in children. Peripheral cyanosis and evidence of decreased perfusion should be sought. Assessment of intravascular volume status in the pediatric patient may be challenging. Orthostatic vital signs are generally not done in neonates, and the JVP cannot be easily seen. Skin turgor, capillary refill, fontanelle fullness, level of consciousness, and urine output, however, are easily assessed, as is total fluid intake. A newborn that consistently is gaining weight is very unlikely to be hypovolemic.

Vital signs change with age and should therefore be compared to the statistical norms for the patients' cohort. Blood pressure measurements in an irritable or uncooperative child can be unreliable or impossible to attain. Auscultation for normal heart sounds and murmurs of concern is important to document. Evidence of heart failure, pulmonary edema, and wheezing on respiratory exam should also raise concerns.

Laboratory investigations in the pediatric population should be based on the presenting illness and the surgery proposed. Often children that are booked for thoracic procedures will have at minimum a CXR that can be evaluated for pulmonary pathology, edema, and evidence of scoliosis and engorgement of the vascular structures. If available the computed tomography (CT) scan or MRI should also be viewed. This will prove a valuable aide in determining the feasibility of lung isolation and the extent of the pathology. Particular attention should be noted if the disease is in communication with the bronchi (e.g., congenital cystic adenomatoid malformation, CCAM) as this will potentially alter the ventilation strategy. Anterior mediastinal masses may compress the great vessels, the trachea, or the heart itself. Evidence of cardiovascular compromise, whether on history or physical exam, warrants further investigation with transthoracic echocardiography. Often an understanding of the disease pathophysiology and associated cardiac anomalies will warrant this investigation. An ECG can be very helpful in these circumstances.

Since most thoracic procedures have the potential for blood loss, a CBC should be obtained preoperatively. This test may also indicate the degree of hypoxia if the hematocrit is significantly elevated. Often electrolytes and renal function indicators will be ordered. In an otherwise healthy child, no blood work may be needed. Baseline arterial blood gases may be useful but may not be practical in the frightened young child. Capillary or venous gases are more easily obtained in pediatrics and provide almost as much useful information as arterial gases. Unlike the adult patient that presents for thoracic surgery, it is often impossible to obtain reliable pulmonary function tests or spirometry. This, however, should not be an impediment to proceeding with the planned surgery. Any further testing should be based on those areas of concern elucidated during the preoperative evaluation.

Lastly, the preoperative evaluation should be used to explain to the child and/or parents the anesthetic plan and the eventual disposition of the patient. Risks and complications should be addressed and assent or consent obtained. Decisions regarding preoperative sedation and parental presence at induction can also be made at this time. The postoperative pain management strategy should be outlined and questions or concerns addressed.

Strategies for Lung Isolation

The indications for lung isolation in children include prevention of contamination by blood or pus, treatment of a large bronchopleural fistula or severe unilateral bronchiectasis, as well as facilitating surgical exposure during thoracic procedures. Although thoracoscopic procedures may be performed without lung isolation in very small infants (the induced pneumothorax is often enough to compress the lung tissue and provide surgical exposure; see Fig. 50.1), one must be prepared to isolate the lungs in the event surgical exposure is inadequate. The techniques and approach to lung isolation in the pediatric population may differ from that of adults since infant and small child-sized bronchial

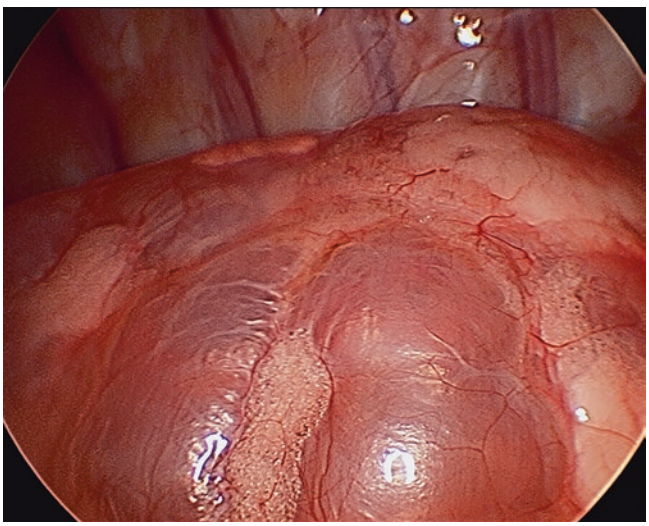

Fig. 50.1 Thoracoscopic view of a 6-month-old infant's right hemithorax in whom adequate surgical lung exposure was achieved with the induced capnothorax and without the need for lung isolation. The right lower lobe almost entirely consists of congenital cystic adenomatoid malformation (CCAM)

tubes are not available. Despite this, the basic principles of lung isolation in the child are similar to those for the adult. There are three fundamental techniques of lung isolation: single-lumen endobronchial intubation, bronchial blockers, and double-lumen bronchial tubes [21].

Historically, the use of single-lumen tubes for selective endobronchial intubation was the only method to isolate the lungs in small children. Although it is now rarely the preferred method of lung isolation, it has the advantage of being readily available, requiring little technical expertise, and can be performed on any patient, regardless of size. Right mainstem bronchus intubation is easily accomplished and has been performed (inadvertently or otherwise) by virtually every anesthesiologist. Left mainstem bronchus intubation, if done blindly, simply requires the ETT be rotated 180° with the patient's head turned to the right. This maneuver turns the bevel of the tracheal tube to favor left mainstem bronchus intubation with advancement. Alternatively, flexible fiberoptic bronchoscopy can be used to place the tracheal tube in the appropriate mainstem bronchus under indirect vision. Regardless of which technique is used, fiberoptic verification of proper tube placement is recommended [22, 23].

Other advantages of this technique include very rapid isolation that can be applied in emergency situations such as pulmonary hemorrhage. Limited technical experience is required, and specialized equipment is not necessary. Because single-lumen tubes are available in a wide variety of sizes, there is no patient that cannot be managed by this method. Note, however, that since airway diameter narrows further down the trachea and bronchi, one should consider placing a slightly smaller ETT than otherwise indicated.

Disadvantages of this technique are numerous. Firstly, conversion to temporary two-lung ventilation (i.e., to reexpand the nondependent lung) may be cumbersome. This requires withdrawing the secured ETT from the bronchus to the trachea. Reisolating the lung with the patient in lateral decubitus position and under surgical drapes can be problematic. As well, an incomplete seal at the bronchus will allow gases to escape and inflate the nondependent lung. Leak gas will also contaminate the room; however, more importantly debris, blood, and secretions from the operative side may soil the poorly isolated lung. If intubating the right mainstem bronchus, obstruction of the right upper lobe is possible, especially if a cuffed ETT is used. Finally, if hypoxemia arises, it is impossible to apply CPAP to the nondependent lung. If adjusting PEEP to the dependent lung does not improve the hypoxemia, repositioning the ETT above the carina and reverting to two-lung ventilation will be the only solution.

Bronchial blockers play an important role in pediatric lung isolation, particularly in patients 3 months to 9 years of age. There are currently three main devices available: Fogarty arterial embolectomy catheters (Edwards Lifesciences, Irvine, CA, USA), Univent® tube (Vitaid, Lewinston, NY, USA), and the Arndt endobronchial blocker (Cook® Critical Care, Bloomington, IN, USA). The use of the Fogarty catheter for lung isolation is well described and has been used for all types of thoracic procedures [24–27]. The catheter can be placed either alongside the standard ETT or within it. If it is to be placed outside the ETT, the catheter is advanced under direct laryngoscopy through the vocal cords. The blocker catheter tip (which if larger than 3F can be slightly flexed; see Fig. 50.2) is then rotated 90° toward the desired lung and advanced into the mainstem bronchus. The ETT is then placed in the trachea. With fiberoptic visualization, the position of the catheter can be verified prior to inflation of the balloon tip. The entire apparatus is then secured to the patient.

If the Fogarty catheter is to be placed within the lumen of the ETT, the method of placement is as follows. As described earlier for selective endobronchial intubation, the ETT is advanced into the desired bronchus. The 15 mm adapter is removed from the tracheal tube, and the Fogarty catheter is placed through the lumen of the ETT into the bronchus. The ETT is withdrawn to a position above the carina while maintaining the endobronchial position of the catheter. Again verification and inflation of the Fogarty should be performed under flexible fiberoptic visualization. The ETT adapter will then have to be securely fastened such that the Fogarty is trapped between the adapter and ETT itself (see Fig. 50.3). A disadvantage of placing the Fogarty within the lumen of the ETT is that it may significantly decrease the internal diameter. This can interfere with ventilation if using a very small ETT, but more commonly it will make passage of the fiberoptic scope difficult. The fit of all scopes and airway devices must be prepared and tested prior to anesthetic induction.

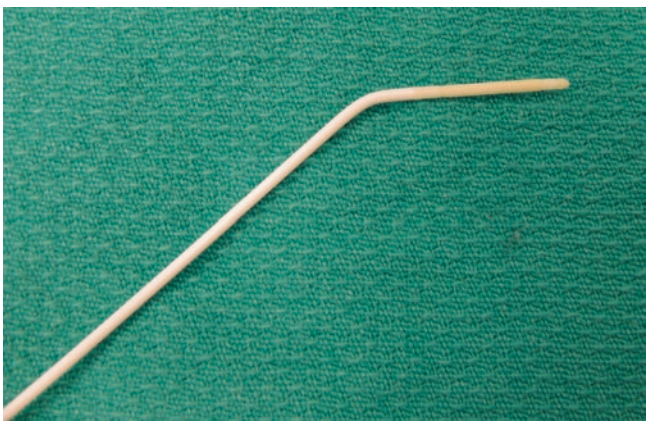

Fig. 50.2 Tip of a size 4F Fogarty embolectomy catheter (Edwards Lifesciences, Irvine, CA, USA) which has been shaped to facilitate maneuverability and insertion into a mainstem bronchus. All Fogarty embolectomy catheters except the size 2F and 3F contain a removable guide wire that can be used to shape the tip in this fashion

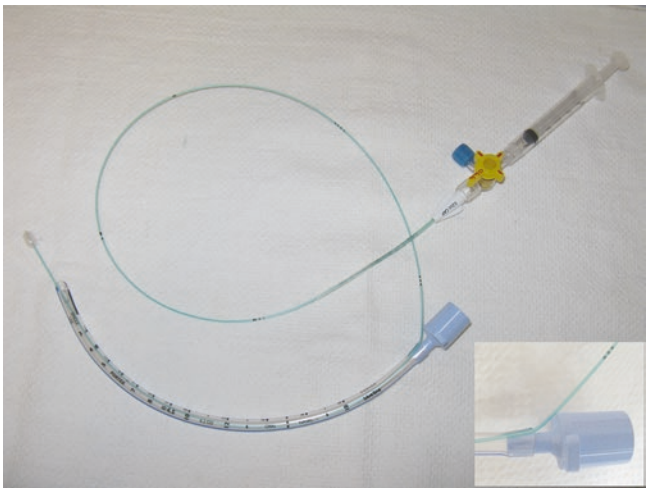

Fig. 50.3 Embolectomy catheter and tracheal tube assembly used for lung isolation in the small child. A size 3F Fogarty embolectomy catheter (Edwards Lifesciences, Irvine, CA, USA) inserted through a 4.5 mm ID tracheal tube (Sheridan) and placed in a mainstem bronchus. The embolectomy catheter is secured in place and sealed between the tracheal tube inner lumen and the 15 mm adapter (inset). Alternatively, the embolectomy catheter may be placed outside the tracheal tube in the mainstem bronchus

Table 50.2 Bronchial blocker sizes used for lung isolation in children

Age	ETT size (ID, mm)	Bronchial blocker size (F)[a]	Max balloon gas capacity (cc)	Inflated balloon diameter (mm)
<2 months	3.0–3.5	3	0.6	5
2–6 months	3.5–4.0	4	1.7	9
6 months–1 year	4.0	4	1.7	9
1–2 years	4.0–4.5	5	3.0	11
2–4 years	4.5–5.0	5	3.0	11
4–6 years	5.0–5.5	5	3.0	11
6–8 years	5.0–5.5 cuffed	6	4.5	13
8–10 years	5.5–6.0 cuffed	6	4.5	13

Abbreviations: ETT endotracheal tube, *ID* internal diameter
[a]Fogarty arterial embolectomy catheters (Edwards Lifesciences, Irvine, CA, USA)

The main advantage of the Fogarty catheter is that it can be used in very small infants as well as older children. Table 50.2 outlines the various embolectomy catheter sizes as well as the corresponding appropriate tracheal tube sizes used in pediatric practice. In general, the smaller the patient, the more challenging proper catheter placement becomes. Deflation of the balloon tip will enable easy and rapid reexpansion of the operative lung without requiring manipulation of the ETT.

