Anesthesia in Thoracic Surgery

5

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5.1 Introduction

In the pediatric population, thoracic surgery is performed to treat a great variety of pathologies, and it may be challenging for the anesthesiologist.

Children may present in varying age and weight and may present with different degrees of pulmonary compromise; so, it is mandatory for the anesthesiologist to understand the pediatric physiology as well as the principles of pediatric anesthesia and thoracic anesthesia in order to provide the best and safe care for these children [1, 2].

Video-assisted thoracoscopic surgery (VATS) is a less invasive approach for thoracoscopic surgery. It renders less postoperative pain, fewer operative complications, and shortened hospital stay. This makes VATS favorable for pediatric patients [3].

This chapter delineates anesthetic management of children submitted to thoracic surgery, the methods to obtain single lung ventilation (SLV), the difficulties encountered while surgery proceeds, and the management of special circumstances. Cardiac surgery is beyond the scope of this review.

The main aspects of the management of postoperative pain will be underlined.

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5.2 Preoperative Evaluation

Different management is required at different ages, and the wide spectrum of conditions and physiologic compensatory mechanisms involved demand each patient an individual and complete assessment.

Preoperative evaluation has the goal to gain information regarding the patient's current status, familiarity, key elements of the child's medical history, and coexisting congenital or acquired conditions such as cardiac diseases or bronchopulmonary dysplasia.

In particular, for younger patients, the medical history begins with the prenatal course and neonatal period because events during pregnancy and delivery may influence the child's current health status [4]. A complete review of systems should be included with emphasis placed on medical comorbidities that may influence either the choice or the outcome of anesthesia [5].

The older patients affected by the thoracic disease may present exercise intolerance, dyspnea, cyanosis, wheezing, coughing, and weight loss, while infants often show fewer specific signs such as poor feeding, irritability, or change in sleep habits [1].

During the visit, a complete and accurate physical examination must be performed; of course, all children undergoing thoracic surgery should have a complete examination of the airway in order to detect potential airway

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management problems, upper respiratory tract infections, abnormal airway or extrinsic tracheal compression that may create difficult intubation, or issues in the placement of devices for SLV. All these findings could increase the anesthesia risks. The physical examination should seek to discover signs of cardiac compromise, such as irritability, rales, cyanosis, jugular venous distention, and hepatomegaly, as a consequence of the primitive disease on the cardiocirculatory system.

Laboratory investigations should be selected regarding the presenting disease and the procedure being performed. A complete blood count (CBC) should be obtained preoperatively and, since blood transfusion may be necessary, the preoperative assessment should include blood type, antibody screen, and blood crossmatch. A chest X-ray is always necessary for those children who are prone to be submitted to the thoracic procedure which the anesthesiologist must evaluate for pulmonary and mediastinal findings, scoliosis, deviation of the trachea, engorgement of the vascular structures, and abnormal cardiac profile.

A CT scan is needed in almost all cases scheduled for surgery; it helps to evaluate the pulmonary parenchyma and its anomalies; to detect the position and the extent of mediastinal masses and their relationships with the surrounding structures such as hearth, great vessels, trachea, and bronchi; to evaluate the position and diameter of the trachea, and to study the abnormalities of the chest.

Patients undergoing thoracic surgery, in particular the youngest and those most affected, are frequently unable to adequately perform preoperative pulmonary functional tests (PPFT). Moreover, as demonstrated by Yuan [6] and Burjek [7], in patients undergoing spinal fusion, there is no association between results, postoperative prolonged intubation, and intensive care unit admission. For these reasons, PPFT are not routinely used for preoperative assessment in a patient scheduled for thoracic surgery.

An ECG and transthoracic echocardiography are needed to evaluate the cardiac anatomy and function in patients with symptoms of hemodynamic compromise.

Moreover, during the preoperative visit begins the relationship among the anesthesiologist, the child, and his family; the anesthetic plan and its risk should be outlined such as the options for postoperative analgesia and the postoperative disposition.

5.3 Intraoperative Management

An inhalation anesthetic agent (sevoflurane) or, if an intravenous (IV) line is present, propofol or midazolam may be used for induction of anesthesia. Opioids (fentanyl and remifentanyl) and neuromuscular blocking drugs (rocuronium and cisatracurium) are administrated to reach a good anesthesia level and to facilitate endotracheal intubation. For open thoracotomies in neonates and infants, SLV is not generally needed because the surgeon is usually able to manually retract the lung. Thoracoscopic procedures may require SLV to improve visualization and reduce the risk of injury of the lung and adjacent structures. If needed the SLV will be established (see later) and mechanical ventilation started with a fraction of inspired oxygen (FiO_2) and tidal volume calibrated on peripheral capillary oxygen saturation (SpO_2) and the amount of carbon dioxide in exhaled air ($EtCO_2$).

For maintenance of anesthesia, there are many options: sevoflurane or propofol plus remifentanil by continuous infusion. The author's choice is sevoflurane plus remifentanil for children under 12 years of age and propofol in target-controlled infusion (TCI) plus remifentanil for adolescents. In neonates, propofol is contraindicated and sevoflurane may precipitate hypotension, especially in those with poor cardiac function or hypovolemic so the association midazolam/remifentanil by continuous infusion is generally preferred.

Regarding the possibility that inhalation anesthesia may impair hypoxic pulmonary vasoconstriction (HPV) and may increase intrapulmonary shunt and hypoxemia, no evidence indicates that the drug used to maintain anesthesia (intravenous versus inhalational) during SLV may affect patient outcomes [8]. A thoracic epidural catheter

may be beneficial in thoracotomy or thoracoscopic procedures when thoracostomy tube drainage is placed following surgery.

To carefully monitor arterial blood pressure and arterial blood gases during intraoperative lung manipulations and SLV, arterial catheterization is strongly recommended. It should be considered mandatory in patients undergoing thoracotomy, neonates, and those with severe lung disease undergoing thoracoscopic surgery. It may be avoided for short thoracoscopic procedures in patents without severe lung diseases. If extensive blood loss is expected or if the patient is already critical, a central venous catheter is recommended to administrate catecholamines and to monitor central venous pressure.

Temperature monitoring is mandatory in neonates and infants and children undergoing long procedures; a bladder catheter with a temperature probe allows central temperature and urine output monitoring.

5.4 Single Lung Ventilation (SLV) During Pediatric Thoracic Surgery

5.4.1 Ventilation and Perfusion During Thoracic Surgery: Adults versus Children

Ventilation and perfusion (V/Q) are highest on the most dependent portion of the lungs for adults and children due to pressure gradient and gravitational pull. Both factors (V and Q) should be well matched. However, during SLV IN VATS, there are factors that can increase V/Q mismatch because of a decrease in functional residual capacity and tidal volume. General anesthesia, suboptimal patient positioning, surgical retraction, and mechanical ventilation contribute to V/Q mismatch [9]. HPV minimizes V/Q mismatch by diverting blood flow away from the atelectatic under-ventilated lung. The HPV response is maximal at normal and decreased at either high or low pulmonary vascular pressure [10].

Furthermore, one can attain maximal HPV when partial pressure in venous blood (PvO_2) is normal and with a decreased response when either high or low PvO_2. Therefore, the use of inhalational anesthetic agents and other vasodilating drugs, together with high or low FiO_2, will diminish HPV response [11]. This principle holds true for children and young adults [12].

The impact of lateral decubitus position on V/Q mismatch on the other hand is different in infants when compared to teens and adults. In adults with unilateral lung disease, oxygenation is optimal when the patient is placed in the lateral decubitus position with the healthy lung dependent (“down”) and the diseased lung nondependent (“up”) because ventilation is normally distributed preferentially to dependent regions of the lung so that there is a gradient of increasing ventilation from the most nondependent to the most dependent lung segments [13, 14].

Presumably, this is related to an increase in blood flow to the dependent, healthy lung and a decrease in blood flow to the nondependent, diseased lung because of the hydrostatic pressure (or gravitational) gradient between the two lungs. This phenomenon promotes V/Q matching in the adult patient undergoing thoracic surgery in the lateral decubitus position.

