

Anesthesia for thoracic surgery in infants and children

ABSTRACT

The management of infants and children presenting for thoracic surgery poses a variety of challenges for anesthesiologists. A thorough understanding of the implications of developmental changes in cardiopulmonary anatomy and physiology, associated comorbid conditions, and the proposed surgical intervention is essential in order to provide safe and effective clinical care. This narrative review discusses the perioperative anesthetic management of pediatric patients undergoing noncardiac thoracic surgery, beginning with the preoperative assessment. The considerations for the implementation and management of one-lung ventilation (OLV) will be reviewed, and as will the anesthetic implications of different surgical procedures including bronchoscopy, mediastinoscopy, thoracotomy, and thoracoscopy. We will also discuss pediatric-specific disease processes presenting in neonates, infants, and children, with an emphasis on those with unique impact on anesthetic management.

Key words: One-lung ventilation; pediatric anesthesia; thoracic surgery; thoracoscopy; thoracotomy

Introduction

Children presenting for thoracic surgery are a heterogeneous group of patients who pose a variety of challenges to the anesthetic care team. A thorough understanding of the pediatric patient, including development changes in cardiopulmonary anatomy and physiology, and the implications of surgical lesions and interventions is essential in order to provide safe and effective clinical care. Perioperative preparation for each individual patient must take into consideration the age and developmental stage of the patient as well as the presence of any accompanying comorbid conditions or underlying physiologic derangements. This narrative review outlines the approach to the perioperative anesthetic management of pediatric

patients undergoing noncardiac thoracic surgery, beginning with the preoperative assessment, and will also consider the implementation and management of OLV and the anesthetic implications of specific surgical techniques. We will also briefly review pediatric-specific disease processes presenting in neonates, infants, and children, with an emphasis on those with unique impact on anesthetic management.

Preoperative Evaluation


The preoperative history and physical examination begin with the identification of the acute problem for which the surgical procedure is indicated as well as an assessment of underlying comorbid conditions and previously undiagnosed

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conditions that may impact perioperative management. The use of preoperative laboratory studies depends on the patient's clinical status, associated comorbid diseases, and the scheduled procedure. For otherwise healthy patients, additional preoperative laboratory should only be obtained if their history, diagnosis, chronic medication list, or comorbidities indicate a clinical need for this information.^[1,2] In general, given the close proximity to the great vessels during most thoracic procedures, cross-matched blood should be available before the operation commences.

Patients presenting for intrathoracic procedures will usually have at least a chest radiograph available, and some will have undergone advanced imaging studies to obtain information on the diagnosis, location, associated mass effect, and vascular connections of a lesion.^[3] The imaging of other organ systems is guided by known or suspected comorbid conditions. A preoperative echocardiogram is indicated in any condition that has a high incidence of associated congenital heart disease (CHD), such as tracheoesophageal fistulae (TEF) and certain congenital thoracic malformations, or when the pathophysiology of the lesion may be expected to impact cardiac function, as is the case for mediastinal masses. Given that the presence of comorbid CHD increases mortality risk following noncardiac surgery, this diagnosis is essential to aid in the planning of the anesthetic care and to provide an assessment of the overall risk of surgery for a given patient.^[4] Particular attention is directed at ductal dependent lesions (interrupted aortic arch, tricuspid atresia) that may require the use of a prostaglandin infusion to provide pulmonary or systemic blood flow.

In contrast to adult patients for whom the preoperative assessment of pulmonary function may be used to determine fitness for thoracic surgery, the need for postoperative respiratory support, or the risks for postoperative complications,^[5] such testing has a limited role in the management of pediatric patients. This is in part due to continued difficulty with performing formal pulmonary function testing (PFT) in younger children,^[6] and also due to the lack of demonstrated utility of these tests in predicting outcomes in the general pediatric population.^[7] There are subpopulations of pediatric patients who do benefit from preoperative PFTs, including those patients with muscular dystrophy,^[8] and patients undergoing spinal surgery. PFT may be used more commonly during the follow-up of these patients and in comparing outcomes between open thoracotomy versus minimally invasive surgical techniques. Most children who undergo thoracoscopic procedures will have normal pulmonary function during medium and long term follow-up.^[9,10]

As there is no specific test to identify the patients who will require postoperative mechanical ventilation, one is left with a clinical assessment of the patient including room air oxygen saturation and an assessment of the patient's exercise tolerance as well as their clinical history of recent or recurrent pulmonary infections. Formerly premature infants with bronchopulmonary dysplasia are at a particularly increased risk of requiring prolonged postoperative mechanical ventilation.^[11] Our clinical experience also suggests that the presence of uncorrected cyanotic CHD may also indicate the requirement for postoperative mechanical ventilation.

Premedication, Anesthetic Induction, and Monitoring

Pharmacologic premedication for anxiolysis is an appropriate intervention for the majority of pediatric patients who are more than 1 to 2 years of age. Oral or intranasal midazolam has been repeatedly demonstrated to have benefit in this setting.^[12] Dexmedetomidine has also been used with similar efficacy in some,^[13] but not all^[14] studies, and may have an improved recovery profile.^[15] Beyond anxiolysis, additional medications that may be considered as part of the preoperative process include bronchodilators such as albuterol and ipratropium for patients with reactive airway disease, and intravenous anticholinergic agents such as glycopyrrolate or atropine, which act to dry secretions and prevent bradycardia during laryngoscopy and endotracheal intubation.

In the healthy infant or child without signs or symptoms of airway compromise or cardiovascular instability, a variety of options are available for the induction of anesthesia, including an inhalation technique with sevoflurane or an intravenous approach.^[16-18] Several lesions benefit from the maintenance of spontaneous ventilation throughout induction and endotracheal intubation, including TEF, some of the congenital thoracic malformations, and mediastinal masses (see below). In patients with significant airway obstruction, such as that caused by subglottic stenosis or vascular rings, an inhalational technique may benefit from the inclusion of helium to improve gas exchange past fixed obstructions.^[19] If positive pressure ventilation is appropriate for the clinical scenario, the induction technique can be followed by the administration of a nondepolarizing neuromuscular blocking agent (NMBA). Conversely, if there is a desire to avoid the use of a NMBA, some combination of lidocaine (1–2 mg/kg), propofol (1 mg/kg), dexmedetomidine (0.5–2 µg/kg) or an opioid such as fentanyl (1–2 µg/kg) or remifentanyl (1–4 µg/kg) can be administered prior to endotracheal intubation.