A drawback to the Fogarty catheter is that the balloon is a low-volume, high-pressure device. For this reason, balloon inflation should be done under direct visualization and only the minimum of pressure be applied to provide bronchial sealing. Table 50.2 illustrates the maximum inflation volumes of the various embolectomy catheters. Since migration of the blocker by even a few millimeters can cause the balloon to slip into the lumen of the trachea and obstruct both lungs, one must be vigilant and prepared to immediately intervene by deflating the catheter cuff.

The Univent® tube has been designed with a channel that contains a bronchial blocker. Conventional laryngoscopy places the single-lumen tube into the trachea, and fiberoptic guidance of the balloon-tip catheter into the operative lung can then be performed. When seated appropriately, the Univent will isolate the lung and allow for easy conversion to conventional two-lung ventilation by simply deflating the bronchial cuff.

Pediatric sizes are available as small as 3.5 mm internal diameter. However, this device has an 8 mm external diameter and as such should not be used in patients less than 6 years old. In these smaller tube sizes, the bronchial blocker and its channel will also encroach into the lumen of the ETT and proportionally increase the airflow resistance as well as necessitate the use of a smaller fiberoptic scope. Univent® tubes below 6.5 mm ID do not have a central lumen in the bronchial blockers. Therefore, oxygen and CPAP cannot be applied with the smaller Univent® tubes [28–30].

The Arndt endobronchial blocker is a more recent addition to the armamentarium available to the pediatric anesthesiologist [31–33]. It consists of a conventional blocker with balloon tip and four-way adapter. The balloon is designed as a high-volume low-pressure system. Pediatric sizes include a 5F and 7F size blocker which can be used in a 4.5 and 6.5 mm ID tracheal tube, respectively (Table 50.3). Preparation and use of the Arndt endobronchial blocker are identical to that for adults (see Chap. 16).

A unique challenge of using the pediatric-sized Arndt blocker is adequate ventilation while the blocker and FOB both occupy the lumen of the ETT. The smallest-sized FOB must be used that allows placement of the endobronchial blocker. If such a small (i.e., 2.2 mm OD) fiberoptic bronchoscope is not available, the blocker can be positioned outside the ETT much like an embolectomy catheter. The tip of the FOB is passed through the nylon loop of the blocker, and the assembly is inserted in the operative bronchus. The FOB

Table 50.3 Pediatric Arndt endobronchial blocker sizes[a]

Blocker size (F)	ETT size (ID, mm)	FOB size (OD, mm)	Balloon inflation volume (cc)
5.0	≥4.5	≤2.8	0.5–2.0
7.0	≥6.5	≤3.5	2.0–6.0

Abbreviations: ETT endotracheal tube, *ID* internal diameter, *OD* outer diameter
[a]Cook® Critical Care, Bloomington, IN, USA

is then removed and the tracheal tube placed using direct laryngoscopy. Alternatively, if the patient remains adequately oxygenated and ventilated with the FOB-blocker apparatus in the operative bronchus, the FOB may be withdrawn to a position above the blocker, and inflation of the blocker cuff can be observed prior to removing the FOB. Once in position the nylon guide can be removed from the bronchial blocker (it cannot later be reinserted), and the central channel can be used for suctioning, providing supplemental oxygen, and CPAP. Fuji Systems (Tokyo, Japan) has recently released a 5F pediatric size of its independent bronchial blocker, the Uni-Blocker®.

The double-lumen endobronchial tube (DLT, Bronchopart®; Rüsch Inc., Duluth, GA, USA) differs significantly from the above designs in that selective intubation of either mainstem bronchus can be achieved with a second lumen located within the trachea. In this way, ventilation can be applied through either lumen individually or collectively. Unfortunately, pediatric sizes are limited due to the necessarily larger outer diameter of such a design. The 26F is currently the smallest available size and has an outer diameter of 9.3 mm, equivalent to a 6.5 mm ID ETT [34]. It is suitable for children approximately 8–10 years of age or approximately 30 kg in weight. Below this, one of the aforementioned isolation techniques is more appropriate. Double-lumen tube sizing will depend on the child's height as well as age. In general, a 28F DLT is suitable for a 12-year-old child, a 32F is appropriate for a 14-year old, and a size 35F is suitable for a 16-year old.

The DLT is straightforward in its application. Conventional laryngoscopy places the device into the trachea where it can be advanced into position by rotation to the appropriate side in a manner identical to that for adult patients. Fiberoptic bronchoscopy is recommended to ensure proper positioning [35]. Most often a left-sided DLT is used as it is easier to insert and eliminates the risk of right upper lobe obstruction. Correct positioning will mean the bronchial lumen is within the appropriate mainstem bronchus and the tracheal lumen above the carina. Inflation of the bronchial cuff can be observed with the FOB placed within the tracheal lumen. Once inflated the specialized circuit adapter can be manipulated such that ventilation to that lumen is obstructed while egress of gases from the lung is permitted.

Advantages of the DLT include easy access to either lung for suctioning or ventilation, application of supplemental oxygen, and CPAP. Conversion to two-lung ventilation is rapid and simple. Disadvantages of the DLT are mainly due to its awkward size and shape. Iatrogenic injury has been reported, and placement in patients with a difficult airway may be particularly challenging [36, 37]. The DLT should be replaced with a conventional ETT if postoperative ventilation is required.

Anesthetic Management of Specific Procedures and Diseases

Bronchoscopy

Evaluation of the airway by bronchoscopy, either rigid or flexible, has both diagnostic and therapeutic indications [38]. It is one of the few pediatric thoracic procedures that can be performed outside of the operating room under sedation or general anesthesia. In fact, depending on the age of the patient and indication for bronchoscopy, the anesthesiologist may not be involved at all, as some pediatric pulmonologists will provide airway topicalization and intravenous sedation in an ambulatory setting. This approach should be reserved for older, cooperative children who do not have severe respiratory compromise. Those patients that do require operative bronchoscopy must be evaluated with particular focus on the reason for bronchoscopy and the level of respiratory derangement. The type of procedure will often determine the means by which the airway is maintained, the type of anesthetic to be given, and whether paralysis is warranted. Rigid bronchoscopy for foreign body removal will require that a general anesthetic be given. Diagnostic evaluation of the trachea and bronchi for other etiologies can generally be performed via flexible bronchoscopy. Communication between the bronchoscopist and anesthesiologist is essential in any such shared airway case. An appropriately sized ETT or supraglottic airway should be selected for the specific fiberoptic bronchoscope in order to ensure ventilation can be maintained during bronchoscopy.

Older children who are able to understand and cooperate with the anesthesiologist and bronchoscopist can be successfully managed with airway topicalization and intravenous sedation. This can include an infusion of one or a combination of propofol, remifentanil, or ketamine, with or without midazolam [39–43]. More recently, an infusion of dexmedetomidine and propofol has been used in this setting [44]. Although ideally this should be carried out in the OR setting, such procedures are now frequently performed outside the operating room to contain costs and increase efficiency. Children tend to need a deeper level of sedation than adults in order to tolerate the bronchoscope, and titrating the sedation/anesthesia to achieve acceptable procedural conditions while maintaining spontaneous respiration can be challenging. Monitoring and preparation for possible conversion to a general anesthetic are essential. A second physician for patient monitoring and airway management should be at hand.

For those patients that are not suitable for sedation and airway topicalization, several options for airway management exist. These include but are not limited to mask ventilation, laryngeal mask, endotracheal intubation, and

ventilation through the side port of a rigid bronchoscope [45]. Face mask ventilation has an advantage over the other methods listed as it allows for fiberoptic inspection of the oropharynx and/or nasopharynx and can be managed by one of two methods. The simplest is intermittent bag-mask ventilation or support with bronchoscopy conducted while the mask is temporarily removed from the patient. This requires coordination between the anesthesiologist and bronchoscopist and may involve periods of hypoventilation or apnea. If an inhalation agent is chosen as the means of anesthesia, then both awareness and waste gas pollution are a concern as the patient will be exhaling the agent into the room during the procedure. Careful titration of TIVA may therefore be the preferred approach for this option [46]. In addition, the diagnostic value of the procedure may be impaired as the bronchoscopist must enter and exit the airway repeatedly. To overcome these limitations, face masks with angled side ports have been developed that allow for continuous application of the mask to the patient and ventilation through the adapter, while the bronchoscopist uses an inline diaphragm that minimizes gas leakage (Fig. 50.4).

Although the laryngeal mask does not allow for inspection of the upper airway, it has nevertheless become the most commonly used conduit for diagnostic and therapeutic bronchoscopy in the pediatric patient outside the critical care unit [47]. The availability of smaller sizes and its ease of use make it ideally suited for this procedure. It is better tolerated than a tracheal tube and accommodates both spontaneous ventilation and positive-pressure ventilation as required. It has been shown in several studies to be well suited for bronchoscopy, even in small infants [48–50]. An angled adapter with an inline diaphragm for the bronchoscope is required. If the LMA has aperture bars, they may need to be removed as they can impair the scope from passing through. In most cases, the bronchoscope will align itself with the glottic opening and not require any further manipulation of the LMA once seated.

Fig. 50.4 Pediatric endoscopy mask (VBM Medizintechnik GmbH, Sulz, Germany) designed to allow simultaneous ventilation and endoscopy of the child. The assembly may be used for flexible fiberoptic intubation or airway endoscopy

Endotracheal intubation provides the most secure, stable, and controlled means of airway management for bronchoscopy. The majority of children in the critical care unit undergoing bronchoscopy will have an ETT in situ and undergo bronchoscopy to assess bronchial patency or pathology, tracheomalacia, and for sputum sampling. Outside the critical care unit, elective tracheal intubation for bronchoscopy may be preferred for infants and small children as well as patients with significant respiratory compromise. A period of postoperative ventilation may also be required for high-risk patients. Disadvantages of bronchoscopy through an ETT include the inability to examine the upper airway as well as bronchoscope size limitations. An appropriately sized scope must be chosen that allows adequate ventilation around itself in the remaining lumen of the ETT.