In infants with unilateral lung disease, oxygenation is improved with the healthy lung “up” [15]. Several factors account for this discrepancy between adults and infants. Infants have a soft, easily compressible rib cage that cannot fully support the underlying lung. Functional residual capacity, therefore, is closer to residual volume, making airway closure likely to occur in the dependent lung even during tidal breathing [16]. When the adult is placed in the lateral decubitus position, the dependent diaphragm has a mechanical advantage because it is “loaded” by the abdominal hydrostatic pressure gradient. This pressure gradient is reduced in infants, reducing the functional advantage of the dependent diaphragm. The infant’s small size also results in a reduced hydrostatic pressure gradient between the nondependent and dependent lungs. Consequently, the favorable increase in perfusion to the dependent, ventilated lung is reduced in infants. Thereby, during thoracic surgery, several factors interact to affect the ventilation/perfusion

(V/Q) balance. Compression of the dependent lung in the lateral decubitus position and SLV with the collapse of the operative lung are both responsible for atelectasis. Hypoxic pulmonary vasoconstriction acts to divert blood flow away from underventilated lung regions, thereby minimizing any V/Q imbalance. However, the overall effect of the lateral decubitus position on the V/Q balance is different in infants compared to older children and adults.

Finally, the infant's increased oxygen requirement, coupled with a small functional residual capacity, predisposes to hypoxemia. Infants normally consume 8–10 mL of oxygen kg/min compared to normal oxygen consumption in adults of 2–3 mL/kg/min [17]. For these reasons, infants are at increased risks of significant oxygen desaturation during surgery in the lateral decubitus position.

5.4.2 Indications and Techniques for SLV in Infants and Children

It has been long established that there are differences between the pediatric and adult airways that are well known to the anesthesiologist. Of all the airway differences, it is the smaller size of the pediatric airway that necessitates the need for a range of airway devices to provide SLV. The preferred method of lung isolation in the adult population, a double-lumen tube (DLT), cannot be used in infants and small children because of the smaller airway size.

The anesthesiologist must have proficient knowledge of tracheobronchial anatomy in order to optimally place lung isolation devices and troubleshoot problems using fiberoptic bronchoscopy. Prior to 1995, nearly all thoracic surgery in children was performed by thoracotomy. In the majority of cases, anesthesiologists ventilated both lungs with a conventional tracheal tube, and the surgeons retracted the operative lung to gain exposure to the surgical field. During the past decade, the use of video-assisted thoracoscopic surgery (VATS) has dramatically increased in both adults and children. Reported advantages of thoracoscopy include smaller chest incisions, reduced postoperative pain, and more rapid postoperative recovery compared to thoracotomy [18–20]. Video-assisted thoracoscopic surgery is being used extensively for pleural debridement in patients with empyema, lung biopsy, and wedge resections for interstitial lung disease, mediastinal masses, and metastatic lesions. More extensive pulmonary resections, including segmentectomy and lobectomy, have been performed for lung abscesses, bullous disease, sequestrations, lobar emphysema, cystic adenomatous malformations (CPAM), and neoplasms. In select centers, more advanced procedures have been reported, including the closure of patent ductus arteriosus, repair of hiatal hernias, and anterior spinal fusion. VATS can be performed while both lungs are being ventilated using carbon dioxide insufflation and placement of a retractor to displace lung tissue in the operative field. SLV is extremely desirable during VATS, however, because lung deflation improves visualization of thoracic contents and may reduce lung injury caused by the use of retractors [21]. Several techniques can be used for SLV in children.

5.4.3 ABCDs of Pediatric Lung Isolation

Slinger teaches that there are the "ABCs" of adult lung isolation: anatomy, bronchoscopy, and chest imaging [21]. In pediatric lung isolation, there are still all the same "ABC" considerations, with the addition of "D" the varying diameters of the pediatric airway with age [22].

A = Anatomy

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B = Bronchoscopy

When choosing a bronchoscope to be placed within an endotracheal tube (ETT), there are two questions to ask: (1) What size bronchoscope can I use that will physically fit and(2) What size bronchoscope can I use and still ventilate the patient [22].

Bronchoscopes come in varying sizes. Bronchoscopes are labeled by the outside diameter (OD) of the scope. The sizing of various types of TTs is done differently depending on the type. A single-lumen tracheal tube (SLT) is labeled by the inside diameter (ID) of the respiration lumen. A double-lumen TT is labeled by the OD of the entire tube, with the measurement reported in French (Fr). For a well-lubricated bronchoscope to physically fit inside the lumen of the TT (and not seize up from friction), the OD of the bronchoscope (OD_B) needs to be <90% of the ID of the TT (ID_{TT}).

In order to allow some ventilation during the time of bronchoscopy, the cross-sectional area of the bronchoscope (CSA_B) cannot take up more than 50% of the cross-sectional area of the TT lumen. The smallest fiberoptic scope in general use is the Olympus BF N20, with an OD of 2.2 mm [22].

It is always a good idea to test the fit of the bronchoscope inside a TT before use in the patient.

C = Chest imaging

As part of the preoperative assessment of the patient, the anesthesiologist should always look at all available chest imaging, X-ray, or computed tomography (CT). These may reveal issues with lung isolation such as a narrowed distal trachea, or a compressed bronchus.

CT scans can also be used to assist in choosing an appropriate TT size.

D = Diameter of the pediatric airway

The average neonatal trachea has an anteroposterior diameter of about 4.3 mm for both males and females [23].

The trachea grows uniformly in males and females to about 14 mm at the age of 15 years. At this time, the female trachea stops growing. However, the male trachea continues to grow to 16–18 mm by the age of 19. The trachea is the shape of an ellipse, with the transverse diameter being larger than the anteroposterior diameter [24, 25]. The sizing of airway devices should be based on the smaller (antero-posterior) diameter.

5.4.4 Options for Lung Isolation

Frequently, infants undergoing thoracotomy do not require lung isolation. Both lungs are ventilated, and the surgeon retracts and/or packs the operative lung as needed for operative exposure increasingly; however, SLV is being requested by surgeons, especially with the advances in technology that have permitted the use of video-assisted thoracoscopic surgery in infants and small children [26].

For the surgeon, there are several advantages to using SLV. The operative lung remains deflated and calm, thereby optimizing surgical exposure and enabling adequate "working space" in a relatively small anatomic compartment. This is particularly helpful when space-occupying lesions of the thorax are present, such as congenital cystic adenomatoid malformation (CPAM), pulmonary sequestration, and bronchogenic cyst. In cases of congenital lobar emphysema, SLV can help to minimize overdistension of the pathologic lobe [3]. Lung isolation will also facilitate demarcation of normal from abnormal lung in cases where incomplete fissures between the lobes make this differentiation difficult. From a mechanical standpoint, lung isolation prevents blood and secretions from the ipsilateral lung from migrating into the trachea and contralateral lung [27]. One obstacle to good surgical exposure in pediatric patients is providing consistent, SLV with relative ease, and reliability.

Techniques for SLV in children have included the use of double-lumen endobronchial tubes (DLTs) or Univent tubes, endobronchial intubation with a standard tracheal tube, use of a Fogarty catheter as a bronchial blocker, collapse of the surgical lung by insufflation of carbon dioxide, or lung retraction. These options all have their individual limitations, and none is entirely satisfactory [28, 29]. The challenge to the anesthesiologist is to choose a safe and effective means for isolating the lungs in each individual

patient. Using the patient's age and airway measurements allows the selection of the appropriate technique and tube. Individual patient characteristics must also be considered.

Guidelines for selecting appropriate tubes (or catheters) for SLV in children are shown in Table 5.1. There are significant variabilities in overall size and airway dimensions in children, particularly in teenagers. The recommendations shown in Table 1 are based on average values for airway dimensions. Larger DLTs may be safely used in large teenagers.

5.4.4.1 Single-Lumen Endotracheal Tube

Single-lumen ETT provides the simplest means of lung isolation. Tube size selection and depth of insertion follow the standard computation based on age; supported by auscultation for breath sounds.

After tracheal intubation, the ETT can deliberately be advanced into the bronchus to isolate the lungs. Difficulties arise when the left bronchus has to be intubated. In order to achieve blind left bronchial intubation, suggested techniques are using a stylet to curve the distal end of the tracheal tube to the left, and using a distally curved rubber bougie that is directed blindly to the left bronchus, followed by railroading the tube over the bougie [30]. Another technique for left lung intubation is when the level of the tube is rotated 180° while the head is turned to the right. The ETT is advanced into the bronchus until the right breath sound disappears [31]. The abovementioned techniques do not require a more advanced equipment unless there is a need to confirm tube placement with fiberoptic bronchoscopy (FOB). Single-lumen ETT is preferred for emergencies such as contralateral tension pneumothorax [32]. One of the challenges in using a single-lumen ETT is the inadequacy to provide a good seal in the bronchus. As a result, it may not be able to provide a collapsed lung for the operative site or protect the normal lungs from contamination [33].