Following anesthetic induction, peripheral intravenous catheters are placed and should be verified prior to and

following positioning the patient for the procedure. Central venous catheters are not commonly used during thoracic surgery for pediatric patients, and are generally reserved for cases in which either adequate peripheral intravenous access is unavailable, or when there is anticipation of the need for the administration of vasoactive agents or monitoring of central venous pressure. The decision to use invasive arterial blood pressure monitoring is guided by the clinical status of the patient and the specific surgical procedure, and is most commonly used in open thoracic resections.^[18] One unique consideration in monitoring for patients undergoing thoracic surgery is the decreased accuracy of end-tidal carbon dioxide (CO₂) in the setting of alternative airway management strategies such as OLV and intraoperative changes in dead space. In this setting, invasive arterial monitoring may be considered to facilitate PaCO₂ monitoring with sampling of blood gases. Alternatively, continuous transcutaneous CO₂ monitoring is a technique with demonstrated utility in a number of pediatric populations and settings.^[20,21]

Intraoperative Management

One-lung ventilation

Many of the surgical interventions used to address intrathoracic pathology will benefit from the isolation of the two lungs in order to either optimize surgical visualization or to prevent physiologic deterioration with positive pressure ventilation. Even though isolation is not absolutely necessary for many operations, its use can substantially enhance surgical access to deeper vascular and pulmonary structures.^[18,22] There are several options for equipment and methods for achieving OLV [Table 1], as has been well described in previous reviews.^[23-25] Placement of airway devices, including bronchial blockers (BB), for OLV may be facilitated with the use of a flexible fiberoptic bronchoscope (FOB) or guidance under fluoroscopy and rigid bronchoscopy.^[26-29] When using a bronchoscope to guide and position an endotracheal tube, the outer diameter (OD) of the FOB must be less than 90% of the internal diameter (ID) of the ETT to ensure an adequate fit, and less than 50% of the ID of the ETT if ventilation is desired during bronchoscopy.^[24] If both a bronchial blocker

and FOB will be passed through the ETT, the maximal allowable OD of the FOB is reduced even further. Although various quick reference calculations can be used to determine the feasibility of a particular combination of equipment, a physical check of the fit between the equipment (ETT, FOB, and bronchial blocker) is strongly recommended prior to the induction of general anesthesia. Additionally, the use of silicone spray greatly facilitates passage of the FOB and bronchial blocker through the ETT.

Regardless of the chosen method for OLV, it is important to confirm lung isolation at several steps, including before and after transition to the lateral decubitus position, and finally by the surgeon upon entry into the thoracic cavity. Although FOBs are commonly employed to verify device positioning, recent reports have been promising with the use of point-of-care ultrasound imaging to verify successful lung isolation.^[30-32]

Selective endobronchial intubation: In neonates and very young infants, lung isolation is generally best accomplished through selective endobronchial intubation. In a blind approach, direct laryngoscopy is used to place the ETT into the mid-portion of the trachea. After bilateral breath sounds have been verified, the ETT is then advanced until breath sounds disappear on the operative side. This technique can reliably achieve successful lung isolation, especially on the right side.^[33] Blind placement into the left main stem bronchus is more challenging. It may be helpful to reverse the usual orientation of the bevel at the distal end of the ETT by inverting it with a stylet or gum elastic bougie, at which point the concave segment becomes convex, and the angle of the bevel faces the patient's right side.^[34] Other possible maneuvers include elevating the opposite shoulder or turning the head to the contralateral side. Endobronchial intubation can also be guided with either bronchoscopic or fluoroscopic direction.^[27,35] Regardless of whether left or right mainstem intubation is planned, the authors recommend the use of an ETT one-half to one size smaller than would otherwise be selected based on the patient's age, and use of a cuffed ETT whenever possible, as this allows for an effective seal without

Table 1: Airway devices for one-lung ventilation in pediatric patients

Age	ETT (ID mm)	BB size (location)	EZ-blocker™	Univent™	DLT
Newborn	3.0	3 Fr (E)	-	-	-
0-2 years	3.5-4.0	3-5 Fr (E)	-	-	-
2-6 years	4.0-5.0	5 Fr (E/I)	-	-	-
6-8 years	5.0-6.0	5 Fr (I)	E	3.5	-
8-10 years	6-6.5	7 Fr (E/I)	E	3.5	26 Fr
10-12 years	6.5-7.0	7 Fr (I)	E/I	4.5	26-28 Fr
>12 years	7.0-7.5	7-9 Fr (I/E)	E/I	4.5-6.0	32-35 Fr

ETT=Endotracheal tube; ID=Inner diameter; BB=Bronchial blocker; DLT=Double lumen tube; Fr=French; E=Extraluminal; I=Intraluminal

the need to advance the ETT excessively deep into the bronchus. The endobronchial technique for lung isolation has several important limitations, with the primary disadvantage being an inability to quickly to change from OLV to two-lung ventilation. In this scenario, the ETT must be repositioned under the surgical drapes, risking ETT dislodgement. Another disadvantage, especially when ventilating the right lung with an ETT that lacks a Murphy's eye, is the possibility of excluding the right upper lobe due to the shorter distance between the carina and the right upper lobe bronchus takeoff.^[27] Additional disadvantages of this approach include the inability to apply either suction or continuous positive airway pressure (CPAP) to the operative lung.

Bronchial blockers: Once a child reaches approximately 6 months of age, the use of a bronchial blocker to achieve lung isolation becomes feasible and is usually the preferred method from 6 months to 8 years of age.^[24,36] Bronchial blockers all feature a balloon at their distal tip which is placed into the bronchus of the operative lung. These devices are placed either in a coaxial (intraluminal) or parallel (extraluminal) position with respect to the ETT. A blocker can be used in a coaxial position only if its diameter is less than 50% of the ETT internal diameter. Thus, the smallest 5 French (Fr) blocker with a diameter of 1.7 mm can only be placed coaxially in a 4.0 or greater sized ETT.

There are several methods for extraluminal blocker placement in smaller patients.^[17,29,37] The bronchial blocker can be placed directly into the bronchus on the operative side using direct laryngoscopy, a rigid bronchoscope, or fluoroscopy [Figure 1]. Alternatively, the main stem bronchus on the operative side can be intubated and the bronchial blocker passed through the ETT. This introducing ETT is removed, followed by

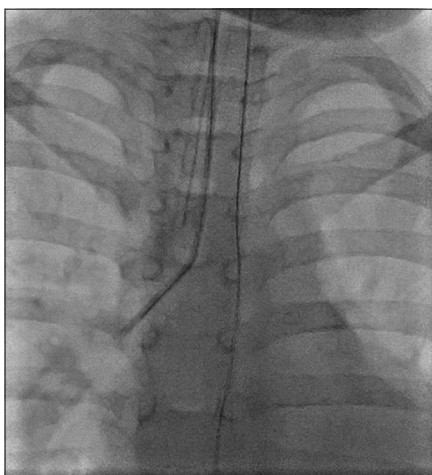


Figure 1: Fluoroscopic image showing the placement of a bronchial blocker in the right main stem bronchus. The light bend at the end of the blocker assists with guiding it into the desired bronchus

reintubation with an appropriately seized ETT, leaving the bronchial blocker in an extraluminal position. The authors' preference is to perform direct laryngoscopy, place the bronchial blocker through the glottis and into the tracheal lumen, followed by the ETT. A FOB can then be placed through the ETT and the bronchial blocker advanced under direct visualization into the desired bronchus. In our experience, having a light bent at the end of the blocker helps with guiding the blocker into the desired bronchus, especially when using fluoroscopy to guide placement [Figure 1]. Successful maintenance of the blocker in the operative side is enhanced by positioning it along the ipsilateral wall of the trachea.