Rigid bronchoscopy offers the advantage of allowing dynamic examination of the airway from the oropharynx to the subsegmental bronchi. Most pediatric rigid bronchoscopes contain a 15 mm side port that allows for gas insufflation and even positive-pressure ventilation. It is the instrument of choice for pediatric foreign body removal. Disadvantages of rigid bronchoscopy include the fact that deep anesthesia is required to tolerate the bronchoscope and, if volatile anesthetic agents are used, room air contamination is a concern. In that case, suction or gas scavenging can be positioned at the base of the bronchoscope to minimize contamination. The practice of many pediatric anesthesiologists is to therefore use a propofol-based TIVA technique with local anesthetic applied to the vocal cords and carina. To this end a low-dose remifentanil (0.05 μg/kg/min) or dexmedetomidine (0.5–2.0 μg/kg/hr) infusion may be a useful adjunct. Typical goals are to maintain spontaneous ventilation without the use of muscle relaxants. However, positive-pressure ventilation can be applied via the side port of the rigid bronchoscope which may be facilitated by muscle relaxation.

Fever is not an uncommon sequela of flexible bronchoscopy, and it is not necessary to treat all such patients with antibiotics. Case reports of fever associated with sepsis following bronchoscopy have been reported; however, these are generally in immunocompromised patients in whom antibiotic therapy is warranted [51, 52]. Similarly rigid bronchoscopy has been shown to induce transient bacteremia, but again antibiotic treatment is generally unnecessary. Complication rates for bronchoscopy are low. The most common adverse event is transient desaturation; however, laryngospasm and bronchospasm can also occur [53, 54].

Thoracotomy and Video-Assisted Thoracoscopic Surgery (VATS)

Traditionally, all thoracic procedures in children were performed via a thoracotomy or median sternotomy. Mechanical retraction of the ribs and lung tissue would often be applied to provide the required surgical exposure. Because of technological advances and greater surgical experience gained from the adult population, video-assisted thoracoscopic surgery (VATS) is now used more readily in the pediatric population, even at the extremes of age and weight (Fig. 39.5) [55–58]. The reported advantages of VATS in the adult population, including less postoperative pain and shorter length of stay, accelerated the use of this technique in children. Although very few outcome studies have been conducted in children, VATS is utilized for an increasing number of conditions including empyema, lung biopsy and resection, mediastinal mass, trauma, pulmonary sequestration, and CCAM (Fig. 50.1) [59]. Even PDA closure is being performed thoracoscopically in very small infants [60]. Trocars for pediatric use are available in 5 and 3 mm diameters (Fig. 50.5).

Whereas thoracotomy does not always require the lungs be isolated in children, VATS is quite challenging without proper lung isolation and collapse of the surgical lung. An exception is in small infants, whose lungs can be collapsed with the induced capnothorax.

Single-lung ventilation in the pediatric population incurs many of the same physiologic derangements as in the adult population (see Chap. 6). Collapse of the nondependent lung preferentially directs ventilation to the dependent (nonsurgical) lung. Hypoxic pulmonary vasoconstriction (HPV) in the nondependent lung increases perfusion to the dependent lung and therefore attempts to correct the shunt. In adults with the diseased lung in a nondependent position, this arrangement may actually improve oxygenation. Unfortunately in infants and neonates, this is often not the case. A compliant rib cage and compressible lung parenchyma allows for mediastinal excursion into the dependent lung thus reducing ventilation of that lung. Poor positioning and increased insufflating pressures will further contribute to this. Decreased hydrostatic pressure gradients between the two hemithoraces translate into relatively little improvement in V/Q matching even when HPV is intact. Moreover, alveolar collapse occurs more readily in infants as FRC approaches residual volume. The higher ratio of oxygen consumption to FRC, as compared to adults, will further exacerbate deoxygenation.

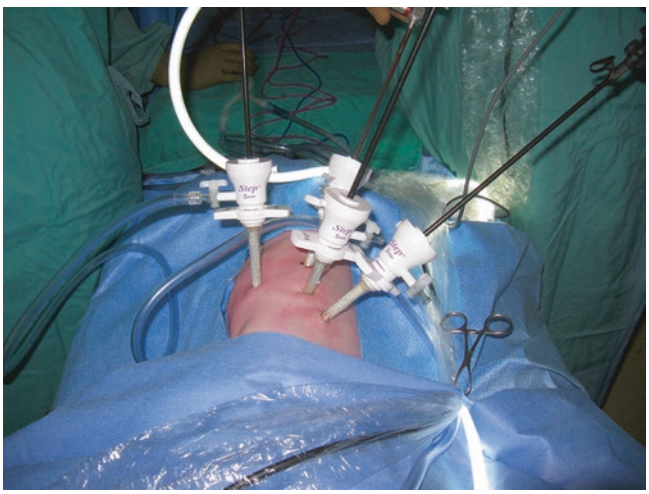

Fig. 50.5 Thoracoscopic trocars inserted in an infant for VATS. Surgical trocars used in children are available in 5 mm (shown) and 3 mm diameters

Many of the same complications of VATS occur in the pediatric population as in adults. Trocar misplacement (into the spleen or liver) may cause significant morbidity. High thoracoscopic insufflating pressures will decrease cardiac output and blood pressure by reducing preload and afterload. Patient positioning is even more important in pediatric procedures as an inappropriately located bolster will easily compress the compliant rib cage and reduce lung volumes in the dependent lung. Abdominal compression in the lateral decubitus position, from padding or "bean bags," will force the abdominal contents into the chest. As with any procedure that involves CO_2 insufflation under pressure, CO_2 gas embolism, though rare, must be considered in the event of sudden severe hemodynamic derangement.

As in adults maneuvers to preserve and treat hypoxemia with single-lung ventilation apply equally in the pediatric setting. Initial routine use of 100% oxygen upon lung isolation offers an increased safety margin and decreases HPV of the dependent lung. Once the procedure is underway and hemodynamic stability confirmed, the FiO_2 may be decreased as tolerated. Pressure-controlled ventilation may be used provided it delivers volumes in the range of 5–10 mL/kg. To this end mild hypercapnia is permitted, to avoid barotrauma. The application of PEEP to the dependent lung may improve oxygenation and if kept to <10 mmHg usually has minimal effects on PVR and does not divert blood flow away from the ventilated lung. Application of CPAP to the nondependent lung is not as practically applicable in the small child and often interferes with surgical exposure.

To conclude, the decision to proceed with a thoracotomy vs. VATS procedure must be discussed ahead of time by surgeon and anesthesiologist. A thorough understanding of the risks and benefits must be assessed by both teams and then explained to the parents/patient. A discussion between the anesthesiologist and surgeon must include a time line with respect to how long the VATS technique will be employed. If surgical goals are not met during this time line, then conversion to thoracotomy should be considered. Most importantly, emergency management of intraoperative bleeding must be

discussed and a plan formulated for emergent conversion to thoracotomy. Pediatric patients, especially small infants and neonates, will very rapidly hemorrhage into the chest cavity. By the time thoracotomy is performed and surgical control of bleeding is established, significant morbidity may have occurred. Resuscitation, even with rapid/immediate transfusion, is extremely difficult in such cases. A low threshold is recommended for release of capnothorax and possible immediate conversion to thoracotomy if significant hemodynamic instability arises.

Empyema

Pediatric pleural effusions are most often infectious in nature with 50–70% being parapneumonic [61]. Other less common causes of pleural effusions, including those associated with renal disease, malignancy, and congenital heart disease, will not be discussed in this section.

There are three generally accepted stages of empyema formation. Stage one is *exudative* with a small volume of sterile fluid accumulation and neutrophil recruitment. Stage two involves bacterial translocation across the now damaged pleural endothelium followed by further neutrophil activation. This *bacterial invasive stage* is characterized by fibrin and collagen fluid loculations. The pleural chemistry will now be acidic as glucose is metabolized and carbon dioxide and lactic acid levels increase. The final stage of *organized empyema* formation results in a thick purulent fluid, filled with cellular debris and deposition of a pleural "peel" along the membrane.

Aside from clinical examination, the most common investigational techniques will involve two-view chest X-rays and ultrasonography (US). US has the advantage of being able to quantify the fluid, indicate loculations, and locate ideal insertion sites for drainage tubes. Computed tomography can also provide detailed assessment of the pleural space but is not usually indicated.

Medical management is still the mainstay of management of parapneumonic effusions in most institutions [62], although early surgical intervention with VATS is associated with shorter hospitalization and equivalent clinical outcomes [63].

Empiric antibiotic therapy is initiated based on the common bacterial pathogens as determined by patient demographics and known community pathogens. Common pathogens include *Streptococcus pneumonia*, *Streptococcus pyogenes*, *Staphylococcus aureus*, *and Haemophilus influenza* [64]. Retrospective case analysis shows that approximately one-quarter of cases will be successfully managed with antibiotic therapy alone [65]. Fine needle thoracentesis and/or small-bore chest tube drainage is required in the remaining cases.

Clinical pathways for pleural effusion drainage are typically institutionally driven and based on the most recent literature. Several different groups have proposed indications for chest drainage [66]. Any effusion greater than 1 cm or 25% of the width of the hemithorax on US or CXR or ongoing respiratory distress despite adequate antimicrobial coverage may warrant small-bore drainage tube insertion. This is typically achieved in the interventional radiology suite with IV sedation and local anesthetic infiltration at the insertion site. Most commonly the use of midazolam, ketamine, dexmedetomidine, and/or fentanyl in titrated doses is sufficient, although sedating doses of propofol will be tolerated by most patients. Nasal prong oxygen and standard monitoring are employed.

If the effusion persists despite drainage tube insertion, it is typically a result of loculation and fibrin deposition. The initial approach is to instill a thrombolytic agent (e.g., streptokinase, urokinase, tPA) through the chest tube into the pleural space. This will ideally break down the adhesions and facilitate further drainage [67]. Approximately 15% of patients will require multiple fibrinolysis treatments [65].

Failure of clinical improvement or progression of fluid accumulation will necessitate discussion regarding surgical decortication. Three percent of patients may require such surgical intervention following conservative medical management [68]. Surgery can be accomplished by open thoracotomy or more commonly video-assisted thoracoscopic surgery (VATS). At this stage the empyema has likely developed a thick fibrous plaque that prevents collapse of the affected pleural space. As such lung isolation is not routinely applied. Trocar insertion into the pleural space is performed without the need for lung isolation as the empyema fluid and thickened pleura have created a fluid-filled space with the affected lung collapsed away from the chest wall.

Anesthetic monitoring of these patients includes conventional noninvasive monitors with the addition of an arterial line if clinically warranted. As blood transfusion may occasionally be required, adequate venous access is essential. Induction of anesthesia is usually not complicated, although these patients may have significant respiratory distress.

In most cases, tracheal extubation and transfer to a monitored ward bed are sufficient; however, these patients may require postoperative ventilation. Intravenous antibiotic therapy should be continued. Most children will recover uneventfully with full resolution of symptoms and no ongoing sequelae.

Patent Ductus Arteriosus (PDA)

Surgical PDA repair is perhaps the most common cardiac procedure to be managed by the noncardiac specialized pediatric anesthesiologist. As technology and surgical technique

have evolved, so too has the surgical management of this disease. The historic use of a large lateral thoracotomy has today been replaced by smaller muscle-sparing "mini" thoracotomies. Moreover, many centers have established good success rates with the VATS technique [60, 69]. Percutaneous coiling of the PDA via interventional angiography is also widely available but will not be discussed herein [70, 71].