5.4.4.2 Univent Tube

The Univent tube (Fuji Systems, Tokyo, Japan) is a conventional ETT with a second lumen containing a small tube that can be advanced into a bronchus [34–36].

Table 5.1 Tube selection for single-lung ventilation in children

Age (years)	ETT (ID)	BB (Fr)	Univent (ID)	DLT (Fr)
0.5–1	3.5–4.0	2–3		
1–2	4.0–4.5	3		
2–4	4.5–5.0	5		
4–6	5.0–5.5	5		
6–8	5.5–6	5	3.5	
8–10	6.0 cuffed	5	3.5	26
10–12	6.5 cuffed	5	4.5	26–28
12–14	6.5–7.0 cuffed	7	4.5	32
14–16	7.0 cuffed	7	6.0	35
16–18	8.0–8.5 cuffed	7–9	7.0	35

ETT, endotracheal tube; ID, internal diameter in mm; BB, balloon-tipped bronchial blocker; Fr, French; DLT, double lumen tube.

Table 1. 26 Fr—Rusch, Duluth, GA; 28–35 Fr—Mallinckrodt Medical Inc., St. Louis, MO
ID internal diameter, *Fr* French size, *DLT* double-lumen tube
Reproduced from: Hammer GB, Fitzmaurice BG, Brodsky JB: Methods for single-lung ventilation in pediatric patients. AnesthAnalg 89:1426–1429, 1999; with permission

A balloon located at the distal end of this small tube serves as a blocker. Univent tubes require a FOB for successful placement. Univent tubes are available in sizes as small as a 3.5 and 4.5 mm ID for use in children over 6 years of age [37]. Because the blocker tube is firmly attached to the main ETT, displacement of the Univent blocker balloon is less likely than when other blocker techniques are used. The blocker tube has a small lumen that allows egress of gas and can be used to insufflate oxygen or suction the operated lung.

The main disadvantage of Univent tubes is that the cross-sectional diameter of the ventilation lumen is smaller in order to accommodate the blocker lumen. This increases airway resistance also limits the size of the fiberoptic bronchoscope that may be used to facilitate positioning [38]. The Univent tube's blocker balloon has low-volume, high-pressure characteristics, so mucosal injuries can occur during normal inflation [39–41]. It is important to remember that the size of a Univent TT refers to the ID, where the OD will be much larger than the equivalent sized SLT. There is only a narrow age range, where the Univent tube is the preferred method for pediatric lung isolation. The Univent TT is not suitable under the age of 6, whereas DLT is the preferred method for patients older than 8 years.

5.4.4.3 Bronchial Blockers

Balloon-tipped bronchial blockers (BB) remain the "technique of choice" in pediatric patients under the age of 6 years [11]. This is because Univent 3.5 uncuffed version tube (recommended for 6–8 years old) and double-lumen EBT (recommended for 8–10 years old) diameters are big for the before mentioned age-group [8]. A variety of balloon-tipped catheters have been used for single lung ventilation, including an Arrow balloon wedge catheter (1) (Arrow International, Inc., Reading, PA), a Cook pediatric bronchial blocker (2) (Arndt blocker, Cook Medical, Inc., Bloomington, IN), and a Fogarty embolectomy catheter (Edwards Lifesciences Corp, Irvine, CA) (3).

Arndt pediatric endobronchial blocker (Cook Critical Care, Bloomington, IN, USA) is a Food and Drug Administration-approved device used to facilitate one-lung ventilation in children and adults. The smallest diameter endobronchial blocker currently manufactured is 5 Fr and can be inserted through an endotracheal tube with an internal diameter of 4.5 mm or greater.

The bronchial blocker is passed through a specialized adapter that is placed at the proximal end of the tracheal tube. This adapter contains the following four ports (Figs. 5.1 and 5.2):

- a connection to the tracheal tube
- a standard 15-mm adaptor for the anesthesia circuit
- a port for the bronchial blocker with a self-sealing diaphragm that can be tightened around the bronchial blocker to hold it in place, and a port for the flexible bronchoscope.

The bronchoscope is passed through its port and then through the wire loop at the end of the bronchial blocker. The bronchoscope and bronchial blocker are then passed under direct vision as a single unit into the main bronchus of the

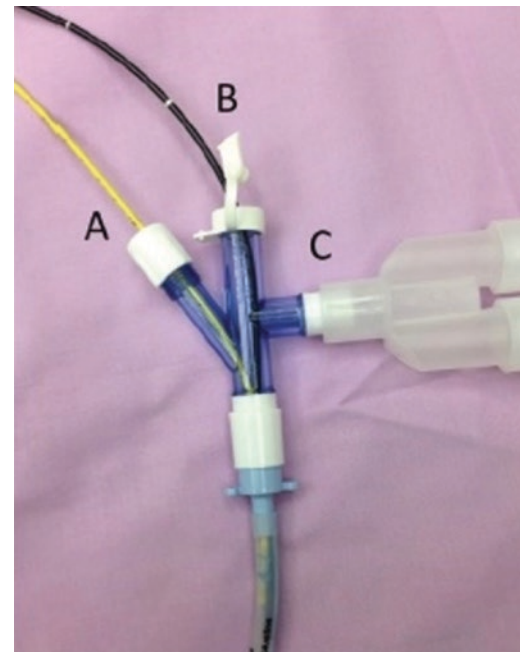

Fig. 5.1 Arndt endobronchial blocker® by Cook, Multiport airway adapter: (**a**) Blocker port, (**b**) FOB port, (**c**) Ventilation port

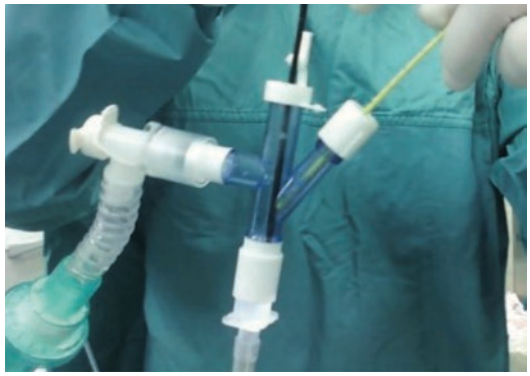

Fig. 5.2 Arndt endobronchial blocker kit

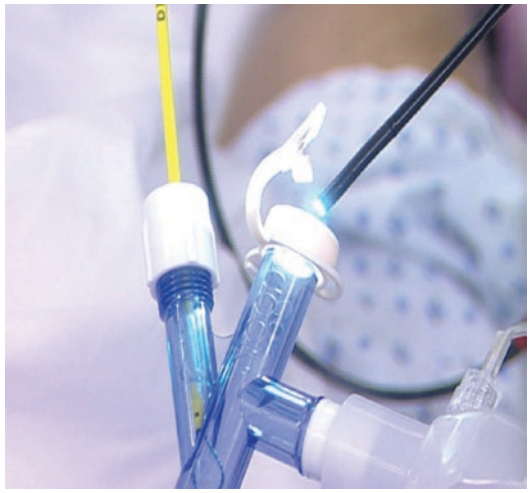

Fig. 5.3 Arndt endobronchial blocker® wire loop is coupled with FOB to direct the blocker to the mainstem bronchus

operative side (Figs. 5.3, 5.4, and 5.5), and the balloon is inflated under direct visualization (Fig. 5.6). When correct placement has been confirmed, the wire loop is removed from the central channel.