Several different off-label devices have been used as bronchial blockers, including a Fogarty® embolectomy catheter [Figure 2], the Miller® atrioseptostomy catheter (Edwards Lifesciences, Irvine, CA, USA), and pulmonary artery catheters.^[29] The Fogarty® catheter and the Miller® atrioseptostomy catheter both feature an angled tip and lack a central channel. The pulmonary artery catheter does contain a central channel but, being flexible, it can be more difficult to place into the bronchus of choice. Of note, the balloons featured in these vascular devices are characterized as low volume and high pressure devices, with the potential to cause ischemia of the bronchial mucosa with any degree of over-inflation. Some of the limitations of the off-label devices led to the development of several specific devices for use in this setting, including the Arndt Endobronchial Blocker® (Cook Critical Care, Bloomington, IN, USA) and the EZ-Blocker® (Teleflex, Inc., Wayne PA, USA).

The Arndt Endobronchial Blocker® is a balloon-tipped blocker with an inner lumen through which a wire with a looped end has been passed [Figure 3].^[38,39] It is accompanied

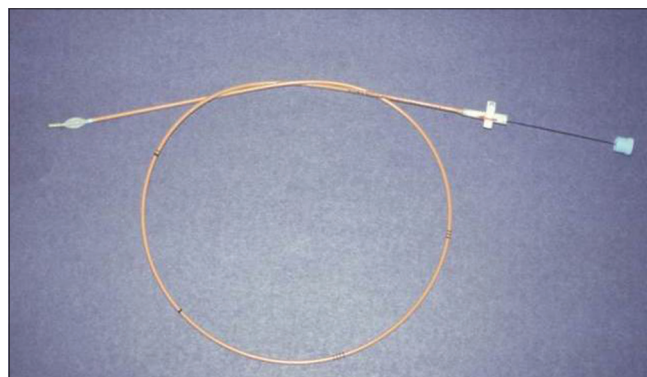


Figure 2: Fogarty® embolectomy catheter for use as a bronchial blocker during one-lung ventilation. These catheters have an inflatable, high pressure balloon at the tip that can be placed into and occlude the bronchus of the operative lung. They are available in a variety of sizes for use in a wide range of patient ages

by an adaptor (Arndt Multi-port Adaptor®, Cook Critical Care) which allows the introduction of a FOB through one port, the bronchial blocker through a second port, and attachment of the ETT to the ventilator circuit through a third port [Figure 4]. In a common method of placement, after the patient's trachea is intubated, the adapter is connected to the ETT and ventilation is initiated.^[38] The bronchial blocker is passed through its port and placed at the entrance of the ETT. A FOB is passed through its respective port and then through the wire loop at the end of the Arndt bronchial blocker. The FOB and blocker are passed through the ETT and trachea into the desired main stem bronchus with the wire loop guiding the bronchial blocker into position. Once the FOB is located in the bronchus of choice, the blocker is advanced off its end, and the high-volume, low-pressure balloon is inflated under FOB visualization. The FOB is then removed. After positioning, the wire can be removed to allow suctioning and the application of CPAP through the central channel. However, after the guidewire is removed, it is not easily replaced, which may greatly impede any subsequent attempts at blocker repositioning.

The EZ-Blocker® is a Y-shaped, 7 Fr double-cuffed bronchial blocker which terminates in two distal extensions, each of which contains a high-volume, low-pressure cuff that is intended to sit within the main stem bronchi [Figure 5].^[40-42] The distal junction point between the two arms measures 6.5 mm, limiting its use in smaller patients. Although it was designed for adult use, the EZ-Blocker has been employed in children as young as 6 years of age. To guide placement, the device can be sheathed within a 5.5 uncuffed ETT which has been cut lengthwise.^[41,42] Once the assembly is passed

through the glottis, the outer ETT is peeled away, leaving the blocker in place, and an appropriately sized ETT is placed through the glottis.

Bronchial blockers that lack a central channel, including many of the vascular catheters, provide no means by which air and gas can exit from the lung once the balloon is inflated. In order to assist in lung deflation and improve surgical visualization, the lung can be manually compressed by the surgeon during a brief period of apnea. The catheter balloon is then inflated prior to the resumption of positive pressure ventilation. Further collapse of the operative lung is facilitated by ventilating with a combination of air and oxygen prior to the apneic period, and immediately switching to 100% oxygen following balloon inflation. The absorption of nitrogen in the air then enhances the deflation from absorption atelectasis.

Regardless of which blocker and method of placement are chosen, there is a risk of displacement from the bronchus during repositioning or during surgical manipulations.^[43] If this occurs, the blocker may occlude the tracheal lumen just distal to the ETT, resulting a clinical picture of abrupt increase in airway pressure and marked reduction in or absence of adequate ventilation^[38] and in some instances, loss of the capnography tracing. Intraluminal blockers have the potential to move within the ETT and therefore need to be stabilized by securing them either with a self-sealing diaphragm or by modifying the ETT near the 15 mm adapter. A small hole is made just beyond the attachment of the adapter at the end of the ETT. By passing the bronchial blocker from the outside into the inside of the ETT through this hole, the blocker can be positioned and secured to the outside of the

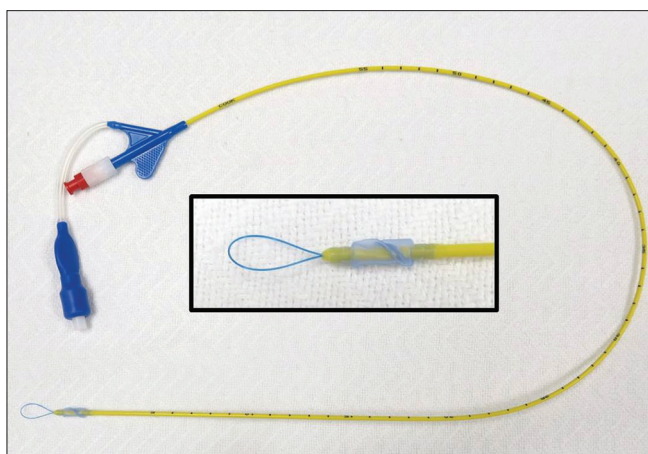


Figure 3: Arndt® endobronchial blocker for one-lung ventilation. The Arndt® bronchial blocker is available in three sizes (5, 7, and 9 French) and features a central channel through which a wire is looped, to facilitate placement by a fiberoptic bronchoscope. When the wire loop is removed, the central channel can be used for suctioning or the administration of oxygen

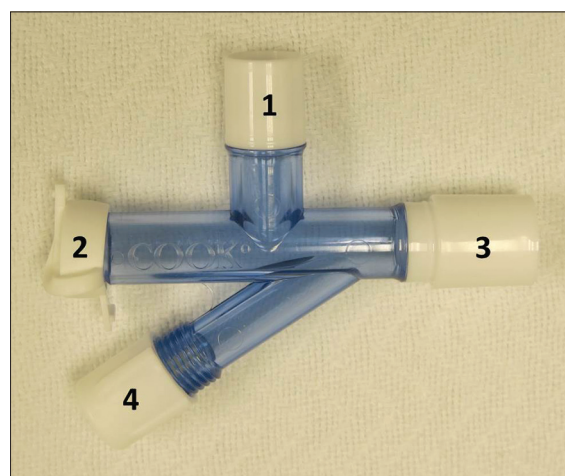


Figure 4: Arndt Multi-port Adaptor® for introducing and securing the Arndt® blocker. The adaptor has four ports for: (1) attachment to the anesthesia circuit; (2) passage of the fiberoptic bronchoscope; (3) attachment to the endotracheal tube; and (4) entry of the bronchial blocker. The blocker port is tightened to secure the blocker in its final position

ETT. Additionally, the use of saline rather than air to inflate the balloon on the end of the bronchial blocker may limit movement within the bronchus.