The ductus arteriosus is an essential conduit directing blood flow away from the high-pressure pulmonary circulation toward the systemic circulation during fetal development. It most often arises at the anterior surface of the main PA and attaches to the descending aorta near the left subclavian artery. In response to the increased PaO_2 after birth, the musculature of the ductus constricts and effectively closes the structure. Smaller birth weight infants and premature infants are more likely to have persistently PDA. If left untreated the left-to-right shunt created by the PDA will result in pulmonary overcirculation, pulmonary edema, and respiratory insufficiency. RV failure may also develop, especially if pulmonary pressures increase. Rarely, this may result in shunt reversal. In children who have a hemodynamically stable PDA, closure is still required as the risk of bacterial endocarditis is quite high [72].

If significant pulmonary overcirculation exists, the patient may require tracheal intubation in NICU to help support ventilation prior to surgery. These patients may often be fluid restricted and given diuretics in order to help alleviate the resultant pulmonary valvular insufficiency. To this end, inotropic support will also occasionally be required. Surgical stress will further strain the already compromised preexisting respiratory and hemodynamic status. Likewise, any preexisting medical condition or syndrome should be evaluated prior to induction of anesthesia. Whether performed via mini thoracotomy or VATS, surgical closure of a PDA is usually of short duration (<1 h typically) and involves minimal blood loss. In order to assess the blood flow in both the ascending (preductal) and descending (postductal) aorta, a noninvasive blood pressure cuff may be placed on a lower limb with an oxygen saturation probe applied to both the right hand and the left foot. Invasive arterial measurement is no longer routinely required. When identification of the PDA is difficult, the surgeon may place temporary clips across the vascular structure and observe the effects on the patient. Correct positioning across the PDA will result in a rise in diastolic pressures, whereas occlusion of the main PA will result in decreased oxygen saturation and $ETCO_2$. Temporary occlusion of the descending aorta will result in a sudden loss of lower extremity saturation tracing and blood pressure while simultaneously preserving the preductal saturation.

Induction of anesthesia is dependent on the preexisting condition of the patient. Those that present with respiratory or hemodynamic compromise may typically receive a high-dose narcotic (e.g., fentanyl 10–20 μg/kg IV) at induction with muscle paralysis. Minimal volatile anesthetics should be used in these cases, and supplemental narcotic dosing may be given as required. Alternatively, a remifentanil infusion along with low volatile anesthetic concentration may be used in those patients suitable for postoperative tracheal extubation. In addition to the standard intravenous used for induction, a larger peripheral intravenous catheter should be inserted after induction. Blood should be available in the operating theater for fluid resuscitation in the event of surgical misadventure. Open thoracotomy for PDA closure does not require lung isolation or single-lung ventilation. Simple retraction is sufficient to provide surgical exposure. Recent studies, however, have shown the efficacy of the VATS approach to PDA repair [73–76]. Ventilatory strategies for this include lung isolation (by any technique described earlier) or placement of a single-lumen ETT and allowing the pneumothorax to dictate surgical exposure. Muraldihar et al. [77] evaluated right mainstem bronchial intubation vs. low tidal volume high-frequency ventilation of both lungs and showed more profound desaturation in the mainstem intubated patients. Miyagi et al. [78] reported on the successful use of the Fogarty catheter as a bronchial blocker for a series of PDA closures performed via VATS. Despite the potential for hemorrhage, many studies have shown the safety and efficacy of this surgical approach for the repair of PDA [79]. Risk factors, regardless of approach, continue to be hemorrhage, residual patency, and recurrent laryngeal nerve injury. Odegard et al. [80] describe a simple yet effective means to identify the recurrent laryngeal nerve and thus prevent injury during VATS procedures by using a thin Teflon nerve-stimulating probe and recording the evoked electromyograms.

Tracheoesophageal Fistula (TEF)

The incidence of TEF is approximately 1 in 3000, and although it may occur in isolation, about 50% of cases will present in association with other congenital anomalies [81]. The VACTERL association (vertebral, anal, and cardiovascular defects, TEF, renal and radial limb defects) has been well described [82, 83]. The most commonly associated cardiac defects are atrial septal defect, PDA, and tetralogy of Fallot [84]. Investigation of these defects is essential prior to any surgical intervention. The trachea and esophagus are derived from the primitive foregut during the fourth and fifth weeks of life. The trachea emerges ventrally from the primitive foregut, and a septum between the esophagus and trachea is created by fusion of the tracheoesophageal folds. Failure of incomplete separation of these two structures can result in isolated esophageal atresia (rare) or more commonly TEF. The Gross classification describes six of the most common forms of TEF [85]. Type C, accounting

for 85% of all cases of TEF, consists of a fistula located slightly above the carina with proximal esophageal atresia. It is suggested shortly after birth with copious salivation associated with choking, coughing, and cyanosis coincident with the onset of feeding. Diagnosis is confirmed by the inability to pass a suction catheter into the stomach, and a gastric air bubble is often visible on radiograph. In most patients, surgical intervention will be planned for within the first week of life. During this time, these patients should be kept in a head-up or lateral decubitus position with a nasoesophageal suction catheter inserted to help prevent aspiration. Early tracheal intubation is rarely required. In otherwise healthy newborn infants, there is almost 100% survivability. Survival declines rapidly if TEF is associated with low birth weight, prematurity, cardiac anomalies, or pulmonary complications [71, 86].

Primary repair consists of fistula ligation and esophageal anastomosis. Occasionally, a staged repair will be required in patients that are unstable and premature or have very low birth weight. This consists of placement of a balloon-tip catheter into the distal esophagus via percutaneous gastrostomy under local anesthesia [87]. This temporizing measure helps prevent reflux and will enable more efficient ventilation, particularly if high airway pressures are required. When the patient becomes more stable, the definitive repair can be performed. This has traditionally been undertaken through a thoracotomy on the side opposite the aortic arch. Fistula ligation is followed by esophageal anastomosis. If the two ends of the esophagus are separated by too great a distance, the fistula is ligated, and a section of the colon can be interposed at a later date. Thoracoscopic repair has been described, and in some centers it has become the preferred surgical approach [88, 89].

Anesthetic management begins with the understanding that positive-pressure ventilation should be minimized on induction. If the fistula is large, pressurized gas flow will follow the path of least resistance through the fistula and into the stomach. This will cause gastric dilatation leading to further impairment of ventilation and possible reflux of gastric contents into the lungs. Profound respiratory failure and cardiac arrest have been reported. The goal of induction is to place the ETT distal to the fistula and proximal to the carina. This is often accomplished by blind mainstem intubation and subsequent retraction of the ETT until bilateral breath sounds are auscultated. Many centers now advocate initial rigid bronchoscopy with the patient breathing spontaneously under volatile or intravenous anesthesia in order to identify the size and location of the fistula prior to tracheal intubation. Flexible fiberoptic bronchoscopy may also be used to verify tube positioning following tracheal intubation. Prior to induction the patient should have thorough suctioning of the esophageal catheter and be well preoxygenated. Pretreatment with atropine is recommended. Traditionally, an awake tracheal intubation would have been performed on these patients. More recently, pediatric anesthesiologists prefer to induce anesthesia with inhaled volatile anesthetic while maintaining spontaneous respiration or alternatively, perform a rapid sequence induction. Once the ETT is carefully positioned to ensure lung ventilation without fistula insufflation, muscle relaxation and gentle positive pressure can be provided. Some anesthesiologists will prefer not to paralyze or provide positive-pressure ventilation until the fistula is ligated. For thoracoscopic TEF repair, lung isolation is generally not attempted. Anesthetic induction and tracheal tube placement are as for open repair; however, maintaining spontaneous respiration until the fistula is ligated is impractical. The induced pneumothorax/capnothorax often produces adequate surgical exposure.

Intraoperative monitoring consists of the usual noninvasive monitors and possibly an arterial line. A large peripheral intravenous for fluid resuscitation should be obtained. A precordial stethoscope placed in the left axilla will help identify movement of the ETT into the right mainstem bronchus. The flexible fiberoptic bronchoscope should be available as it may be required to confirm intraoperative tube placement. Tracheal suction catheters should be on hand as surgical manipulation of the nondependent lung may cause debris or secretions to obstruct the ETT.

Intraoperative complications usually consist of ventilation difficulties, leading to hypoxemia and/or hypercapnia. Increasing FiO_2, adjusting ventilatory settings, and providing muscle relaxation may help improve this. Occasionally, and more commonly during thoracoscopic procedures, a degree of hypercapnia and desaturation must be tolerated. Although some of the most robust patients may be suitable for postoperative tracheal extubation, most will benefit from a short period of elective ventilation. The tracheal tube is carefully withdrawn to a position proximal to the fistula, and the nondependent lung is gently reexpanded under direct vision. The hemithorax is simultaneously filled with warmed saline to ensure there is no air leak from the repaired fistula site. Early postoperative complications include atelectasis, increased airway secretions causing small airway collapse, and electrolyte disturbances associated with increased fluid requirements. Later complications include esophageal anastomotic leak, formation of bronchoesophageal fistula, and esophageal stricture formation [90].

Mediastinal Mass

Management of the pediatric patient with a mediastinal mass presents unique and serious challenges to the anesthesiologist. A common misconception is that a mediastinal mass is more likely to cause symptoms in children compared to adults [91]. In fact children are less likely to be symptomatic

compared to an adult [92–94]. The presence of symptoms may be predictive of malignancy in the adult; however, this does not seem to hold true for children [95]. A finding of orthopnea (supine dyspnea) in the child may be predictive of significant tracheal narrowing [96, 97], and its presence should alert the clinician to the possibility of airway obstruction upon induction of anesthesia. The presence and degree of orthopnea should be assessed in every patient. The older child with mild symptoms can lie supine with some cough or pressure sensation. The patient with moderate symptoms will only be able to lie supine for short periods, and the severely symptomatic patient will not tolerate the supine position [98]. Characterizing the degree of orthopnea in the infant or small child is more challenging. The infant without symptoms will not seem stressed when supine, whereas the mildly symptomatic infant may look frightened or upset when supine. It is difficult and of little clinical use to attempt to distinguish between moderate or severe symptoms in the small child or infant. In either case, the infant will look severely distressed, may be gasping, or even cyanotic when supine.

Despite the predictive value of orthopnea in older children with a mediastinal mass, life-threatening complications may occur in the absence of symptoms, particularly in infants and small children [99].

The other major complication is cardiovascular collapse secondary to compression of the heart or major vessels. The presence of a pericardial effusion is associated with an increased risk of cardiovascular complications during anesthesia [100]. Death upon induction of general anesthesia in patients with an anterior mediastinal mass is always a risk. Anesthetic deaths have mainly been reported in children [101]. This may be due to the fact that:

1. Children have a more compressible cartilaginous airway structure.
2. The presenting signs and symptoms correlate poorly with tumor size.
3. Children are less able to give a reliable history.
4. Children more often receive a general anesthetic for tissue biopsy.

Diagnosis and Risk Stratification

The most important diagnostic test in the patient with a mediastinal mass is CT of the trachea and chest. Although a chest X-ray is often helpful in detecting a mediastinal mass, the CT scan provides useful information such as the size and compressive effects of the mass. For proper tumor staging, however, a CT scan of the chest, abdomen, and pelvis is required. Fortunately, this can be accomplished with an average scan time of under 20 s with the more modern, faster CT scanners. In addition, the patient's head and chest can be elevated to 30° without affecting scan quality. Alternatively, the scan can be done with the patient in lateral or even prone position, if necessary.