The Arndt blocker has a 2-mL cuff and lower inflation pressures and an inner lumen that contains a flexible nylon wire that extends along the length of the catheter and terminates as a flexible loop. This loop slides over the bronchoscope and aids in positioning. It is important to note that once the nylon guide is removed, it cannot be reattached, which may make repositioning attempts difficult should the blocker fall out of place. In the first generation of this device, it was

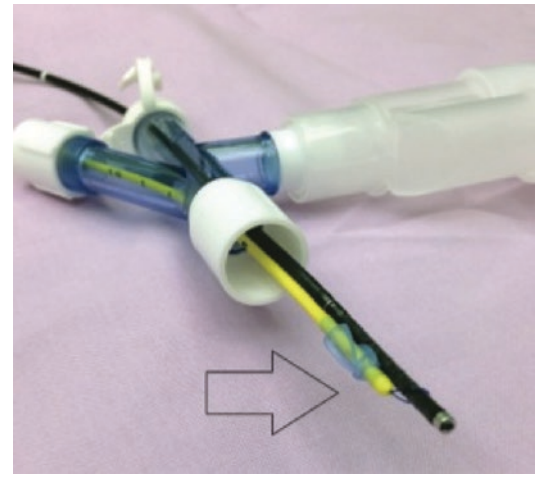

Fig. 5.4 Arndt endobronchial blocker® wire loop is coupled with FOB to direct the blocker to the mainstem bronchus

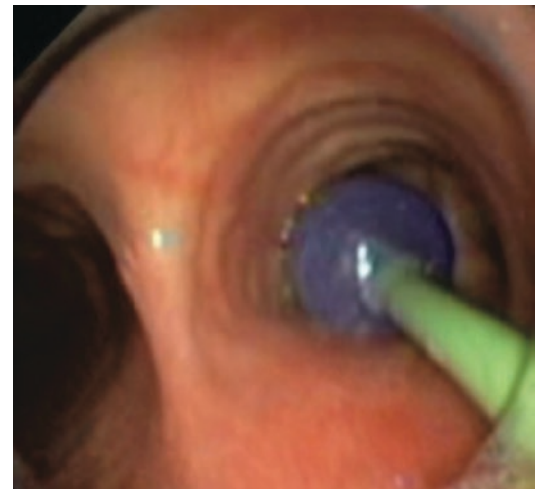

Fig. 5.5 Display the proper placement of a BB with the balloon fully inflated in the right mainstem bronchus

not possible to reinsert the string after it had been pulled out, losing the ability to redirect the bronchial blocker if necessary. Once the nylon wire is removed, the central lumen may be used for suctioning and to apply continuous positive airway pressure (CPAP).

The risk of hypoxemia during blocker placement is diminished, and repositioning of the blocker may be performed with fiberoptic guidance during surgery. Even with the use of a FOB with a diameter of 2.2 mm, however, the indwell-

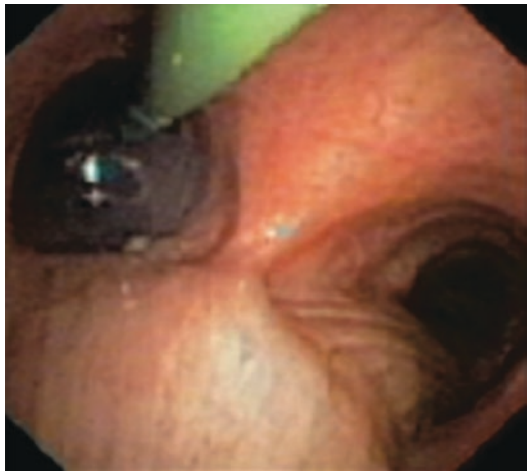

Fig. 5.6 Display the proper placement of a BB with the balloon fully inflated in the left bronchus

ing ETT must be at least 5 mm internal diameter (ID) to allow passage of the catheter and FOB. The use of this technique, therefore, is generally limited to children between the age of 18 months and 2 years

When a bronchial blocker is placed alongside the ETT, it can be placed directly into the bronchus on the operative side using direct laryngoscopy followed by fiberoptic guidance.

Alternatively, the mainstem bronchus on the operative site can be intubated, the bronchial blocker can be passed through the ETT, the ETT is then withdrawn, and the trachea reintubated so that the bronchial blocker lies on the outside of the ETT. Personal preference is to perform direct laryngoscopy and place the bronchial blocker through the glottic opening into the tracheal lumen followed by tracheal intubation with the ETT.

The OD necessitates a large SLT (at least 8.0 mm) to accommodate the bronchial blocker. Because the smallest lumen through which the pediatric endobronchial blocker can be inserted is an endotracheal tube with a 4.5mm internal diameter, it cannot be placed from within an endotracheal tube of a size appropriate for infants the size of our patient. However, as we have described herein, the pediatric endobronchial blocker can be effectively utilized in a small infant when attached to the outside of an appropriately sized endotracheal tube and positioned with the assistance of a fibroscope (Fig. 5.7).

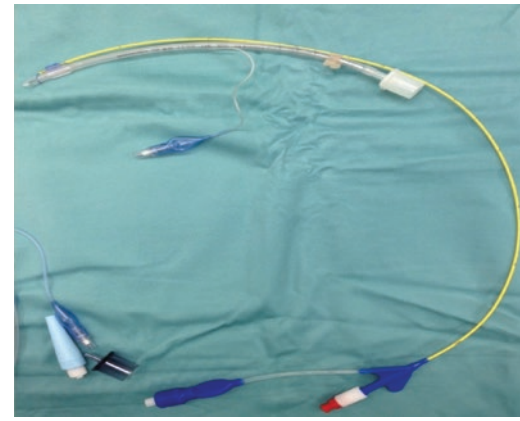

Fig. 5.7 Arndt blocker 5 French positioned outside the tube B

Given the outside diameter of the bronchial blocker and the inside diameter of the ETT in neonates, the bronchial blocker must be placed outside the ETT.

The degree to which this occurs depends on the outside diameter of the bronchial blocker and the inner diameter of the ETT. In the neonatal population, the bronchial blocker will obscure a significant percentage of the cross-sectional area of the ETT, thereby impairing ventilation. Correct placement will be guided by bronchoscopic visualization and it is not feasible, even when using ultrathin neonatal scopes, to pass both the bronchial blocker and the bronchoscope through the ETT [41].

The use of a bronchial blocker also eliminates the need to change a DLT to an SLT at the conclusion of the procedure. This is important because the airway at the conclusion of the procedure may be different from that in the initial period due to secretions and edema.

The main advantage of these blockers is that they can be placed through a conventional SLT. When a blocker is placed in the right main bronchus, it usually is positioned close to the carina to block the right upper lobe. Because the blocker balloon requires a high distending pressure, it easily slips out of the bronchus into the trachea because of changes in position or surgical manipulation. That movement can result in

Table 5.2 Arndt endobronchial blocker characteristics and guidelines

Arndt size (Fr)	External diameter (mm) cuff down	Best patient age (years)	Smallest ETT size (mm) for placement within ETT	Cuff inflation volumes (mL)	Fiberoptic bronchoscope (mm)
5.0	1.7	<8	4.5	0.5–2	2.2 or 2.8
7.0	2.3	8–12	6.5	2–6	2.8
9.0	3.0	>12	8	Spherical: 4–8 Elliptical: 6–12	2.8

obstructing ventilation and losing the seal between the two lungs (Table 5.2).

Fogarty embolectomy catheter or an end-hole, balloon wedge catheter may be used for the bronchial blockade to provide SLV [42–45]. The more commonly used Fogarty catheters come in a variety of sizes [39]. All but the smallest 2 and 3 Fr catheters have a removable guidewire that allows the user to angle the tip and direct the catheter into the desired bronchus to be isolated. The catheters may be placed either within or external to the TT. Positioning of the catheter is facilitated with a fiberoptic bronchoscope before balloon tip inflation. Because the Fogarty catheter has a low-volume, high-pressure balloon, it is imperative that a fiberoptic bronchoscope is used to observe the position and inflation of the balloon catheter to avoid damaging bronchial mucosa [46].

Placement of a Fogarty catheter is facilitated by bending the tip of its stylet toward the bronchus on the operative side. A fiberoptic bronchoscope may be used to reposition the catheter and confirm appropriate placement. When an end-hole catheter is placed outside the ETT, the bronchus on the operative side is initially intubated with an ETT. A guidewire is then advanced into that bronchus through the ETT. The ETT is removed, and the blocker is advanced over the guidewire into the bronchus. An ETT is then reinserted into the trachea along the blocker catheter. The catheter balloon is positioned in the proximal main stem bronchus under fiberoptic visual guidance. With an inflated balloon blocker, the airway is completely sealed, providing more predictable lung collapse and better operating conditions than with an ETT in the bronchus. There is no central channel for deflation or CPAP to the operative lung. Deflation of the operative lung occurs by absorption atelectasis and requires a considerably longer period of time.