Double lumen endotracheal tubes: In older children and teenagers, lung isolation is achieved most frequently with a double-lumen endotracheal tube (DLT) which is almost always left-sided [Figures 6 and 7]. The smallest commercially available DLT is a size 26 French, which can be utilized in patients as young as 8 years of age and as small as 30 kg.^[44] The DLT provides several advantages over bronchial blockers, including rapid switching between one and two-lung ventilation, the ability to suction both lungs, and the option of administering CPAP or oxygen insufflation to the operative lung. In a randomized study in adults, DLTs provided the fastest method of achieving lung isolation and required the fewest repositioning maneuvers intraoperatively in comparison to three available bronchial blockers.^[45] Limitations of the DLT include the larger external diameter, possible difficult placement in patients with challenging anatomy, the need for an ETT exchange to a single lumen ETT should the patient need ventilation postoperatively, and the need for ultrathin pediatric FOBs when 26 or 28 Fr sizes are used.

The Univent™ (Fuji Systems, Tokyo, Japan) is a single-lumen ETT with a channel in which a moveable bronchial blocker is incorporated.^[46,47] The blocker can be deployed into the operative bronchus with FOB guidance, and then withdrawn back into its channel to resume two-lung ventilation. It can be left in place if postoperative ventilation is required without the need for an ETT exchange. It also contains a central channel through which oxygen may be insufflated during OLV. Although several of these features provide benefit over the

DLT, the Univent™ shares similar limitations with regards to size and feasibility of use in smaller pediatric patients. The Univent™ devices are sized by the internal diameter of the single lumen used for ventilation, which is only a fraction of the total size of the device. The outer diameter of these tubes is significantly larger than their standard counterparts; the smallest of the two available pediatric sizes, the 3.5 mm internal diameter cuffless device, has an outer diameter of 7.5–8.0 mm. This is equivalent to a standard 5.5–6.0 ETT, thereby limiting the use of the Univent™ to patients greater than 4–6 years of age.

Maintenance Anesthesia

Although there are rare and unique reports of the use of spinal anesthesia as the primary technique during thoracotomy for ligation of a patent ductus arteriosus,^[48] general anesthesia is utilized for the vast majority of thoracic procedures. Planning for the management of anesthesia and ventilation during the maintenance phase of surgery must take into consideration the impact of anesthetic agents on hypoxic pulmonary vasoconstriction (HPV) and differences between pediatric and adult patients with regards to respiratory physiology. HPV is a normal physiologic response specific to the pulmonary vasculature in which a low oxygen partial pressure causes reflex contraction of vascular smooth muscle.^[49] The overall effect of this reflex is that blood flow to poorly ventilated alveoli is shifted preferentially to alveoli with adequate ventilation.^[50,51] During intrathoracic procedures, as vessels in the ventilated lung are usually already near maximal vasodilation due to the high inspired oxygen concentration, manipulations of HPV are focused on avoiding factors that could attenuate the reflex in the operative lung, as this would worsen perfusion and ventilation matching.^[49] Any nonspecific vasodilator (dobutamine, nicardipine, nitroglycerin, sodium nitroprusside, inhalational anesthetic agents) can impair HPV and worsen oxygenation, as does alkalosis (metabolic or

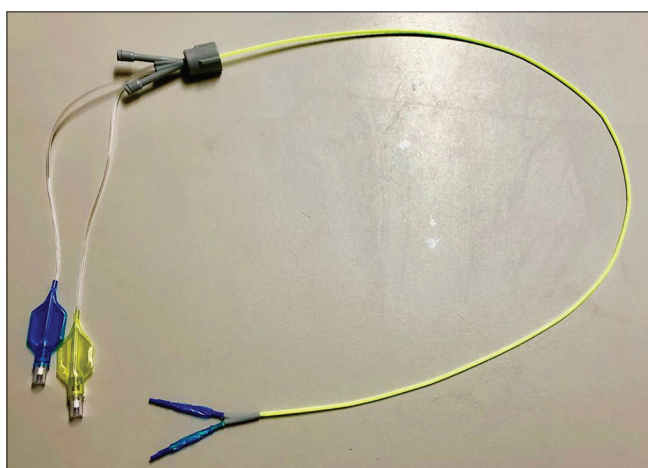


Figure 5: The Rusch® EZ blocker™ endobronchial blocker for one-lung ventilation. The Y-shaped 7 French catheter has a dual lumen system with two high-volume, low-pressure cuffs. It is positioned so that there is a balloon situated in each mainstem bronchus

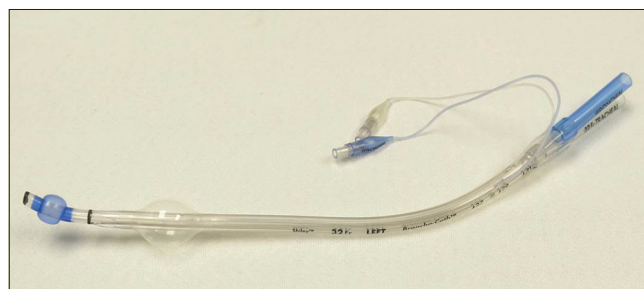


Figure 6: Standard double-lumen endotracheal tube for one-lumen ventilation. Double lumen endotracheal tubes (DLTs) are available in a variety of sizes, the smallest of which (26 French) may be suitable for patients as young as 8 years of age and 30 kg or greater in weight. The small internal lumens of the 26 French and 28 French DLTs can only accommodate ultrathin pediatric bronchoscopes

respiratory) and hypothermia. Anecdotal work has suggested various pharmacologic agents that may improve oxygenation during OLV including vasoconstrictors which enhance HPV^[52] as well as inhaled nitric oxide and iloprost which cause regional vasodilatation of ventilated alveoli and improve matching of ventilation and perfusion.^[53-57]

General anesthesia during thoracic surgery is typically maintained with a balanced technique with either inhalational or intravenous agents. Studies that have examined the potential benefits of one anesthetic regimen over another have found mixed results. All of the currently utilized volatile anesthetic agents inhibit HPV in a dose-dependent fashion, without clinically meaningful differences between isoflurane, sevoflurane, and desflurane.^[58,59] Certain clinical trials demonstrated improvements in oxygenation during OLV with a propofol anesthetic in comparison to sevoflurane, isoflurane, or desflurane.^[60,61] However, others showed equivalent arterial oxygenation levels and systemic oxygen delivery when comparing sevoflurane, isoflurane, and propofol.^[62-64] Opioids are an important component of a balanced maintenance technique. Remifentanyl is frequently utilized during pediatric thoracic surgery and, in adult patients, does not negatively impact oxygenation.^[17,65] Dexmedetomidine has been increasingly employed as well, with studies again showing mixed results with respect to its impact on oxygenation.^[66,67] Maintenance anesthesia may also be supplemented with continuous neuraxial or regional techniques if the catheter is placed at the beginning of the procedure.^[68,69]