It is essential to determine the patient's most comfortable position prior to starting the CT scan. Most patients, including the otherwise uncooperative child, will often assume that position while confined to the hospital bed. Furthermore, many major pediatric centers have adopted the resourceful practice of performing the scan at a time that coincides with that child's natural sleep. Distraction (with music or video) has been used with success in older children. For practical purposes, this means that the scan can be done with the patient in his/her most comfortable position during natural sleep, thus minimizing the need for sedation. The anesthesiologist should never feel compelled to have the severely symptomatic patient lay flat and supine, be deeply sedated, or anesthetized for a CT scan. In such a situation, if the above measures are unsuccessful or impractical, serious consideration should be given to steroid administration or selective irradiation prior to CT in order to reduce the tumor mass.

For those patients that are uncooperative but do not have severe symptoms, sedation may be administered, provided a cautious approach is adopted. Although nothing is absolute, careful titration of a single agent may be safer or preferable to polypharmacy, particularly for small children. A 6-year review of over 16,000 sedations performed on children revealed that the odds of having an adverse event were nearly 5 times higher when multiple agents were used (odds ratio [OR] 4.9, 95% CI 2.9–8.4) [102]. As a single agent, nitrous oxide 50% in oxygen is often all that is needed in small children to provide analgesia and sedation. Alternatively, midazolam or etomidate 0.1 mg/kg, ketamine or propofol 0.25 mg/kg IV boluses, or continuous infusion may be carefully titrated to effect. Although many agree that the risk of airway obstruction and hypoxemia increases when a combination of benzodiazepines and opioids is used [103], sedation even with a single agent may not be tolerated in the high-risk patient [104]. Of equal importance is appropriate monitoring of the patient, early recognition and treatment of complications, and attention to patient positioning during the procedure. The flat, supine position is never mandatory.

Obstruction of the superior vena cava (SVC) causing venous hypertension and engorgement of venous collaterals leading to cyanosis and edema of the head, neck, and upper extremities is known as the SVC syndrome [105]. The most common cause of SVC syndrome in children is primary lymphoma or lymphoblastic leukemia [106]. SVC syndrome is often present without associated airway compromise in the adult with a mediastinal mass. In children with such a mass, however, the SVC syndrome is closely associated with and may predict the development of acute airway compromise. Tracheal intubation may be more difficult due to laryngeal edema that results from SVC obstruction. This obstruction

may also cause pulmonary artery or myocardial compression or affect right ventricular output, causing right heart failure [107]. Anesthetic-induced myocardial depression will aggravate these effects, with potentially disastrous consequences. Cerebral venous drainage and cerebral perfusion pressure may also be reduced in the patient with significant SVC obstruction. As such, any patient presenting with SVC syndrome should be considered high risk. Patients with cardiovascular symptoms and SVC syndrome or those patients unable to give an adequate history should therefore have transthoracic echocardiography to assess for cardiac, systemic, or pulmonary vascular compression.

Historically, children with tracheobronchial compression greater than 50% on CT have been considered high risk for general anesthesia [108]. More recent reviews have found the presence of orthopnea or SVC syndrome may be predictive of anesthesia-related complications [104, 107], but the extent of symptoms do not correlate well with the degree of tracheal narrowing on CT scan [96]. Based on these studies and the authors' clinical experience, the following risk stratification guideline regarding safety for general anesthesia is suggested. The patient with minimal to no orthopnea and near-normal tracheobronchial area on CT scan will likely tolerate general anesthesia. In contrast, the child with moderate to severe orthopnea and tracheobronchial area < 50% of normal on CT scan or the patient with evidence of SVC syndrome or a pericardial effusion should be considered high risk. Unfortunately, there are several patient groups whose risk for general anesthesia remains uncertain. They include the child with mild orthopnea whose tracheobronchial diameter is unknown and older child who is unable to give a history.

Direct examination of mediastinal mass tissue has been the traditional and preferable approach to making the diagnosis. In high-risk or symptomatic patients, however, the risk of general anesthesia and thoracotomy, mediastinoscopy, or VATS may be considerable. Excisional biopsy of extrathoracic lymph nodes has often been sufficient to confirm the diagnosis and allow for appropriate therapy. Increasingly, cytometric and immunocytochemical studies of pleural fluid have also been used with success to secure a diagnosis, obviating the need to deliver deep sedation or general anesthesia. Thoracentesis is particularly useful in lymphoblastic lymphoma, which is associated with a high incidence of pleural effusion [109, 110].

In the high-risk patient without extrathoracic lymphadenopathy or a pleural effusion, percutaneous needle biopsy of the tumor under ultrasound or CT guidance may be a safe alternative [111, 112]. In centers equipped with interventional radiology expertise, core needle biopsies can be obtained under ultrasound guidance with the patient in a semi-upright or lateral position [113, 114]. This can be achieved under local anesthesia and mild sedation as required. The most obvious disadvantage to needle biopsy is the inherent "failure to diagnose" rate due to insufficient tissue for complete histological and molecular classification, although a failure rate exists also for open biopsy [115].

The use of prebiopsy corticosteroid treatment to reduce tumor size has generally been avoided if possible due to the extreme and rapid responsiveness to this (and radiation) therapy. There is widespread belief that prebiopsy steroid therapy will impair accurate histological diagnosis and result in suboptimal treatment or recurrence with a less favorable prognosis. A 10-year review of children presenting with an anterior mediastinal tumor sheds light on and refutes this myth [116]. Twenty-three of the 86 patients in that series received prebiopsy hydrocortisone because of clinical evidence of respiratory compromise. Prebiopsy steroid treatment was felt to have had an adverse effect on the pathological diagnosis in 5 of the 23 children; however, survival in those 5 patients was unaffected, and the authors concluded that prebiopsy steroid administration is defensible in symptomatic patients. In a more recent series, one third of children with a mediastinal mass were treated with corticosteroids prior to diagnosis because they were considered high risk. A clear diagnosis was made in 95% of these patients despite steroid therapy [99]. In these cases, close and ongoing consultation with the oncologist is essential. Prebiopsy steroid therapy may be justifiable (and arguably necessary) if the patient has symptoms and CT evidence of significant airway or cardiovascular compression and is too young or uncooperative to tolerate local anesthetic alone. A typical regimen consists of 20 mg prednisone equivalents per meter square of body surface area, administered three times daily. Coordination between the oncologist, surgeon, and anesthesiologist is essential as biopsy tissue should be obtained between 12 and 24 h after starting steroid therapy. These patients should be monitored and treated in anticipation of developing tumor lysis syndrome, a constellation of metabolic abnormalities which can include hyperkalemia, hyperuricemia, hyperphosphatemia, secondary hypocalcemia, and acute renal failure [117].

Another alternative to preoperative steroids in the high-risk patient includes irradiating the tumor while leaving a small area covered with lead for subsequent biopsy. This is not a viable option for the majority of pediatric patients presenting with a mediastinal mass as it requires the patient be cooperative and able to lie still for the duration of the treatment.

Flow-volume loops are commonly ordered as part of the preoperative assessment for patients with an anterior mediastinal mass. Specifically, the development of an increased expiratory plateau when changing from the upright to the supine position is thought to be pathognomonic for a variable intrathoracic airway obstruction and an indicator of patients who are at risk for airway collapse during induction of anesthesia.

However, a careful examination of the literature reveals that this emphasis on flow-volume loops derives from a single case report [118]. Apart from isolated case reports, studies of flow-volume loops have shown a poor correlation with the degree of airway obstruction [119–121]. The use of flow-volume loops in the assessment of patients with anterior mediastinal masses is well described in standard anesthesia texts and frequently asked on anesthesia specialty exams. However in clinical practice, it is difficult to see how flow-volume loops add any useful information beyond that which is obtained from the history and chest imaging. Certainly flow-volume loops may show some correlation with airway obstruction in selected patients. However, modern chest imaging will tell the clinician not only if there is an obstruction but also its location, severity, and extent. This is the truly vital information in deciding how to manage the airway of a patient with an anterior mediastinal mass.

Although deep general anesthesia and muscle relaxation can be avoided in most patients with symptomatic lesions, invariably the anesthesiologist will be faced with the uncooperative child with a compressive mediastinal mass requiring general anesthesia for a diagnostic or therapeutic procedure. Management of these patients is guided by their symptoms and the CT scan. A stepwise induction of anesthesia with continuous monitoring of gas exchange and hemodynamics is recommended. This may be achieved by inhalation of a volatile agent such as sevoflurane or IV titration of propofol, ketamine, and/or dexmedetomidine which maintains spontaneous ventilation until either the airway is definitively secured or the procedure is completed [122]. Awake intubation of the trachea before induction is a possibility only in older, mature pediatric patients if the CT scan shows a distal area of noncompressed trachea to which the ETT can be advanced before induction. If muscle relaxation is required, ventilation should first be gradually taken over manually to assure that positive-pressure ventilation is possible and only then can a muscle relaxant be administered. In some centers, muscle relaxation is avoided throughout the entire procedure if at all possible, as there have been cases of cardiorespiratory collapse that were likely caused by the resultant loss of muscle tone [123].

Airway or vascular compression can develop at any stage of the procedure and should be anticipated. In the preoperative assessment, the patient will often report that there is one side or position that causes less symptoms of compression. This, along with the findings on chest imaging, should be communicated to the entire operative team prior to anesthetic induction. In the event of intraoperative life-threatening airway or cardiovascular collapse, the patient should immediately be placed in that predetermined position, which will often result in a dramatic clinical improvement. The prone position has also been lifesaving in this setting [124]. Rigid bronchoscopy and ventilation distal to the obstruction may be necessary. As such, an experienced bronchoscopist and rigid bronchoscopy equipment must always be immediately available. In emergent situations, it is often not possible to push a standard ETT distally through the collapsed trachea. Ventilation and oxygenation can be reestablished temporarily with either a ventilating rigid bronchoscope or with jet ventilation via a rigid scope. Ultimately a reinforced ETT should be placed distal to the obstruction to stent the airway. This can be done by passing an airway exchange catheter or bougie distally under direct vision through the rigid bronchoscope, then withdrawing the bronchoscope, and using the airway catheter as a guide for the ETT [125]. In fact it may be reasonable to use an armored tube in all patients with a mediastinal mass; however, a stylet will still be needed to advance the tube distal to the compressed portion of the airway. Depending on the response to the above emergency measures, the patient may have to be awakened as rapidly as possible and other options for surgery explored.

Heliox may be used in the event of subtotal airway collapse to decrease the work of breathing. Heliox is a mixture of helium and oxygen (most commonly 70:30) and decreases the turbulent airflow resistance through a narrowed airway due to the decreased density of helium.

Femorofemoral cardiopulmonary bypass (CPB) before induction of anesthesia is a possibility for older and more cooperative children who are considered "unsafe" for general anesthesia. Although emergency percutaneous CPB has been used successfully in an adult patient with impending complete airway obstruction [126], this is not a practical option in the young, frightened child. In addition, even the smallest femoral bypass cannulae are too large in diameter to be used in the patient weighing less than 15–20 kg. In such a case, preoperative steroid therapy should be considered.

The concept of CPB "standby" during attempted induction of anesthesia is fraught with danger because there is not enough time after sudden airway collapse to establish CPB before hypoxic cerebral injury occurs. It is not a practical option in the pediatric patient with a large anterior mediastinal mass. For patients who present with primarily cardiovascular rather than airway compression, rigid bronchoscopy will not be a useful resuscitation maneuver in the event of cardiovascular collapse. Resuscitation intraoperatively may require emergent sternotomy and lifting the tumor off the heart and great vessels [127]. For this reason, whenever possible, patients with cardiovascular compression should be prepped and draped for surgery prior to induction of anesthesia.