A potential problem with this technique is the dislodgement of the blocker balloon into the trachea. The inflated balloon will then block ventilation to both lungs or prevent the collapse of the operative lung. The balloons of most catheters used for bronchial blockade have low-volume, high-pressure properties, and overdistention can damage or even rupture the airway. A recent study, however, reported that bronchial blocker cuffs produced lower "cuff-to-tracheal" pressures than double-lumen tubes (DLTs) [47].

When closed-tip bronchial blockers are used, the operative lung cannot be suctioned and CPAP cannot be provided to the operative lung if needed. Recently, adapters have been used to facilitate ventilation during the placement of a bronchial blocker through an indwelling ETT [48].

5.4.4.4 Double-Lumen Tubes (DLTs)

Often considered the gold standard for lung isolation, the double-lumen endobronchial blocker or DLT is suitable for children older than 8 years of age [49]. The DLT is composed of two lumens fused in parallel with one lumen that is angled and longer than the other and meant to be inserted into the desired bronchus, while the shorter lumen remains in the trachea. Both lumens are cuffed such that single-lung ventilation and double-lung ventilation may be easily achieved by clamping and releasing the appropriate limb on the adapter piece. Marraro [49] described a bilumen tube for infants. The inflated bronchial cuff allows ventilation to be diverted to either or both lungs and protects each lung from contamination from the contralateral side.

The equation of Size = Age × 1.5 + 14 can help to estimate the sizing needed. The smallest DLT size is a 26 Fr, which is generally suitable for children 8–10 years of age. One study sug-

gested that the use of the 26 Fr DLT may be considered for children as young as 8 years and as small as 30 kg of weight and 130 cm of height. They should meet at least two of these parameters [50]. DLTs are available in left or right-sided tubes, although the left-sided tube is more commonly used as it avoids potentially obstructing the right upper lobe bronchus. Double-lumen tubes are inserted in children using the same technique as in adults [51].

Insertion is performed by direct laryngoscopy, or in the case of a difficult airway, a fiberoptic scope or tube exchanger may be used. Once the bronchial tip is past the vocal cords, the preformed stylet is removed and the tube rotated 90° towards the desired bronchus [52]. The adapter piece is then connected and tracheal cuff inflated and connected to the ventilator. Fiberoptic bronchoscopy is recommended to confirm placement. When inflated, the bronchial cuff should still be seen within the bronchus, but the majority of the cuff should be within the bronchus to avoid dislodgement during surgery. If a bronchoscope is unavailable, placement may be confirmed by auscultation of the lungs after occlusion of ventilation to the desired lung and verifying the absence of breath sounds.

Advantages of a DLT include the ability to quickly alternate from single-lung ventilation to double-lung ventilation, ease of insertion, application of CPAP, and suctioning of the operative lung. The most obvious disadvantage of the DLT in the pediatric population is its size limitation. Because of its configuration and larger diameter, the DLT is more challenging for patients with difficult airways. When lung isolation is not needed, the bronchial cuff should be deflated to decrease the risk of mucosal injury. If postoperative intubation and ventilation are required, the DLT should be replaced with an SLT to avoid unnecessary trauma to the tracheal-bronchial tree [20].

Double-lumen tubes are safe and easy to use. There are very few reports of airway damage from DLTs in adults and none in children. Their high-volume, low-pressure cuffs should not damage the airway if they are not overinflated with air or distended with nitrous oxide while in place.

The most important problem associated with the use of a DLT is malpositioning [53, 54]. The tube can be mispositioned in several ways.

The DLT may be accidentally directed to the side opposite to the desired main stem bronchus. In this case, the lung opposite the side of the connector clamp will collapse. Inadequate separation, increased airway pressures, and instability of the DLT usually occur. Because of the morphology of the DLT curvatures, tracheal or bronchial lacerations may result. If a left-sided DLT is inserted into the right main stem bronchus, it obstructs ventilation to the right upper lobe. It is essential to recognize and correct such a malposition as soon as possible. The DLT may be passed too far down into the right or the left main stem bronchus. In this case, breath sounds are greatly diminished or not audible over the contralateral side. The tube should be withdrawn until the opening of the tracheal lumen is above the carina.

5.4.5 Strategies for Treating and Avoiding Hypoxemia During Single Lung Ventilation

Successfully performing SLV involves not only achieving lung isolation and collapse but also ensuring that oxygenation of the patient is well maintained. The following measures have been found useful in avoiding or treating hypoxemia [53]:

- Ensure correct placement of the SLV device in use (blocker or ETT). It is advisable to confirm the position of the device used after positioning the patient to rule out inadvertent displacement that may have occurred during patient positioning
- Ventilation with 100% oxygen is recommended because it not only provides a higher margin of safety but also causes vasodilatation of vessels in the dependent ventilated lung, thereby promoting redistribution of blood from the nondependent unventilated lung
- Keep the inspired concentration of the inhaled anesthetic agent to less than 1 minimum

alveolar concentration (MAC) to avoid excessive inhibition of HPV and decrease in cardiac output
- Use of 5–10 mL/kg body weight tidal volume. If the inflation pressure is high, the respiratory frequency may be increased at lower tidal volume to avoid excessive airway pressures
- Application of CPAP to the nondependent lung improves oxygenation by preventing the total collapse of the alveoli [54–56]
- A useful increase in oxygenation can be achieved with pressure as low as 1–2 cm H_2O CPAP applied to the inflated lung [57, 58]
- CPAP commenced after lung inflation is more effective than CPAP commenced from a fully deflated lung because the opening pressure of collapsed alveoli is higher than the CPAP pressure. CPAP greater than 10 cm H_2O should be avoided because it may lead to excessive inflation of the operative lung and interfere with the surgical procedure
- Application of 5–10 cm H_2O positive end-expiratory pressure (PEEP) to the dependent ventilated lung is helpful in some patients. This level of PEEP does not cause a significant increase in pulmonary vascular resistance that may result in diverting blood to the unventilated lung, leading to an increase in the shunt
- Adequate cardiac output must be maintained to ensure good tissue perfusion to prevent an excessive decrease in mixed venous oxygen content. Because these patients have a large shunt (20–30%), high mixed venous oxygen content will help in decreasing the effect of shunted blood in causing arterial desaturation.

5.4.6 Conclusion

To overcome the challenges of rendering one-lung ventilation technique in infants and children coming for video-assisted thoracoscopic surgery, one must be mindful of the respiratory insult caused by SLV under general anesthesia and positioning during the operation. Although it is prudent to use a device one is technically familiar with, the anesthetists must also be aware of whether if it is appropriate for the patients' age and weight (Table 5.3). Furthermore, if the device is equipped with safety features such as ventilating both lungs in the event of hypoxia, and if it can provide efficient lung isolation intraoperatively. The anesthesiologist caring for patients who require SLV and lung isolation faces many challenges. An understanding of the primary underlying lesion, as well as associated anomalies that may affect perioperative management, is paramount. Working knowledge of respiratory physiology and anatomy is required for the planning and execution of appropriate intraoperative care. Familiarity with a variety of techniques for SLV suited to the patient's needs allows maximal surgical exposure while minimizing trauma to the lungs and airways.