Developmental differences in respiratory physiology are most dramatic in neonates and young infants, in whom

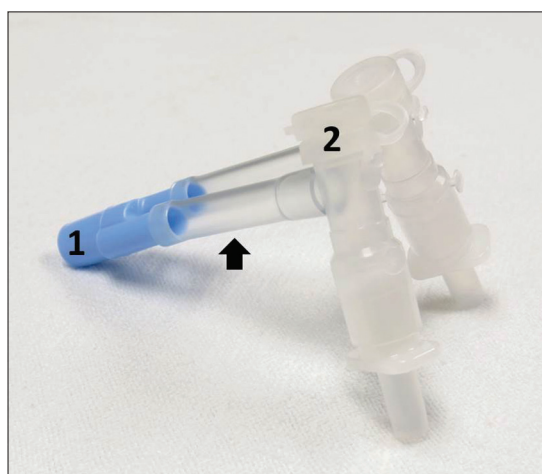


Figure 7: Adaptor for a double-lumen endotracheal tube. The adaptor has a standard 15 mm connector (1), and 2 ports (2) for passage of a fiberoptic bronchoscope or a suction catheter. The short segment of the tubing (black arrow) can be clamped during one-lung ventilation, and the port (2) is opened to allow the lung to deflate

general anesthesia alone significantly increases ventilation and perfusion mismatching and the risk of clinically relevant atelectasis.^[70] In contrast to adult patients, pediatric patients oxygenate better when the healthy lung is uppermost.^[71,72] This is in part due to a reduced hydrostatic pressure gradient between the two lungs and a compliant rib cage that does not fully support the underlying tissue. The loss of functional residual capacity under general anesthesia and an elevated oxygen consumption at baseline render young children at high risk of intraoperative hypoxemia, which is exacerbated in the lateral position. Comparisons between pediatric patients under 10 years of age with older children have confirmed that younger patients to be at higher risk of intraoperative hypoxemia and hypercarbia during thoracoscopic procedures.^[73]

A number of ventilatory options are available for intraoperative use. Conventional modes are probably the most commonly encountered, although lung-protective ventilation strategies are increasingly recommended by some for use in pediatric patients.^[74,75] If adequate oxygenation cannot be maintained during OLV, several interventions may be required on the part of the anesthesiologist [Figure 8], including increasing the inspired oxygen concentration and the use of recruitment maneuvers for the ventilated lung. Continuous positive airway pressure (CPAP) of 4–5 cmH₂O to the operative lung

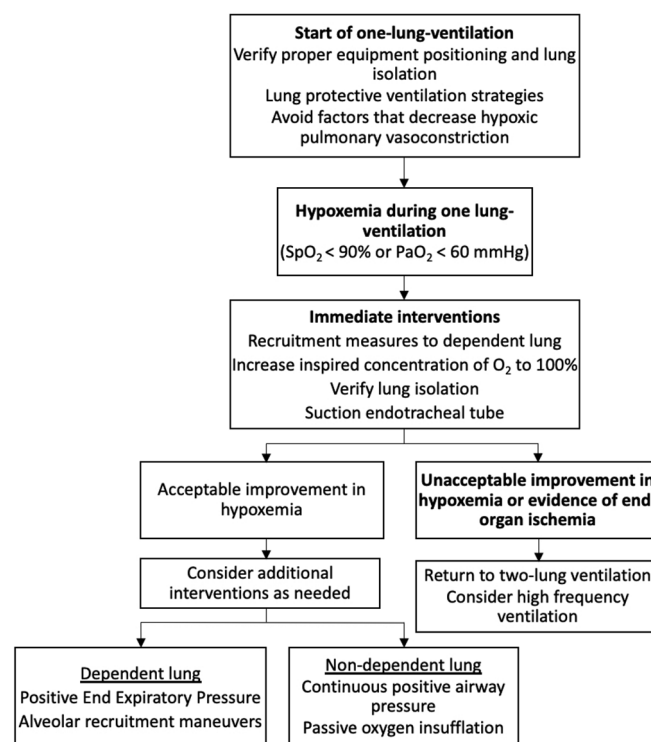


Figure 8: Flowchart for suggested management of oxygenation during one-lung ventilation. SpO₂: Arterial oxygenation saturation by pulse oximetry; PaO₂: Partial pressure of oxygen

may be considered, although the consequent distention of the operative lung can impair surgical visualization during both open and thoracoscopic approaches.^[76] If these measures fail, it may be necessary to provide two-lung ventilation intermittently. Alternatively, high-frequency ventilatory methods have been shown to limit lung movement and improve surgical visualization during a variety of thoracic procedures and may be used as elective management approaches or rescue modes for patients for whom conventional strategies prove to be insufficient.^[75,77-82] Regardless of the particular approach, ventilation should be adjusted as needed to maintain normocarbida throughout the procedure.

Intraoperative Anesthetic Care for Specific Diagnostic and Surgical Procedures

Airway endoscopy: Airway endoscopy, including direct laryngoscopy and rigid or flexible bronchoscopy, is a widely utilized diagnostic and therapeutic tool in the care of children with intrathoracic tracheal pathology.^[83-85] A key consideration for anesthetic management is the preservation of oxygenation and ventilation while sharing the airway with the surgeon. Inhalational, intravenous or combination approaches may be used for induction and maintenance of anesthesia.^[84,86] Prior to instrumentation of the airway, topical lidocaine (1%–4%) is administered to the supraglottic and glottic structures as well as the trachea in a dose of 2–4 mg/kg to blunt responses to airway stimulation. Intravenous glycopyrrolate is also often administered preemptively to decrease airway secretions and prevent bradycardia. After induction, an inhalational technique with sevoflurane may be supplemented as needed with propofol, ketamine, or dexmedetomidine.^[87-89] Alternatively, a total intravenous approach may be employed.^[86,90-93] Neuromuscular blockade and controlled ventilation are preferable in situations in which patient movement could cause severe complications, such as balloon dilation of a stenotic lesion, laser-assisted procedures, or even during foreign body removal.^[85,88,94]

Ventilation and oxygenation may be managed during airway endoscopy with several different techniques, including intermittent episodes of apnea interspersed with mask ventilation or periodic placement of an ETT, and spontaneous ventilation with oxygen and volatile agent insufflation through the end port of the laryngoscope, the 15 mm adapter side port of the bronchoscope or an uncuffed ETT placed in the nasopharynx.^[95] These techniques may be poorly tolerated in neonates and young infants secondary to the negative effects of sevoflurane on central control of ventilation, which may result in apnea or hypoventilation,

combined with a reduced functional residual capacity and increased oxygen consumption. Alternatively, automatic jet ventilators have been successfully employed for these interventions, including laser procedures of the larynx and trachea.^[96,97] When laser use is planned, general safety precautions include the minimization of the inspired oxygen concentration and avoidance of nitrous oxide, the elimination of smoke from the airway, and the removal or protection of any flammable material in the operating field. Additionally, if an ETT is utilized, the risk of an airway fire can also be minimized through the use of various alternatives to the standard polyvinylchloride ETT, although no ETT is completely laser resistant.^[82,98]