Congenital Diaphragmatic Hernia (CDH)

Congenital herniation of the abdominal contents into the thoracic cavity occurs in approximately 1 in every 2500 live births [128]. The majority of cases will present prenatally if

the mother has undergone standard ultrasonography [129, 130]. Occasionally, the diagnosis will be made in the early postnatal period. Intrusion of abdominal viscera into the thorax during fetal lung development leads to pulmonary hypoplasia and pulmonary vascular hypertension. This may promote persistence of fetal circulation (i.e., patent foramen ovale and PDA) after birth. Most cases of CDH occur on the left side at the foramen of Bochdalek, accounting for 80% of unilateral herniations. Less common is herniation at the foramen of Morgagni or at the esophageal hiatus itself. Mortality is related to the size of the defect and the association of cardiovascular anomalies. Approximately 10–30% of patients with CDH will have other congenital anomalies. These include congenital cardiac disease, chromosomal abnormalities (e.g., trisomy 18 and 21), CNS (e.g., spina bifida, hydrocephalus), and gastrointestinal anomalies (e.g., TEF, malrotation, atresia) [131]. Right-sided hernias are more often associated with these other defects. Large diaphragmatic hernias not diagnosed prenatally will present at delivery with severe respiratory distress and cyanosis. Physical findings include decreased breath sounds unilaterally or bilaterally. Indrawing, nasal flaring, and accessory muscle use indicate impending respiratory failure. Palpation of the trachea often reveals deviation away from the affected side. Peristaltic (bowel) sounds may be heard over the affected hemithorax. Chest X-ray will reveal mediastinal shift away from the affected hemithorax as well as air-filled bowel loops in the chest. The position of a nasogastric tube will be above the diaphragm.

As a result of compression and interference with normal lung development, the affected lung is reduced in volume and hypoplastic. Pulmonary surfactant deficiency contributes to poor lung compliance. This results in poor gas exchange and worsening of hypoxia, hypercapnia, and acidosis. PVR may remain elevated with persistent fetal circulation. High airway pressures and hemodynamic instability can further drive pulmonary hypertension. With elevated PVR and a PDA, right-to-left shunting will occur. Other sites of shunting may also exist depending on the associated cardiac pathology. Systemic hypoxia will continue because of this shunting, and disease progression will accelerate. Without appropriate preoperative support, this cascade of hypoxia, acidosis, increasing PVR, and right-to-left shunt will lead to cardiac dysfunction and patient demise. Routine preoperative echocardiogram is mandated to screen for the aforementioned defects, PVR and ventricular function.

Management strategies for CDH have changed over the last few decades [80, 132]. Currently, preoperative stabilization followed by surgical repair is recommended. That being said the optimal timing of repair is currently debated. Much of the recent work has focused on optimizing hemodynamic and ventilatory support in this patient population [133]. At present no one best strategy has been universally agreed upon. Historically, resuscitative efforts were aimed at achieving alkalosis through active hyperventilation with the goal of minimizing pulmonary vascular hypertension. Contemporary "gentle" ventilation guidelines aim to minimize barotrauma by limiting maximal inspiratory pressures (<25 cmH_2O) and tidal volumes. Much like in the management of adult RSD, a degree of hypoxia and hypercapnia is accepted. Survivability has actually been shown to improve in these patients managed in this way provided PaO_2 is kept at 60 mmHg and $PaCO_2$ approaches 65 mmHg [134–136]. Until invasive arterial vascular access can be gained, one may aim for a preductal oxygen saturation of 85% with postductal saturation of 60%. Failure to achieve these goals with conventional ventilation may be an indication for conversion to high-frequency oscillatory (HFO) or jet ventilation. To facilitate this method of ventilation, judicious use of sedatives, narcotics, and muscle relaxants will be required. Alternatively, progressive hypercapnia and acidosis with an A-a gradient >500 mmHg are indications for ECMO [137, 138].

Pharmacologic adjuncts for the management of pulmonary hypertension have included inhaled nitric oxide, sildenafil, prostaglandins, and prostacyclins [139]. In this case, inotropic support is often required. With improvements in preoperative management, the overall survival rate has been reported as >75% [140].

The anesthesiologist may first become involved during resuscitative efforts at the time of birth. Early insertion of a nasogastric tube will be necessary to decompress the stomach. The reduced volume of air in the stomach will aid ventilatory mechanics. Likewise bag-mask ventilation should be kept to a minimum to avoid further gastric distension. If oxygen saturation continues to decrease despite NG tube insertion and high-flow oxygen, then tracheal intubation is appropriate. Sedatives, narcotics, and muscle relaxants are often administered to facilitate tracheal intubation and positive-pressure ventilation.

Intraoperatively the anesthesiologist must attempt to maintain ventilation and oxygenation as discussed earlier. Conversion from HFO to conventional ventilation should be attempted prior to surgery, although CDH repair is possible with the patient on HFO ventilation [141, 142]. Peak airway pressures should be limited to avoid barotrauma and worsening PVR. A sudden rise in airway pressures or decrease in lung compliance can indicate a contralateral pneumothorax which must be diagnosed and treated promptly as it may be associated with a worse outcome. Anesthetic management typically includes a narcotic and muscle relaxant technique. In addition to basic monitoring, an arterial line (preferably right radial) as well as pre- and postductal oxygen saturation monitors should be placed. Decreasing postductal saturation may indicate worsening right-to-left shunt and increasing PVR. Closure of the diaphragmatic hernia may compromise venous return from the lower extremities, and therefore

intravenous access in the upper limbs is preferred. Insertion of an internal jugular venous line is not essential and risks causing a pneumothorax but if already present can be a useful adjunct for monitoring right-sided pressures and venous oxygen saturation.

Surgery usually consists of an abdominal incision with the herniated contents being reduced into the abdomen. Small defects can then be closed primarily, while larger ones may require the use of a synthetic patch. Closure of the abdomen may also necessitate the use of a patch to avoid cardiopulmonary compromise in the event of elevated abdominal pressures. With reduction complete, the hypoplastic lung should not be aggressively ventilated as this will increase the risk of barotrauma and contralateral pneumothorax and is typically of little or no therapeutic value.

Minimally invasive repair of CDH has been documented in the pediatric population [143]. Unfortunately the literature in favor of this technique likely suffers from patient selection bias (most stable patients selected for this technique). Current consensus statements do not recommend the routine use of minimally invasive repair [143, 144].

Lung Biopsy

Optimum management of solid lung masses almost always requires correct pathological diagnosis via biopsy of the affected tissue. Obtaining such samples, however, can be challenging, especially when dealing with pediatric patients. The traditional method for acquiring these samples has been open lung biopsy, which is associated with morbidity and considerable pain. Increasingly, less invasive procedures such as endobronchial biopsy and image-guided percutaneous biopsy have been used in children [145]. Concerns regarding endobronchial biopsy include bleeding and the histologic adequacy of the sample obtained. Minor mucosal bleeding is common and not of great concern as experience with airway foreign body removal would indicate that minor bleeding of the mucosa is not associated with a worse outcome [146]. Although not all lung masses are accessible via transbronchial biopsy, it is useful as a diagnostic measure in patients with poorly controlled asthma [147], cystic fibrosis (CF) [148, 149], and postlung transplant monitoring [150]. Salva et al. [54] prospectively studied 170 children between the ages of 2.5 and 16 years who underwent flexible endobronchial biopsy for a variety of chronic respiratory conditions. At least three biopsy samples were taken from each patient. These children received a general anesthetic in an ambulatory setting with the use of an LMA (as described earlier). The results were encouraging as no patient required intervention for mucosal bleeding and there were no cases of pneumothorax, hemoptysis, or pneumonia.

Image-guided percutaneous lung biopsy can be performed with CT or ultrasound guidance depending on the location and accessibility of the tumor. Deep sedation with local anesthetic infiltration [151] or general anesthesia can be performed depending on age, cooperation, and medical status of the patient. Disadvantages compared to general anesthesia include the inability to suspend respiration to aide biopsy localization. In a series of CT-guided percutaneous lung biopsies performed in children between the ages of 0.6 and 20 years, most cases were performed successfully with deep sedation. Adequate tissue samples were obtained in 85% of the cases [152]. Perioperative complications that did not require intervention included subclinical pneumothorax (17%), pleural effusion (3%), subcutaneous hemorrhage (12%), and postprocedural hemoptysis (3%). There was one case of tension pneumothorax requiring chest tube insertion. There was no association between adverse events and the number of biopsy attempts. All children received a chest X-ray approximately 6 h after the procedure or sooner as clinically indicated. Despite an overall complication rate of 28%, percutaneous biopsy fares favorably when compared to historic data on surgical open biopsy. Procedure length, overall hospital stay, and procedural costs also tend to favor percutaneous biopsy.

For those patients in whom percutaneous biopsy has failed to yield a diagnosis and those in whom the lung pathology is not amenable to such a technique, surgical lung biopsy is required. This can be performed with open thoracotomy or VATS. Although postoperative morbidity is increased in comparison to percutaneous biopsy, surgical biopsy is still considered by many the gold standard diagnostic tool. Gluer et al. [153] prospectively evaluated the feasibility, efficacy, and safety of the VATS technique for lung biopsy in patients with diffuse parenchymal lung disease. This was performed with general anesthesia using a single-lumen tube without lung isolation. The average age of the 21 patients was 3 years (range 12 days to 15 years). Only two cases required conversion from VATS to mini-thoracotomy, and no other intraoperative complications were noted. Studies comparing thoracoscopic and open lung resection in children have shown comparable success rates, safety parameters, and clinical outcomes [154, 155]. As experience with pediatric VATS procedures increases, we are seeing an increase in the number of biopsy procedures performed using this technique.

Cystic Fibrosis (CF)

Thick inspissated secretions causing airway obstruction, atelectasis, and superimposed pneumonia are some of the pulmonary sequelae of this multiorgan disease. Respiratory dysfunction can be quite pronounced with patients becoming extremely ill. Progression of the disease can lead to cor pul-

monale, pneumothorax, antibiotic-resistant infections, and bronchiectasis. Intestinal malabsorption and pancreatic and liver dysfunction are the most frequent extrapulmonary effects. Measures such as chest physiotherapy, bronchodilators, antimicrobial treatments, and medications to break down secretions (i.e., Pulmozyme), have significantly improved outcome and quality of life for many patients. Despite this, eventual respiratory failure is the rule, and, for many, lung transplant may be the only alternative. Children with CF may present for surgery at various stages of life. The neonate may present with meconium ileus or for central line placement for nutritional supplementation. Older children may present with pneumothorax requiring chest tube insertion and bronchoscopy for lavage of inspissated secretions, and microbrial diagnosis of infections can happen at any stage of life.