Table 5.3 Advantages and disadvantages of the different tubes

Single-lumen endotracheal tube	Double-lumen endobronchial tube	Balloon-tipped bronchial blockers
Advantages		
No special equipment	Faster positioning	Ideal for patients with complex airways
Preferred in emergencies	Complete lung isolation	Best device for infants and children
	No bronchoscope needed for positioning	No replacement for postoperative ventilation is required
	Lower risk of displacement	Selective lobar blockade
	It can be used in mono and bi ventilation	
Disadvantages		
Risk of hypoxemia	Only patient older than 8 years	The transition from mono to biventilation is complex
The bronchus is not perfectly sealed	Need to replace the tube at the end of the procedure	Requires high skills in positioning
	Risk of trachea-bronchial injuries	Easly dislocation, requires a lot of maintenance

5.5 Anesthesiologic Management of the Main Surgical Pathologies in Pediatric Population

5.5.1 Congenital Lung Lesions

1. **Congenital lobar emphysema (CLE).** CLE is a postnatal abnormal overdistension of an otherwise anatomically normal lobe of the lung that communicates with a bronchus [59]. Progressive hyperinflation of the lobe occurs either due to anomalies of bronchial cartilage or due to external bronchial compression with resultant air trapping on expiration [60]. Usually, CLE is monolateral, and the upper lobes are most affected while lower lobes are usually spared. CLE generally presents in full-term neonates during the first 6 months of life; the clinical features depend on the degree of overdistension and the consequences on surrounding tissues. Tachycardia, tachypnea, retractions, cyanosis, grunting, and coughing may be present. The chest may present asymmetric with decreased breath sounds over the affected lobe.
2. **Congenital pulmonary adenomatoid malformation (CPAM).** CPAM is a lung lesion that develops from adenomatous overgrowth of terminal bronchioles without simultaneous alveolar growth. It comprises about 25% of all congenital lung malformations, with an estimated incidence of 1/25000–1/30000. The lesion may be cystic, solid, or mixed, and generally, it communicates with the tracheobronchial tree, while arterial supply and venous drainage are provided by the pulmonary circulation. CPAM may become overdistended due to air trapping and cause compression and shifting of the mediastinal structures. Spontaneous pneumothorax, pneumonia, or lung abscess may also develop. About 80% of the affected infants present some degree of respiratory distress. Signs and symptoms include tachypnea, grunting, retractions, cyanosis, and failure to thrive. If lesions are small, infants may be asymptomatic, but generally, it has been detected on prenatal ultrasonography and/or MR imaging.
3. **Pulmonary sequestration.** In this case, the malformation involves an abnormal, malfunctioning part of lung tissue not communicating with a bronchial tree. The blood supply comes from systemic abnormal arteries. It may be intralobar (90%) or extralobar. Infants with intralobar sequestrations are otherwise generally healthy, while those affected by extralobar lesions present frequent associated congenital anomalies such as congenital diaphragmatic hernia (CDH) or chest wall deformities. Children with pulmonary sequestrations generally present recurrent pneumonia involving the same lobe or adjacent atelectatic pulmonary tissues after the first or the second year of life. Because of the systemic arterial supply, children may develop high-output cardiac failure from shunting through the sequestration.

5.5.1.1 Anesthesia Consideration and Management of Congenital Lung Malformations

- Small patients present an increased risk of respiratory adverse events because of their particular age-specific characteristics and because of the effects of anesthesia on pediatric lung function [61]. A complete preoperative evaluation is mandatory to evaluate the degree of preoperative pulmonary compromise, the pathophysiology of associated lesions, the consequences of surgery, and the ability to tolerate SLV. Preoperative evaluation requires a chest X-ray, TC scan, and an echocardiogram to rule out congenital heart diseases and to evaluate cardiac function. The preoperative bronchoscopic examination may be useful in patients with CLE to evaluate the presence and the degree of bronchial stenosis and its possible reversibility.
- Neonates with relevant cardiopulmonary compromise necessitate intubation and ventilation in the pediatric intensive care unit (PICU) before surgery.
- While CLE usually necessitates a complete thoracotomy lobectomy, CPAM and pulmonary sequestration may be excised with a thoracoscopic segmental resection that requires SLV(see above).

- Inhalation or intravenous (IV) induction may be performed; patient affected by CLE and CPAM should be intubated without muscle relaxation and spontaneous ventilation maintained until either the chest is opened (thoracotomy) or SLV is established (thoracoscopy) because air trapping may cause overdistension of the affected lobe, compression of the normal lung, mediastinal shift, and a reduction in cardiac output [62]. If necessary, positive pressure ventilation or hand ventilation may be used at low peak inspiratory pressure.
- Infants are predisposed to hypoxemia because of their elevated oxygen consumption (8–10 mL/kg/min vs 3–5 mL/kg/min in adults), their small functional residual capacity (FRC), and their more compliant chest wall which cannot completely support the dependent lung in a lateral position [63]. As a consequence of this, FRC gets closer to residual volume and alveolar collapse occurs more easily [15]; in addition, shifting of the mediastinum, compromised venous return, and decreased cardiac output may all cause impaired gas exchange, hypoxemia, and hypotension [64].
- FiO_2, peak inspiratory pressure (PIP), tidal volume (TV), and PEEP should be calibrated on SpO2 and $EtCO_2$ keeping in mind that a decreased pulmonary blood flow may be responsible for a decreased $EtCO_2$. An arterial line for continuous pressure monitoring and to check pH, partial pressure of oxygen (PO_2), partial pressure of carbon dioxide(PCO_2), glucose, and hematocrit are always required. A certain degree of hypercarbia may be tolerated in order to avoid ventilator parameters and to reduce the risk of volume and barotrauma. Nitrous oxide is contraindicated in the case of CLE because of its ability to expand empty body cavity [65]. Balanced, total intravenous, or blended (general/thoracic epidural) techniques may be used for maintaining anesthesia.
- Temperature monitoring is critical because children lose heat rapidly; every effort must be used to maintain optimal body temperature.
- Due to the proximity of great vessels, blood should be available in the operating room.
- At the end of most of the thoracic procedure, older children may be extubated; neonates and infants undergoing thoracic surgery are admitted to PICU for postoperative monitoring and those with high degree of cardiopulmonary compromise postoperative ventilation will be necessary.

Sedatives are used for pain control and to maintain a good adaptation to the ventilator in order to avoid developing air leaks at the bronchial sutures.

5.5.2 Congenital Diaphragmatic Hernia

Congenital diaphragmatic hernia (CDH) is the result of the failure of fusion of the components of the diaphragm in early embryogenesis; the herniation of abdominal contents into the chest may be paraesophageal, retrosternal, or, the most common, posterolateral (Bochdalek hernias, 90%); the majority of them occur on the left side. The lung parenchyma and the pulmonary circulation always present some degrees of hypoplasia, while the heart and the mediastinum are often displaced. Mortality correlates with the size of the defect, the degree of pulmonary hypoplasia, the gestational age, the birth weight, and the presence of additional abnormalities as part of a syndrome or chromosomal abnormality.

Almost all affected newborns present respiratory distress due to pulmonary parenchyma and pulmonary vascular hypoplasia; pneumothorax and pulmonary hypertension may worsen child conditions. Patency of ductus arteriosus and communication at the atrial level will determine the right to left shunting due to increased pulmonary resistance. Rapidly after birth hypoxemia, hypercarbia and acidosis will develop.

Immediate intubation and ventilation are necessary; 100% FiO_2, high-frequency oscillatory ventilation (HFOV), and nitric oxide may be necessary to maintain adequate gas exchange; in some cases, extracorporeal membrane oxygenation (ECMO) is required.

5.5.2.1 Anesthesia Consideration and Management of Neonates with CDH

- Surgery is often performed in PICU in order to avoid destabilization of patients during transportation to the operating room and to maintain advanced ventilatory support.
- Pre- and postoperatory brain ultrasounds must be performed to check the presence of intracranial hemorrhage and its extension.
- Almost all neonates affected are submitted to the anesthesiologist fully prepared by a neonatologist who managed postnatal stabilization: ETT, arterial line, central venous line, nasogastric (NG) tube, and urinary catheter are mandatory.
- If neonates are not yet intubated induction of anesthesia should be planned carefully: anesthesiologist may decide between intubation under mild sedation(the best choice for neonates or small infants) or rapid sequence intubation with propofol, opioid, and rocuronium (the latter if he doesn't recognize the sign of difficult intubation).
- Aspiration of gastric contents with an NG tube is necessary before induction.
- Monitoring will include preductal pulse oximeter and pre or postductal arterial line for continuous pressure monitoring and blood samples in order to check gas exchange being aware that arterial oxygen saturation may be affected by the right to left shunting; near-infrared spectroscopy (NIRS) monitoring is strongly suggested.
- Balanced or total intravenous anesthesia may be chosen.
- Ventilation and oxygenation may be challenging: if possible, maintain PIP under 30 cm H_2O and be aware of contralateral pneumothorax; 100% FiO_2 is frequently indispensable and nitric oxide may be necessary to maintain oxygenation (preductal SpO_2 goal = 90–95%).
- Intraoperative infusion of inotropic drugs (adrenaline or dopamine) and volume infusion are frequently needed to support cardiac function and maintain adequate systemic arterial pressure values.
- Be aware of intraoperative hypoglycemia, acidosis, and hypothermia.
- Postoperative ventilation and sedation are always necessary.