Flexible bronchoscopy, once limited to a diagnostic modality has seen an increasing number of therapeutic applications.^[83-85] In general, it offers several benefits in comparison to rigid bronchoscopy, including a more thorough assessment of the distal airways including the upper lobe bronchi. Limitations include an inability to ventilate through the bronchoscope and poor optical performance, especially in the neonatal sizes.^[99] The rigid bronchoscope is a less expensive and more durable option that has long been considered the gold standard for many therapeutic interventions, including foreign body removal and control of airway hemorrhage. Once a bronchoscope is introduced through an ETT, the decreased effective diameter for gas exchange is associated with reductions in airflow and resultant alveolar hypoventilation.^[100] This may be countered through bronchoscopy through a laryngeal mask airway or by the administration of helium along with oxygen, as the lower density of helium allows for decreased resistance to air movement.^[19,101] Although rigid bronchoscopes do offer a means for ventilation through the hollow interior, the turbulent nature of flow through the bronchoscope significantly increases resistance in comparison to an ETT of a similar diameter.^[102]

Airway surgery: Tracheomalacia and tracheal stenosis are the most commonly encountered congenital airway abnormalities in the pediatric setting.^[103,104] An endoscopic approach to management is feasible for some low grade or short segment defects, and may be performed under inhalational or intravenous anesthesia without an ETT using spontaneous or jet ventilation.^[83,97,104,105] Prior to the induction of anesthesia, it is important that anesthesiologists review all preoperative imaging studies and identify the degree and location of airway compression or collapse. While some areas of stenosis may be bypassed or supported with a standard or reinforced ETT, critical stenosis may require rescue with rigid bronchoscopy or even extracorporeal

support should standard approaches to ventilation prove insufficient.

Surgical management with an open approach is the standard for high-grade defects and lesions that are not responsive to conservative measures, or are associated with concomitant congenital vascular anomalies.^[103,104,106] Major tracheal operations require alternative strategies for oxygenation and ventilation during the time period when the trachea is opened for repair. In some settings, a sterile ETT is passed into the distal trachea or a main stem bronchus, thereby allowing mechanical ventilation.^[107] In other, complex open reconstructions, such as those needed for the highest grade laryngotracheal clefts, the maintenance of oxygenation and ventilation is only possible with the use of either cardiopulmonary bypass or extracorporeal membrane oxygenation.^[103,108]

Mediastinoscopy: Mediastinoscopy is a relatively uncommon, but effective, diagnostic procedure in the pediatric population and is used for access to tissue in the anterior mediastinum, either through a cervical approach or an anterior approach.^[109-111] Although spontaneous ventilation is usually preferred in the setting of mediastinal masses, neuromuscular blockade is usually used to minimize the risk of intraoperative complications secondary to patient movement. Since these procedures are commonly performed in the head-up position to minimize venous engorgement, disruption of vascular integrity may lead to an air embolism which would be exacerbated by spontaneous ventilation. For these reasons, with appropriate patient selection and preparation, general anesthesia with an ETT and administration of neuromuscular blocking agents is a common and safe approach to mediastinoscopy in pediatric patients.^[109,110]

Although blood loss is generally minimal, the proximity of the procedure to the great vessels warrants large bore intravenous access and readily available cross-matched blood. The anesthesiologist should be prepared for rapid conversion to open thoracotomy or sternotomy if needed. Lower extremity peripheral intravenous catheters may be preferred in patients with signs of significant superior vena cava obstruction, in whom upper extremity blood return to the heart may be diminished. When placing standard anesthetic monitors, it is useful to place one pulse oximeter saturation probe on each upper extremity. The right probe waveform is used to monitor for unintentional compression of the innominate artery during the procedure, which would risk hypoperfusion of the right carotid artery with resultant cerebral ischemia. The left probe provides

a continuous oximetry reading and plethysmography for the systemic circulation. The utilization of near-infrared spectroscopy monitors placed on the forehead may also alert the anesthesiologist of any changes in cerebral oxygenation and perfusion.

For the procedure, the operating room table is usually turned 90° from the anesthesiologist and the patient positioned with a shoulder roll underneath the scapulae. The neck is extended while the table tilted to allow for a slightly head-up position, approximately 30°, to minimize engorgement of the vasculature in the mediastinal space. For the superior, or cervical, approach, a small transverse suprasternal incision is made, and the scope is advanced through the pretracheal fascia into the mediastinum.^[111] An alternative approach to anterior mediastinal masses is with anterior mediastinoscopy, in which an incision is made between the second and third intercostal spaces. Although the surgical visibility is better and there is less risk of damage to the major mediastinal structures, the anterior approach is often reserved for patients who are already experiencing complications of the mediastinal mass, for whom a cervical or superior approach is contraindicated. Therefore, these patients may be at higher risk of cardiovascular or respiratory compromise under anesthesia.

Thoracotomy and thoracoscopy: Although advances in minimally invasive surgical techniques continue to improve, the thoracotomy remains an important component of surgical management.^[112-116] Access to the entire chest cavity is offered most easily through a posterolateral incision, usually through the 4th or 5th interspace.^[117,118] Muscle sparing techniques and an axillary approach have been suggested to potentially improve early postoperative lung function, reduce requirements for pain medications, and minimize long-term musculoskeletal complications such as thoracic and spinal deformities.^[22,119] During thoracoscopy, the anesthesiologist should be cognizant that with port placement, needle entry below the 3rd or 4th interspace has the potential to result in injury to abdominal organs.^[114]

The standard lateral decubitus position is employed for most indications, although a modified supine or prone position may be necessary to allow access for anterior or posterior thoracoscopic procedures, respectively.^[118,120] After patient positioning, if OLV is used, its efficacy is again demonstrated, and the lung isolation technique is adjusted as needed. At the start of thoracoscopic surgery, the operative hemithorax may be insufflated with CO₂ using a needle in order to further collapse the lung and avoid injury during trocar placement.^[116,121] An artificial pneumothorax with CO₂

improves lung compression and surgical visualization, and may even prevent the need for OLV, especially in neonates and infants.^[114,118,120,122] Low insufflation pressures and flow rates of CO₂ tend to be well tolerated from a hemodynamic standpoint in both animal and clinical studies.^[122,123] However, excessive increases in intrapleural pressure may significantly compromise cardiopulmonary function.^[124] Pressures are generally limited to less than 10 mmHg and flow rates to less than two liters per minute in older children, and reduced further to 4–5 mmHg with one liter per minute of flow in neonates and infants.^[125] Following completion of the surgical procedure, recruitment breaths are administered to the operative lung under visualization by the surgeon. Most patients undergo tracheal extubation following return to the supine position and reversal of neuromuscular blockade.