Anesthetic management is predicated on optimizing preoperative respiratory function. Consultation with the pulmonologist is indicated for all patients with CF. Medical management including appropriate antibiotic treatment, optimizing bronchodilator use, and initiating Pulmozyme therapy often requires the patient be admitted to hospital prior to the scheduled procedure. Preoperative laboratory investigations should include arterial blood gas, electrolyte panel, liver function tests, and blood glucose. Reviewing the most recent spirometry or PFTs and available chest imaging will also help in determining the degree of respiratory dysfunction. Chest physiotherapy for secretion clearance should be ordered preoperatively and early in the postoperative period. Controversy exists as to the most favorable perioperative fluid management strategy. Although aggressive fluid supplementation may decrease the viscosity of pulmonary secretions, some anesthesiologists prefer to limit fluid administration to decrease the volume of secretions. To date no one best strategy has been found. Whichever approach is taken, it is advisable to have the patient euvolemic at the start of the procedure. Bronchoscopy, bronchoalveolar lavage, and transbronchial biopsies may be performed through an LMA with the patient breathing spontaneously; however, anesthetic depth must be sufficient to prevent coughing and laryngospasm. Increasingly, muscle relaxation and gentle positive-pressure ventilation through the LMA have simplified anesthesia for bronchoscopic procedures in children with CF. If a tracheal tube is to be used, it must be adequately large to allow for ventilation around the fiberoptic scope as well as tracheobronchial suctioning. Routine noninvasive monitoring is acceptable for straightforward procedures; however, an arterial line may be helpful in more involved cases to assess oxygenation, ventilation, and blood glucose monitoring.

Inhalational induction may be slow in patients with severe respiratory dysfunction, and therefore intravenous induction is often preferred in this patient group. Intraoperative complications to be aware of include mucus plugging, pneumothorax, bronchospasm, and atelectasis. Inspired gases should be humidified, and tracheobronchial suctioning should be performed at regular intervals throughout the procedure. Some clinicians advocate against the use of ketamine in children with CF as this drug can increase airway secretions. Regional techniques for pain management have the theoretical advantage of minimizing respiratory depression associated with systemic narcotic use and should be considered. In the mature child or teenager with CF undergoing peripheral surgery, regional anesthesia with or without mild sedation may be a reasonable option. A plan for postoperative ventilatory support must be discussed among the surgical team, anesthesia, intensivist, and the patient/family. Respiratory compromise due to surgery, postoperative sedation, narcotic analgesia, and a weakened cough will increase the likelihood of needing postoperative ventilator support.

Pulmonary Alveolar Proteinosis

PAP is a rare disease in which accumulation of phospholipoproteinaceous material in the alveoli causes pulmonary impairment [156]. A deficiency in granulocyte-macrophage colony-stimulating factor (GM-CSF) activity results in defective macrophages and reduced clearance of surfactant from the lungs [157]. Regular administration of GM-CSF as well as bronchoalveolar or whole-lung lavage is an important part of treatment for this disease and often results in temporary improvement of symptoms and radiographic appearance (see also Chap. 45).

The small child with PAP requiring whole-lung lavage presents a particular challenge to the anesthesiologist. In adolescents and adults, double-lumen bronchial tubes are often used to isolate the lungs for lavage; however, such tubes do not currently exist for use in smaller children. Several techniques have been described to isolate the lungs in smaller children in order to allow for lavage. No single method has been shown to be ideal, and each has its risks and limitations. Extracorporeal circulation has been used which allows for thorough bilateral whole-lung lavage; however, it is invasive and may be associated with significant morbidity [158]. Lavage through a flexible bronchoscope adjacent to a cuffed ETT allows for improved lung isolation [159]; however, this can be a lengthy process and also carries a risk of causing trauma to bronchial mucosa. Lavage through a pulmonary artery catheter has also been performed either through a rigid bronchoscope [160] or through an ETT [161]. This method also allows for lung isolation; however, the diameter of a pulmonary artery catheter port is small, and drainage may be inadequate. The most commonly used method of lung lavage in children is individual or multilobar lavage through a flexible fiberoptic bronchoscope. This may

be performed through an ETT or an LMA. It is more time-consuming than whole-lung lavage, however, may be associated with lower lavage returns, and does not isolate the lung.

For whole-lung lavage in a child under the age of 9 years, true lung isolation may be achieved by using an assembly that mimics commercially available double-lumen tubes. Two cuffed tracheal tubes are passed through the glottis, one seated endobronchially to isolate the lung to be lavaged and the second seated in the trachea. These tubes are then connected to the angled and Y-connectors from a standard double-lumen bronchial tube set (Fig. 50.6) [162]. Although this approach may allow for proper lung lavage, one-lung ventilation, and obviate the need for postprocedural ventilation, the nature of the underlying illness may nevertheless dictate the need for monitoring in a high-acuity setting. Because of the nature of the procedure and the airway assembly, total intravenous anesthesia is likely preferable if this technique is to be used. This type of airway assembly can be used in the small child requiring differential lung ventilation and/or strict lung isolation for a variety of procedures other than lung lavage. Disadvantages include the necessarily smaller sizes of the two tracheal tubes needed to simultaneously pass through the vocal cords. Dexamethasone 0.1 mg/kg IV may be given prior to the procedure to reduce the risk of mucosal edema at the level of the cricoid cartilage.

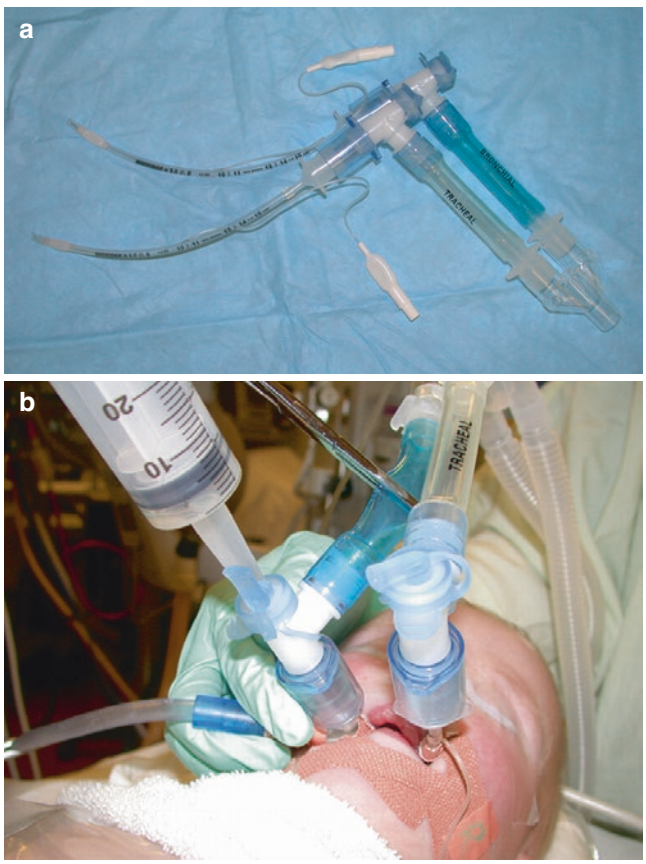

Fig. 50.6 (**a**) Airway assembly for use in the small child that mimics commercially available double-lumen bronchial tubes. Two cuffed tracheal tubes are passed through the glottis, one seated endobronchially to isolate the lung to be lavaged and the second seated in the trachea. These tubes are then connected to the angled and Y-connectors from a standard double-lumen bronchial tube set. (**b**) Whole-lung lavage being performed in a 3-year-old child via the bronchial tube of the airway assembly, while positive-pressure ventilation is applied via the tracheal tube

Trauma, Pneumothorax, and Hemothorax

Due to the unique and changing physiology and psychology of children, the management of the pediatric trauma patient may be quite different from that of the adult. Although isolated chest injuries are rare in children (5–15% of traumas), when associated with other injuries, the mortality rate can be as high as 25% [163–165]. Between 60% and 80% of all pediatric trauma is blunt impact, usually from motor vehicle collision [105]. Incomplete ossification of the ribs in children means that the rib cage is more likely to deflect under traumatic assault as opposed to fracture. Therefore, pulmonary contusions are more likely in children as compared to adults even in the absence of overlying rib fractures [166]. Conversely, a child that presents with rib fractures has likely suffered a severe, high force trauma to the chest. Insertion of a thoracic epidural catheter should be considered in the analgesic management of the child with multiple rib fractures [167]. Penetrating chest injuries due to gun violence and knife stabbings are less common in children. The presence of rib fractures in the infant should raise suspicion of child abuse [168, 169].

Pulmonary contusion is perhaps the most common traumatic thoracic injury in the pediatric population [170, 171]. Within the lung parenchyma, this manifests as alveolar edema and consolidation, sometimes associated with hemorrhage. Because of the child's higher metabolic oxygen consumption, lung injury may be accompanied by significant hypoxemia. Mechanical ventilation may be required although most pulmonary contusions can be treated by less invasive measures [172]. This includes BiPAP, supplemental oxygen, pain control, fluid restriction, and incentive spirometry when appropriate. Preventing and treating atelectasis are essential as this will reduce the risk of pneumonia and further respiratory compromise.

Pneumothorax may occur spontaneously in susceptible patients but is more often encountered at the conclusion of surgical thoracic procedures or in the setting of trauma. An open pneumothorax, one in which the pleura communicates with atmosphere, is treated with the insertion of a chest tube that allows for drainage without further entrainment of air upon inspiration. The chest tube apparatus is usually placed under water seal or to a suction device. Toward the

end of most major thoracic procedures, the surgeon will choose to electively place such a device. For minor intrathoracic procedures, some surgeons will elect not to place a chest tube. In these cases, air is removed as the chest wall is closed, while the anesthesiologist provides positive pressure to the lung. These maneuvers should minimize any residual pneumothorax. A postoperative chest X-ray is required with careful monitoring of the patient for signs of increasing pneumothorax. Most small (i.e., <10%) pneumothoraces are insignificant and will resolve over a period of a few days.

Tension pneumothorax occurs when air accumulates in the pleural space without communicating with atmosphere. As the pressure builds within the pleural space, the ipsilateral lung will further collapse with increasing mediastinal shift. Clinical deterioration of the patient will become apparent. Hypotension, hypoxia, and decreased cardiac output will require emergent management. Diagnosis is confirmed by decreased breath sounds on the ipsilateral side, tracheal deviation away from the affected lung, and shift of the maximal cardiac impulse. Radiographic diagnosis should not delay the emergent placement of a chest tube or needle decompression followed by chest tube insertion.

Bleeding into the pleural cavity can occur intraoperatively or postoperatively following any thoracic procedure. The amount of blood loss due to hemothorax in this setting should be minimal if hemostasis was achieved prior to closure. In the case of thoracic trauma, however, the amount of blood loss can quickly become life-threatening. Disruption of intercostal arteries or veins is the most common culprit in this setting. As with tension pneumothorax, the accumulation of blood will compromise ventilation and cardiac output. If this blood is not promptly drained, it may reorganize into a fibrous scar thus causing chronic atelectasis and V/Q mismatch. In addition to this, the blood may become a medium for bacterial growth with ensuing sepsis and empyema formation. Operative exploration of a hemothorax must be considered when there is ongoing drainage from the chest tube and/or the patient remains hemodynamically unstable. Some clinicians advocate a quantitative approach that would require surgical exploration if greater than 15 mL/kg of blood is recovered upon chest tube insertion or if ongoing drainage exceeds 4 mL/kg/h [173].