5.5.3 Tracheoesophageal Fistula and Esophageal Atresia

The incidence of tracheoesophageal fistula (TEF) is between 1:3000–1:4000 live births. In 80–85% of neonates, it is associated with esophageal atresia (EA). About 30% of babies with TEF are born prematurely. A common association is the VACTERL complex, including vertebral, anorectal, cardiac, tracheoesophageal, renal, and limb defects. Birth weight <2.000 g and cardiac defects represent the greatest risk factors for increased mortality [66].

The classification of TEF was developed by Gross who described types A through F.

Type C, proximal atresia with distal fistula slightly above the carina, is the most common (85–90%).

EA/TEF may be suspected on prenatal ultrasonography in the case of maternal polyhydramnios and, in the case of proximal fistula, by the absence of stomach bubble.

Postnatal presentation is characterized by excessive salivation, vomiting after feeding, and coughing; respiratory distress and cyanosis are the results of aspiration as the blind esophageal pouch fills and by reflux of gastric contents up the distal esophagus into the lungs through the fistula.

EA is diagnosed by the inability to pass a catheter into the stomach; a chest X-ray will show the catheter in the blind esophageal pouch, while the presence of air into the stomach will reveal the presence of a distal TEF. A preoperative echocardiogram and a renal ultrasound are necessary for every child affected by TEF and/or EA to identify cardiac or renal anomalies, which, when present, may affect anesthetic management [67].

Isolated TEF is usually treated during the first or second month of life, through a right cervical incision, and less frequently through a right thoracotomy or thoracoscopy. EA without fistula can be managed with a gastrostomy and surgically

repaired at the age of 2–3 months in a unique surgical stage. EA/TEF is surgically repaired during the first week of life, traditionally through a right thoracotomy. The thoracoscopic approach has been recently introduced in tertiary-level pediatric hospitals and is becoming increasingly popular for a positive outcome.

5.5.3.1 Preoperative Airway Management of TEF/AE

- At the time of PICU admission, a fiberoptic bronchoscopy is always performed to visualize the upper respiratory tract anatomy and the TEF position.
- Spontaneous ventilation is the best option to avoid air leak into the stomach; when lung compliance is optimal, spontaneous ventilation should be maintained with continuous suctioning of the proximal esophageal pouch in order to avoid gastric distension and acute pneumoperitoneum, the two-life threatening complication that may occur in ventilated children with large TEF.
- In case of poor lung compliance, tracheal intubation is needed; the tip of the tube is positioned below the TEF under direct vision and the ventilator is set at the minimal required positive pressure. In case of large TEF or TEF positioned at the level or below the carina most of the air flow may direct to the stomach; in this case, a balloon-tipped catheter may be placed in the fistula under direct bronchoscopic vision. In case of massive distension and difficult ventilation, abdominal decompression could be acutely needed.

5.5.3.2 Anesthesia Consideration and Management of Infants with TEF/AE

- Induction of anesthesia can be performed with inhalational sevoflurane in a mixture of oxygen and air. Spontaneous breathing can be safely maintained and intubation can be performed under deep sedation. As discussed earlier, the tip of the tracheal tube is positioned below the TEF under direct vision. Small doses of opioids like morphine or fentanyl can be administrated to reduce the risk of coughing. The other option is apneic intubation using preintubation neuromuscular blockades. In this case, a bagging with low pressure is mandatory to minimize air leak through the TEF. Otherwise, this will not the case of large TEF or patients with poor lung compliance or both.
- Intraoperative anesthetic drugs are not widely standardized. Sevoflurane is the general anesthetic most frequently used in combined with fentanyl or remifentanil. The last one, despite the risk of hypotension, permits a flexible change of the anesthetic level in a short period of time. Paralysis during surgery is mandatory; both rocuronium and cisatracurium may be used.
- Careful monitoring is required in these patients. An arterial line for continuous pressure monitoring systematic and intraoperative blood gases central lines inserted in all neonates undergoing AE/TEF repair. A central venous line is recommended to administrate fluids and catecholamines.
- Mechanical ventilation is challenging even for the experienced pediatric anesthetist. Accidental intubation of the TEF, air leak from the TEF, coexisting pulmonary pathologies, prematurity, and thoracoscopy can be listed as possible risk factors.
- Once obtained, tracheal intubation with the tip of the tube below the TEF, paralysis, and mechanical ventilation can be safely obtained.
- The commonly performed surgical approach for thoracoscopic repair is from the right side. In the case of right-sided aortic arch, the surgical access is from the left side.
- Single lung ventilation is required to optimize the surgical view and manipulation. Specific devices for single-lung ventilation as bronchial blockers or double-lumen tubes are not available for neonates [68], but thoracoscopic view can be achieved with double lung ventilation. Pressure insufflate for thoracoscopy is usually 5 mmHg, and this is enough for lung compression. Surgeons can push away the lung from the posterior mediastinum to improve the view and space for surgical repair.

- Pressure-controlled ventilation (PCV) is usually preferred because adequate lung volume can be achieved with lower peak inspiratory pressure (PIP) compared to volume-controlled ventilation (VCV). The lower PIP is a consequence of a limited and constant inspiratory pressure and a decelerating flow. The combination of these factors over time improves gas exchange [69].
- PIP, positive end-expiratory pressure (PEEP), respiratory rate, and fraction of inspiratory oxygen are regulated step-by-step to maintain acceptable respiratory and metabolic parameters.
- All patients undergoing TEF/AE repair are admitted to PICU for postoperative ventilation and monitoring.

Sedatives are used for pain control and to maintain a good adaptation to the ventilator to avoid the dehiscence of the suture.

5.5.4 Mediastinal Masses

Primary thoracic neoplasms in children are rare [70]. Mediastinal masses are more common than intrapulmonary masses in children [71] and their anesthetic management may be challenging due to the severe complications that can originate during induction and maintenance of general anesthesia [72]. In younger patients, these tumors may be asymptomatic or present with symptoms like cough, stridor, dyspnea, and cyanosis; older children and adolescents may present cough, dyspnea, and in the most severe cases orthopnea. The presence of orthopnea may be predictive of tracheal compression, and it should be assessed in every patient. The tumor may compress the heart and the great vessels, and the patients may present cardiovascular signs as hypotension, arrhythmias, and superior vena cava (SVC) syndrome.

Computed tomography (CT) scans are necessary to evaluate the degree of tracheal and cardiovascular compression, and in the most symptomatic patients, it must be performed without or only with a mild sedation in order to avoid exacerbation of the symptoms. Careful titration of sedative drugs such as midazolam, ketamine, or propofol or alternatively small concentration of sevoflurane may be sufficient for sedation of uncooperative children.

Patients with cardiovascular symptoms, sign of cardiac or great vessels compression, or with SVC syndrome must be submitted to echocardiography.

5.5.4.1 Anesthesia Consideration and Management of Children With Mediastinal Mass

- During general anesthesia, children with a mediastinal mass are at risk of total airway obstruction and cardiovascular collapse due to exacerbation of extrinsic airway and/or cardiovascular compression.
- Prediction of anesthesia-related risk is difficult. Anghelescu et al. found that orthopnea, SVC syndrome, and mainstem bronchus compression were the main preoperative features significantly associated with anesthetic complications [73]; regarding radiological findings, other authors [74] found that maximum risk is present when the tracheal cross-sectional area is less than 50% of normal on CT scan. In these cases, careful consideration should be given to performing a biopsy under local anesthesia or initiating chemotherapy or limited radiation therapy prior to subjecting the child to general anesthesia [75].
- Intraoperative management includes the use of short-acting anesthetics, avoidance of muscle relaxants, and, if possible, maintenance of spontaneous breathing. If a patient is susceptible to airway obstruction, mask induction with sevoflurane in 100% oxygen is preferred to intravenous induction in order to maintain spontaneous ventilation and airway patency. Alternatively, IV titration of propofol, ketamine, and/or dexmedetomidine which maintains spontaneous ventilation may be used. If the patient presents severe orthopnea, induction of anesthesia should be in sitting position, intravenous access should be placed in the lower extremities, and a rigid bronchoscope and experienced bronchoscopist must be available [76]. As soon as possible, an arterial

line should be placed for monitoring arterial pressure. If an ETT placement is necessary, an armored tube should be used and positioned with its extremity distal to the compressed portion of the trachea. This maneuver may be impossible, and the anesthesiologist must be forced to put the tip of the tube proximal to the obstructed airway then checking if good ventilation may be established.