Evaluations of safety and outcomes for thoracoscopy versus thoracotomy in children have found mixed results.^[126-129] Some studies report lower incidences of thoracic and spinal deformities,^[130] potential improvements in long term-pulmonary function,^[9] and no increases in complications in patients undergoing lobectomies via thoracoscopy.^[121,131-133] However, during thoracoscopy with utilization of an artificial pneumothorax, CO₂ insufflation leads to a high rate of systemic CO₂ absorption.^[134,135] In infants undergoing repair of congenital diaphragmatic hernia (CDH) and TEF via thoracoscopy, this is associated with significant intraoperative hypercapnia and acidosis, leading some groups to question its safety.^[136-138] Other groups have found that with careful patient selection and the use of low insufflating pressures and alternative ventilatory strategies, many neonates can be safely managed during thoracoscopic repair of their lesions.^[77,78,125,137,139]

Intraoperative Anesthetic Care for Specific Lesions

Congenital Thoracic Lesions: Congenital thoracic lesions are a heterogeneous group of developmental lesions that includes congenital pulmonary airway malformation (CPAM, formerly known as congenital cystic adenomatoid malformation or CCAM), intralobar and extralobar pulmonary sequestration (IPS and EPS, respectively), and congenital lobar emphysema (CLE, also known as congenital large hyperlucent lobe). Patients with these lesions frequently present in infancy for surgical lobectomy, although some lesions are amenable to segmentectomy or wedge resection.^[133,140-142] A unique consideration in this patient population is the variable response of the individual lesions to positive pressure ventilation. Any lesion with an abnormal connection to the tracheobronchial tree, in particular CLE and some cases of CPAM, is at risk of progressive distention

with ventilation due to a ball-valve effect within the diseased area, with deleterious effects on both the surrounding lung parenchyma and the major structures of the thorax necessitates. Therefore, it is crucial that the expected behavior of the lesion be determined prior to the induction of anesthesia. Additionally, the preoperative evaluation of these patients should also recognize an elevated incidence of comorbid anomalies, including up to 20% for CHD in patients with CLE,^[142] and CDH in 20%–30% of patients with EPS.^[143] Induction of anesthesia should maintain spontaneous ventilation if there is any concern over a potential ball-valve effect, until either the contralateral lung is isolated with OLV, or the hemithorax is opened. An inhalational technique is often preferred, but carefully titrating a combination of intravenous medications may be possible as well. If the review of the anatomy and the lesion show that positive pressure ventilation will be tolerated, the induction of anesthesia can be followed by the administration of a neuromuscular blocking agent.

CPAM is one of the more common congenital lung malformations and consists of tissue with cystic, solid, or mixed components that communicates with the normal tracheobronchial tree, but does not participate in gas exchange.^[144,145] The majority of lesions are diagnosed during antenatal sonography, and fetal interventions may be offered at some specialized centers.^[146] The majority of neonates will be asymptomatic at birth, although a third may present with respiratory distress in the neonatal period. For patients with asymptomatic CPAMs, the timing of resection continues to be a source of great debate, although it is generally considered appropriate to resect lesions prior to the onset of symptoms.^[140,141] In fact, the development of symptoms prior to resection has been associated with increased postoperative morbidity in these patients.^[147] Although there is a small risk of expansion of cystic components with positive pressure ventilation, the majority of CPAMs are not impacted in this manner, and a routine induction with neuromuscular blockade is appropriate.^[18]

A pulmonary sequestration is a portion of lung parenchyma that is isolated from the remainder of the lung tissue and is lacking a connection to the tracheobronchial tree.^[143] Extralobar and intralobar pulmonary sequestration (EPS and IPS, respectively) are distinct clinical entities.^[143,148] EPS exists outside of the normal pleura surrounding the lung; the majority are found on the left side, between the lower lobe and the diaphragm. Eighty percent of lesions receive their arterial blood flow from the descending thoracic or abdominal aorta, and 80% have venous drainage into the azygous system. Associated anomalies are present in more

than 65% of patients, with a high incidence of CDH. IPS exists within a lobe of the lung and has no separate pleural surrounding. Ninety-eight percent are found in the lower lobes, and they almost exclusively drain normally into the pulmonary veins. Comorbid congenital anomalies are rare. Whereas EPS presents in infancy with respiratory distress, most cases of IPS will present in older children and even young adults with symptoms of recurrent infection. High resolution computed tomography has long been the gold standard to delineate the blood supply and drainage of the lesion during surgical planning, although magnetic resonance imaging is utilized with increasing frequency.^[140] Since neither IPS nor EPS have a bronchial connection, there is no risk of overexpansion with positive pressure ventilation. OLV is utilized only to facilitate surgical visualization during identification and ligation of the feeding arterial vessels and the venous drainage.

Congenital lobar emphysema (CLE) is a rare developmental lung malformation that is defined as the hyperinflation of one or more pulmonary lobes due to partial obstruction of the bronchus from any one of a number of causes.^[142,149] Almost half of patients are symptomatic at birth with varying degrees of respiratory distress, and the remaining half usually present within 6 months of life. The left upper lobe is most commonly affected, followed by the right middle and the right upper lobe; the lower lobes are rarely affected. While some asymptomatic lesions may be followed conservatively, the presence of symptoms warrants surgical intervention.^[140,142] These lesions are at particularly high risk of progressive over inflation secondary to a ball-valve effect. In the perioperative period, this is of concern during positive pressure ventilation, but it can, in fact, also occur in the spontaneously breathing and crying child.^[142] An inhalational induction is the preferred approach for these patients, with the avoidance of nitrous oxide given its potential to expand the abnormal lung further. Lung isolation and high-frequency jet ventilation are both useful methods in the perioperative period,^[150] although some patients may tolerate gentle positive pressure ventilation to both lungs without deterioration in their cardiopulmonary status.^[149,151] Opening of the thoracic cavity and externalization of the affected lobe will prevent any further effects from the lesion, and may be lifesaving in the event of acute deterioration.^[142]

Tracheo-esophageal fistula (TEF): Esophageal atresia (EA) occurs in approximately 1 in 4,500 births and is usually associated with a tracheoesophageal fistula, the most common of which is a distal fistula with proximal EA.^[152] The fistula is typically located slightly above the carina, but may also be located either directly at or below this

level [Figure 9]. More than half of patients with TEF also present with comorbid congenital anomalies, ranging from the presence of well-described syndromes, such as VACTERL association (vertebral, anorectal, cardiac, tracheoesophageal fistula, renal, and limb abnormalities) and CHARGE association (coloboma, heart defects, choanal atresia, growth retardation, genital anomalies, ear abnormalities), to chromosomal abnormalities and isolated organ system defects.^[11,153,154] CHD is the most commonly encountered comorbid condition and its presence is associated with increased perioperative mortality.^[16,153,155] Therefore, a preoperative echocardiogram is indicated in all patients prior to proceeding to surgical repair.

Traditional teaching for the induction of general anesthesia for TEF repair is to avoid positive pressure ventilation until the fistula is either occluded or bypassed with an ETT, in order to prevent gastric distention,^[156] resultant impairments in ventilation, and the reflux of gastric contents into the airway. One method for bypassing the fistula is to place the tip of the ETT between the fistula and the carina by advancing the ETT blindly into the right main bronchus and then gradually withdrawing it just until breath sounds are first heard on the left side. Alternatively, a device such as a Fogarty catheter may be placed into the fistula under bronchoscopic guidance. Currently, practice may be shifting toward the administration of neuromuscular blockade and gentle positive pressure ventilation without direct occlusion of the fistula site.^[152] However, occlusion may be necessary in the setting of large, distal fistulas or poor pulmonary compliance.^[16] Lung isolation is not usually required in TEF repair for surgical exposure.