Major airway disruption is rare in pediatric trauma but may occur in the setting of penetrating injury or rapid acceleration or deceleration. When present these injuries can be immediately life-threatening. In 80% of cases, the disruption is located at the distal trachea or main bronchus [174, 175]. Airway injury should be suspected in the setting of pneumomediastinum, subcutaneous emphysema, large persistent air leak within the chest tube, and frank respiratory collapse. Diagnosis is usually confirmed by bronchoscopy, either rigid or flexible. When airway injury is suspected, intubation should be performed fiberoptically and the ETT placed distal to the disruption to avoid further trauma or creation of a false passage. Immediate operative repair of major airway injuries may be required although minor injuries can be observed with delayed surgical repair as required. Distal injuries can be treated with simple resection, while more proximal injuries may require quite extensive repairs. Postoperative complications may include dehiscence, airway stenosis, atelectasis, and pneumonia. A severe blow to the chest while the vocal cords are adducted can lead to a rare injury pattern that is unique to pediatrics. Traumatic asphyxia presents with neck and facial swelling and ecchymosis, subcutaneous emphysema, and pneumomediastinum [176]. The sudden increase in intrathoracic pressure causes a small tear in the upper trachea and forces air into the tissues of the neck, face, and around the mediastinum. Management is often supportive and nonsurgical.

Lung Transplantation

Pediatric lung transplantation continues to account for a small fraction of all lung transplant operations performed. Despite this, the number of transplants performed on children is increasing, and the minimum age of transplantation is decreasing. Many large pediatric transplant centers have established living donor programs and life-sustaining temporizing measures such as the Novalung® have been introduced for use in children awaiting a donor lung (Toronto Lung Transplant Program, Hospital for Sick Children Statistics, 2009, personal communication). The vast majority of pediatric lung transplant procedures are carried out in children between 10 and 17 years of age. CF accounts for over 64% of cases in children, followed by primary pulmonary hypertension (14%), pulmonary interstitial disease (7%), and retransplant (7%) [177]. Actuarial survival rates tend to be favorable for pediatric lung transplantation as compared to those for older adults.

A multidisciplinary team and approach are crucial to meet the surgical, medical, psychological, physical, and dietary challenges that will be faced. At the time or writing, children smaller than 10 years of age (i.e., those too small to accept a double-lumen bronchial tube) usually undergo lung transplantation under cardiopulmonary bypass. Other indications for the use of bypass during lung pediatric transplantation include primary pulmonary hypertension and severe right ventricular dysfunction. There also continues to be a significant rate of conversion from off-bypass double sequential lung transplant to urgent bypass in children due to worsening pulmonary hypertension or relentless hypoxemia. The advantage of off-bypass

sequential lung transplantation is the avoidance of systemic anticoagulation needed for cardiopulmonary bypass. A short period of postoperative ventilation is provided to monitor for early complications such as ischemic-reperfusion injury, infection, acute rejection, bleeding, and anastomotic leaks.

Postoperative and Pain Management

The postoperative disposition of a child who has undergone a thoracic procedure will depend on many criteria including the type and length of surgery, extent of resection or manipulation, and nature of the underlying condition. In general, infants and small children will be more frequently managed with a short period of postoperative ventilation when compared to adult patients. Regardless of the type of surgery or reason for intervention, the pediatric patient should be monitored for respiratory status and adequate pain control in a suitable environment. Constant care or high-acuity nursing and monitoring should be considered even if the patient's trachea was extubated in the operating room.

Because many procedures are now being done with the less invasive video-assisted thoracoscopic technique, postoperative pain management has become somewhat easier. These patients can often be managed with nonopioid analgesics, a simple narcotic infusion, or patient-controlled analgesia. Table 50.4 outlines commonly used analgesics in pediatric practice. Local anesthetic can also be infiltrated prior to the placement of trocars, and multimodal analgesia should be considered in all patients. Pain control for the pediatric patient has recently regained a renaissance with the more aggressive use of regional anesthesia techniques. These techniques are being applied to a wider range of the pediatric population with good success and minimal complications. The proper management of postoperative pain can avoid some of the negative physiologic outcomes associated with poorly treated pain. These include heightened sympathetic drive, increased metabolism, decreased immune function, and, specifically for thoracic procedures, poor respiratory function [177]. A simple option for regional analgesia includes intercostal nerve blocks performed prior to skin incision or just before surgical closure under direct visualization. Local anesthetic dosages should be reduced as plasma uptake at this site is rapid [178]. The overlap of thoracic dermatomes requires that the nerves above and below the surgical site also be blocked. Indwelling intercostal catheters can also be placed by the surgeon and managed as a constant infusion postoperatively [179].

Table 50.4 Commonly used analgesics in pediatric practice[a]

Analgesic	Dose[b]	Infusion dose	PCA dosing (μg/kg q 6–10 min) or comment
Morphine	50 μg/kg	10–40 μg/kg/hr	10–30
Fentanyl	0.5 μg/kg	0.5–2 μg/kg/hr	0.2–0.5
Hydromorphone	0.15 μg/kg	3–5 μg/kg/hr	3–5
Remifentanil	0.5 μg/kg	0.05–2 μg/kg/min	Intraoperative use only
Ketamine	0.15 μg/kg	1–4 μg/kg/min	Narcotic-sparing effect; may be useful if opioid side effects considerable
Acetaminophen	75 mg/kg/day po	N/A	q4h dosing for oral, q6h for rectal
Ibuprofen	5–10 mg/kg po q6h	N/A	For children >6 months of age
Ketorolac	0.5 mg/kg (maximum 15 mg) q6h	N/A	For children >6 months of age. Limit to 48 h, and then switch to po ibuprofen

Abbreviations: PCA patient-controlled analgesia, *po* per os
[a]Adapted from Sick Kids Acute Pain Handbook, 2010. The Hospital for Sick Children, Toronto, Canada
[b]Doses are intravenous unless otherwise specified

The epidural space in the child can be assessed in a similar fashion to that of adults. Ideally the epidural catheter tip should be placed at the dermatome level corresponding to the surgical site. Specific pediatric-sized Touhy needles should be used to minimize complications and provide for better control. Unlike in adults, thoracic epidural catheters are almost always placed when the child has already been anesthetized. Therefore, greater care must be exercised when advancing the needle as the patient will not be able to articulate the presence of radicular pain. Despite this drawback, there is no evidence to suggest the incidence of complications is higher in children compared to adults [180].

In smaller infants, the caudal epidural space can be easily accessed and a catheter advanced to the required thoracic level, using an ultrasound-guided approach [181]. As in adults many different local anesthetic solutions and adjuncts have been used in the pediatric population. The most commonly used local anesthetics continue to be bupivacaine and ropivacaine for either "single shot" or continuous infusion epidurals [182]. Suggested neuraxial blocks and dosing guidelines suitable for pediatric thoracic procedures can be found in Table 50.5. Epidural narcotics are commonly coadministered as they reduce the dosage requirement for local anesthetics and improve the block quality. Epidural morphine, fentanyl, and hydromorphone are the most commonly prescribed narcotics for this use [183, 184]. The purpose of optimizing pain management strategies is not only to keep the child comfortable but also to avoid pulmonary dysfunction by enabling deep breathing and coughing. This can aide in the prevention of atelectasis and postoperative pneumonia. Early ambulation is also encouraged to further accelerate the recovery of the patient and prevent those diseases associated with prolonged immobilization and hospitalization.

Table 50.5 Neuraxial blocks and dosing guidelines suitable for pediatric thoracic procedures[a]

Type of block	Solution	Infusion rate (mL/kg/h)
Thoracic epidural[b]	0.125% bupivacaine + epi 1:400,000 ± fentanyl 1–2 μg/mL	0.1–0.16 maximum 10 mL/h
Thoracic epidural[b]	0.1% bupivacaine + epi 1:500,000 ± fentanyl 1–2 μg/mL	0.1–0.16 maximum 12 mL/h
Thoracic epidural[b]	0.0625% bupivacaine + epi 1:800,000 ± fentanyl 1–2 μg/mL	0.1–0.16 maximum 14 mL/h
Paravertebral[c]	0.125% bupivacaine + epi 1:400,000	0.2 maximum 15 mL/h
Intercostal[d]	0.125% bupivacaine + epi 1:400,000	0.016–0.032 per rib maximum 1 mL/h/rib
Intrapleural[e]	0.125% bupivacaine + epi 1:400,000	0.2–0.3 maximum 20 mL/h

[a]Adapted from Sick Kids Acute Pain Handbook, 2010. The Hospital for Sick Children, Toronto, Canada
[b]Alternatively, caudal or lumbar approach with epidural catheter threaded to thoracic level. Suggested loading dose of 0.2–0.25 mL/kg of 0.25% bupivacaine + epi 1:200,000 up to maximum 10 mL
[c]Suggested loading dose of 0.3–0.5 mL/kg of 0.25% bupivacaine + epi 1:200,000 up to maximum 15 mL
[d]Suggested loading dose of 0.05 mL/kg (maximum 2 mL) of 0.25% bupivacaine + epi 1:200,000 per intercostal space
[e]Suggested loading dose of 0.2–0.3 mL/kg (maximum 20 mL) of 0.25% bupivacaine + epi 1:200,000

Clinical Case Discussion

A 3-year-old child with a newly diagnosed left lung mass presents for tissue diagnosis followed 1 week later by thoracotomy and tumor resection.

The initial workup of the child will focus on the functional status and size of lung mass. Imaging will be essential to identify the size and location of tumor and to rule out a mediastinal mass. A CT scan will be required which may be done without sedation if the child is cooperative. Otherwise a stepwise approach of cautious sedation may be required. Any sedation should be delayed to verify the absence of a significant mediastinal mass. Tissue samples may be obtained through a mini-thoracotomy; however, in tertiary pediatric centers, image-guided needle core biopsy is preferred and associated with lower morbidity. Most 3-year olds will require deep sedation or general anesthesia. Spontaneous respiration can be maintained during the biopsies, which might be CT or ultrasound guided. Often tracheal intubation is not required, and the patient's airway can be managed by face mask, bag-mask support, or insertion of an LMA. Sedation/anesthesia may be achieved by TIVA (propofol or ketamine, alone or in combination with a short-acting opioid or benzodiazepine) and/or inhalation. Occasionally, a brief period of apnea will be requested to facilitate biopsy. This may be achieved temporarily deepening the anesthetic and providing positive-pressure ventilation. Postbiopsy X-ray should be performed to ensure there is no significant residual pneumothorax. Chest tube insertion is rarely required.

Tumor resection may be performed via VATS or open thoracotomy. In either case the anesthesiologist should be prepared to isolate the lung. Options in a 3-year old include (1) selective right mainstem bronchus intubation with a 4.5 or 5.0 mm ID tracheal tube, (2) insertion of a size 5F embolectomy catheter in the left mainstem bronchus inside or (more practically) outside a 4.5 mm ID tracheal tube, or (3) a 5F Arndt endobronchial blocker inserted in a 5.0 mm ID tracheal tube and placed in the left mainstem bronchus. Regardless of the option chosen, fiberoptic verification of proper tube or blocker positioning is crucial. A 2.2 or 2.8 mm OD pediatric fiberoptic bronchoscope should be used to ensure adequate ventilation may be provided while the scope occupies the lumen of the tracheal tube. The author prefers not to perform selective right mainstem bronchus intubations as quite often the tube slips distal to the right upper lobe takeoff, resulting in atelectasis of that lobe and worsening hypoxemia. Monitoring should include an invasive arterial blood pressure line in addition to standard monitors. Pain control will depend partly on whether VATS or open thoracotomy is performed. As a general guideline, central neuraxial blockade is offered in the event of open thoracotomy, and systemic analgesics are administered if VATS is performed. Postoperative monitoring in a high-acuity setting (step-down or critical care unit) is warranted for the first 12–24 h.

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