- Airway obstruction may significantly worsen with positive pressure ventilation, and the anesthesiologist must be ready to put the patient in a lateral position in order to reduce the compression on the airway. The possibility to reestablish good ventilation and oxygenation with a ventilating rigid bronchoscope or with jet ventilation through a rigid bronchoscope have both been described as viable solutions but they are probably very difficult to achieve in most cases.
- In adolescents and children weighing more than 30 kg with severe clinical symptoms and large mediastinal anterior tumor may be indicated the isolation of femoral vessels in mild anesthesia supported by local anesthesia to provide for the availability of cardiopulmonary bypass before proceeding to tracheal intubation and positive pressure ventilation.
- Once the induction has passed and good ventilation and oxygenation have been established, maintenance of anesthesia must be performed by both total intravenous or balanced anesthesia; careful monitoring of cardiovascular and respiratory parameters is mandatory during surgery.
- If surgery is completed without complications, patients may be extubated in the operating room and carefully monitored in the immediate postoperative period.

5.5.5 Pectus Excavatum Or Carinatum

Pectus excavatum and carinatum are the most common morphological chest wall abnormalities [77]. In pectus excavatum, several ribs and the sternum grow abnormally producing a concave deformity of the anterior chest wall. It can be diagnosed at a very young age or, more commonly, it may become noticeable in the early teenage years. Pectus excavatum is the most common type of congenital chest wall deformity (90%) with an estimated incidence of 1 in 300–400 birth with male predominance (3:1). Pectus carinatum is defined by the anterior protrusion of the sternum and adjacent cartilages [78]. Pectus excavatum and carinatum are often associated with scoliosis. Many patients are brought to the attention of the surgeon during adolescence when the appearance of the chest becomes very disturbing to young teenagers. Patients with pectus excavatum may present with a wide range of symptoms; most of them do not have cardiorespiratory symptoms even in the presence of mildly abnormal function tests [79], while others complain of dyspnea during exercise, palpitations, and chest pain. Mitral valve prolapse may be present in about 30–60% of patients.

5.5.5.1 Anesthesia Consideration and Management of Patients with Pectus Excavatum/ Carinatum

- Surgical repair is always performed during adolescence and the minimally invasive Nuss technique [80] and its modifications [81] is the method of choice for last 20 years.
- Imaging studies include posterior–anterior and lateral chest X-ray and thoracic CT scan.
- Echocardiography is necessary for patients suspected of Marfan syndrome to evaluate for possible aortic root dilation.
- Pulmonary function tests are needed especially for patients symptomatic with exercise.
- A combination of general endotracheal anesthesia, thoracic epidural, or cryoanalgesia is the methods of choice.
- Standard monitoring plus an arterial line is generally used.
- In adolescents, a thoracic epidural catheter may be placed before anesthesia under mild anxiolysis; it should remain in place for 48–72 h postoperatively. A segmental epidural blockade should be the goal with approxi-

mately 2 mL of local anesthetic per segment to be blocked administered [82].

- A total intravenous technique with target-controlled infusion (TCI) of propofol and remifentanil is generally used.
- Muscle relaxation is necessary to facilitate intubation and result useful to optimize surgical conditions.
- At the end of the surgical procedure, the anesthesiologist must inflate the lung by manual application of large tidal breaths in the Trendelenburg position in order to avoid the placement of a chest tube.
- Emergence agitation and pain often require the administration of morphine and sedatives.
- Patient-controlled analgesia (PCA) and FANS with or without thoracic epidural are always used to control postoperative pain.

5.6 Management of Postoperative Pain

Appropriate treatment of postoperative pain contributes to a shorter time of hospitalization, lower hospital costs, and increased level of patient satisfaction [83]. Ideally, every hospital should have a system for providing patients safe and effective analgesia when they are experiencing acute pain after surgery [84]. After thoracic surgery pain management is important to keep the child comfortable to avoid pulmonary dysfunctions such as atelectasis and postoperative infection and to facilitate earlier mobilization. Post-thoracotomy pain is considered as one of the most intense postoperative pain, whereas it appears less acute after VATS; for these reasons, as a general guideline, complex analgesic techniques are used in the events of open thoracotomy while after VATS pain may be controlled with systemic non-opioid analgesics [2]. Post-thoracotomy pain is exacerbated by breathing, coughing, movements, and respiratory physiotherapy, so in the first 48–72 h, the patients need to be managed with an association of patient-controlled analgesia (PCA) or parents/nurses controlled analgesia (PNCA) with morphine, locoregional techniques, and systemic non-opioid analgesic.

Options for locoregional analgesia include:

- intercostals nerve blocks performed prior to skin incision or at the end of surgery just before surgical closure under direct visualization
- paravertebral block with local anesthetic injection in the paravertebral space, performed through single-shot or continuous techniques
- continuous thoracic epidural analgesia through a catheter placed in the epidural space with the tip positioned at the dermatome level corresponding to the surgical incision.

Although newer techniques have been developed, pediatric epidural analgesia is an accepted method of advanced analgesia in children [85]. The technique of catheter placement is the same used in adults except for the timing of placement as anesthesia is often required for a safe maneuver.

Many different local anesthetic solutions and adjuvants have been used in the pediatric population. The most popular local anesthetics used are levobupivacaine and ropivacaine [86]; clonidine and opioids are commonly co-administered, as they reduce the dosage requirement for local anesthetics and improve the block quality. While the safety profile of epidural clonidine justifies its systematic use, opioids may cause respiratory depression; thus in the case of their epidural use for postoperative pain control, patients should be strictly monitored and an acute pain service staff should be available to provide timely response to any complications. In the author's experience, the association of ropivacaine or levobupivacaine with clonidine may be the right choice for safe and successful management of post-thoracotomy pain.

Table 5.4 shows the suggested doses to be administrated in the pediatric population.

In conclusion, after thoracic surgery children need proper management of postoperative pain that should be considered as an essential part of anesthesia; for this reason, anesthesiologists

Table 5.4 Local anesthetics and clonidine for continuous epidural analgesia

		Bolus		Continuous infusion		
		Local anesthetic	Adjuvant	Anesthetic solution	Rate	Others bolus
Age <12 months	< 5 kg	Ropivacaine 0.2% 0.6–0.8 mL/kg	Clonidine 1–2 mcg/kg	Ropivacaine 0,1% Clonidine 1 mcg/mL	0.2–0.4 mL/kg/h	0.6 mL/kg of solution
	> 5kg < 10kg	Levo-Bupivacaine 0.5–0.2% 0.6–0.8 mL/kg	Clonidine 1–2 mcg/kg	Ropivacaine 0,1% Clonidine 1 mcg/mL	0.2–0.4 mL/kg/h	0.61 mL/kg of solution
Age >12 months	10–25 kg	Levo-Bupivacaine 0.2% 0.6–0.8 mL/kg	Clonidine 2 mcg/kg	Ropivacaine 0.125% Clonidine 1mcg/mL	0.2–0.4 mL/kg/h Max 10 mL/h	0.61 mL/kg of solution Max 15 mL
	25–40 kg	Levo-Bupivacaine 0.25% 0.6–0.8 mL/kg	Clonidine 2 mcg/kg	Ropivacaine 0.125% Clonidine 1 mcg/mL	0.2–0.4 mL/kg/h Max 15 mL/h	10–15 mL of solution
	>40 kg	Levo-Bupivacaine 0.375% 10–20 mL max 20 mL	Clonidine 2 mcg/kg Max 100 mcg	Ropivacaine 0.125% Clonidine 1 mcg/mL	0.2–0.4 mL/kg/h Max 15 mL/h	10–20 mL of solution

who care for children submitted to this kind of surgery must be familiar with the use of techniques as PCA/PNCA and epidural thoracic anesthesia/analgesia and should be supported by an acute pain service staff for daily surveillance of efficacy and safety of pain therapy.

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