Following the induction of anesthesia, bronchoscopy is performed by some centers in order to identify the location of the fistula, guide endotracheal intubation, or facilitate placement of an occlusive device in the fistula to assist with ventilation.^[152,155] Thoracotomy remains the most common

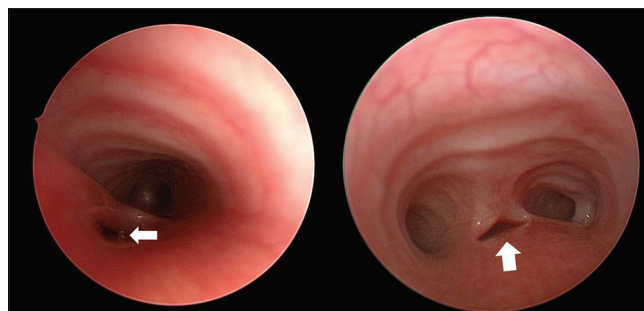


Figure 9: Tracheoesophageal fistulae (arrows). There can be significant variation in the position, size, and shape of the opening of the fistula. Here, one fistula is located above the carina (left image) and one is located directly at the level of the carina (right image)

surgical approach, although thoracoscopic repairs have been utilized with increasing frequency.^[157,158] In either approach, the repair will include ligation of the fistula and the repair of the esophageal atresia.^[112] In most cases, the EA is repaired using a primary anastomosis; however, occasionally a staged approach is utilized in which the fistula is ligated, and the atresia is repaired at a later time.

Whether the neonate's trachea is extubated at the end of the case is frequently institution-dependent, with many electing to continue mechanical ventilation into the postoperative period, with or without neuromuscular blockade.^[153,154] There is a theoretical risk of disruption of the anastomosis should postoperative noninvasive positive pressure ventilation be necessary, but this has not been well described in clinical practice.^[111] There is a higher incidence of upper airway complications following tracheal extubation in this population, including vocal cord paralysis,^[159] which may be more common with a thoracoscopic approach.^[160]

Congenital diaphragmatic hernia: Congenital diaphragmatic hernia is a developmental defect of the diaphragm that allows herniation of the abdominal contents into the thoracic cavity with associated pulmonary and vascular hypoplasia.^[161] Historically, CDH was treated as a surgical emergency; however, current practice is usually to delay repair until physiologic stability has been achieved.^[162,163] This is often defined as an oxygen saturation greater than 92%, age-appropriate blood pressure requiring no more than low-dose vasoactive infusions, pulmonary artery pressure less than systemic pressure, and absence of anemia.^[164] Ventilatory management of these neonates in the intensive care unit focuses on the avoidance of barotrauma and the tolerance of permissive hypercapnia.^[165] These strategies, which should be continued throughout the intraoperative period, include maintaining a peak inspiratory pressure less than 25 cm H₂O and the use of positive end expiratory pressure of 3–5 cm H₂O to achieve a preductal oxygen saturation greater than 85% and a PaCO₂ less than 60 mmHg.^[162] When these goals cannot be achieved with conventional mechanical ventilation, high-frequency oscillatory ventilation or extracorporeal membrane oxygenation may be used.^[163]

As described previously, the utilization of a thoracoscopic approach for CDH repair remains controversial,^[165] and even proponents of the technique recognize that there are many patients who are not suitable candidates.^[139,166] An initial study into predictive factors for successful thoracoscopic repair of CDH found that neonates with the following characteristics were appropriate candidates for

thoracoscopic repair: (1) no comorbid congenital heart disease; (2) no extracorporeal membrane oxygenation requirement; (3) peak inspiratory pressures lower than 26 cm H₂O during mechanical ventilation; and (4) oxygen index less than 5 on the day of surgery. The patients with a minimally invasive approach had a faster return to full enteral feeds, required fewer postoperative ventilatory days, and received less opioid medications and sedatives during recovery.^[167]

Anterior mediastinal mass: Patients with anterior mediastinal masses pose a particular challenge to anesthesiologists, as the induction of general anesthesia or even the administration of sedation has the potential to result in total airway obstruction, compression and collapse of the great vessels, and cardiac arrest with the inability to provide effective resuscitation [Figure 10]. Given this risk, if tissue is necessary for diagnosis and guidance of therapy, it should be obtained through biopsy of sites outside of the main mediastinal mass under local anesthesia, whenever possible. If the decision is made to proceed with general anesthesia for either biopsy, resection, or emergent need for other surgery, spontaneous ventilation should be maintained.^[168,169] Preoperative assessment for these patients should elicit their current symptomatology and review all imaging studies. Several measurements on computed tomography have been suggested for use in identifying the high-risk population who may develop complete airway obstruction during anesthetic induction.^[170,171] The presence of preoperative orthopnea, upper body edema, and bronchial or great vessel compression has also been used to predict adverse outcomes.^[172] For the highest risk patients, it is often appropriate to initiate therapy without a tissue diagnosis, rather than expose patients to the impact of sedation and general anesthesia.^[169]

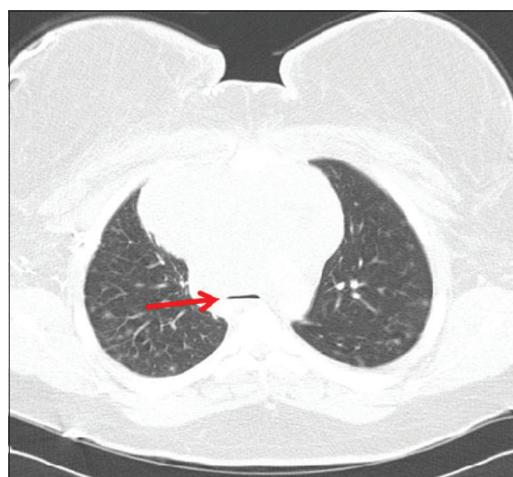


Figure 10: Anterior mediastinal mass. Computed tomography imaging demonstrates a large anterior mediastinal mass and severe tracheal compression (red arrow)

Summary

The provision of safe and effective anesthetic care during thoracic surgery in children necessitates a thorough understanding of the fundamental principles of both pediatric and thoracic anesthesia. These patients may be otherwise healthy or may present with a variety of comorbid congenital anomalies and markedly diminished baseline physiologic reserve. Unique considerations specific to this practice setting include the potential requirement for alternative ventilatory strategies including OLV, the possibility of an airway that is shared with the surgeon, and the implications of positive pressure and mechanical ventilation for the commonly encountered surgical lesions. Thoracoscopic procedures, which may improve the postoperative course, also pose a specific set of challenges and risks. Although there are several general principles for pediatric thoracic surgery, the anesthetic approach must be adjusted and tailored to each specific child, with vigilance maintained throughout the entire perioperative period.

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