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Anaesthesia for thoracoscopy in paediatric patients

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Modern equipment and surgical techniques have enabled endoscopic procedures in smaller patients, making thoracoscopy a possibility for a variety of diagnostic and therapeutic procedures, even in very young patients.[1,2] (Table I)

To understand the perioperative anaesthetic requirements of paediatric patients for video-assisted thoracoscopic surgery (VATS), a review of the physiology of one-lung ventilation in the lateral decubitus position and techniques of lung isolation are imperative. A review of the general considerations of paediatric anaesthetic practice fall outside the scope of this review, but should be kept in mind during VATS procedures in children.

Pulmonary physiology of one-lung ventilation in children[1,3]

Several factors cause ventilation-perfusion mismatch in patients undergoing anaesthesia and one-lung ventilation (OLV) in the lateral decubitus position (LDP). Anatomical and physiological differences in children compared to adult patients further predispose these patients to hypoxaemia during such procedures.

In the awake, upright adult, the right lung receives 55% and the left lung 45% of the total lung blood flow. Perfusion favours lower (dependent) parts of the lung due to gravitational effects. In terms of ventilation, dependent lung areas are on the steep, high compliant part of the alveolar volume-transpulmonary pressure curve with ventilation favouring these parts of the lungs, matching ventilation with perfusion.

When the patient is still awake, but positioned in the LDP, gravity increases blood flow to the dependent lung with an average of 40% blood flow to the non-dependent lung and 60% to the dependent lung (disregarding the slight differences between the left and right lungs). Ventilation now also favours the dependent lung. This is due to a vertical gradient in pleural pressure (Ppl) and because the dome of the lower part of the diaphragm is pushed higher into the chest by the abdominal contents compared to the upper part, resulting in a more curved shaped lower diaphragm with enhanced contraction and further increase in ventilation to the dependent lung.

When the patient is anaesthetised and OLV commences, in the absence of confounders or inhibitors of hypoxic pulmonary vasoconstriction (HPV), the absence of ventilation to the non-dependent lung results in HPV with a 50% reduction of blood flow to the non-dependent lung (which now receives 20% of blood flow) and subsequent 50% increase in flow to the dependent lung (which now receives 80% of blood flow). Inhalational anaesthetic agents reduce the effect of HPV so that the reduction in blood flow to the non-dependent lung is approximately 40% with 1 MAC isoflurane (compared to 50% in the absence of vapours). The final blood flow is approximately 24% to the non-dependent (non-ventilated) lung and 76% to the dependent (ventilated) lung in the anaesthetised patient during OLV in the LDP.

During OLV in the LDP, the use of muscle relaxants prevents the diaphragm from contracting, and the effect of the curved bottom part of the diaphragm on ventilation is lost. Under anaesthesia the dependent lung (which is being ventilated) moves to a lower,

Table I. Indications for video-assisted thoracoscopic surgery (VATS) in children[1,2]

Lungs:	***Mediastinum:***	***Diaphragm:***
• Biopsy of pulmonary tissue	• Thymectomy	• Repair of congenital diaphragmatic hernia
• Pulmonary resections (wedge resections to lobectomies)	• Posterior mediastinal neurogenic tumour resection	***Spine and nerves:***
• Closure of recurrent pneumo thorax	• Excision of mediastinal cysts	• Fusions and corrections
• Diagnosis of broncho-pleural fistula	***Major vessels:***	• Thoracic sympathectomy
Pleura:	• Ligation of patent ductus arteriosus	• Drainage of abscess
• Decortication of empyema thoracis	***Heart:***	
• Pleurodesis	• Pericardectomy	
Trachea:	***Oesophagus:***	
• Trachea-oesophageal fistula repair	• Heller's myotomy	
	• Oesophagus resections	

less compliant part of the alveolar volume-transpulmonary pressure curve resulting in a reduced functional residual capacity (FRC). Muscle relaxants also reduce FRC which is often further reduced by the mediastinum resting on the dependent lung, weight of the abdominal contents pushing more into the thoracic cavity of the dependent lung and poor positioning impeding expansion of the dependent lung. Ventilation may be further decreased due to pre-existing pulmonary disease or pooling of secretions in the dependent lung.

The above effects lead to ventilation-perfusion (V/Q) mismatch and susceptibility to hypoxaemia during OLV. The supine position (for orthopaedic and other procedures) enhances the mismatch due to the loss of gravitational effect. Blood distributes to both lungs, whereas ventilation only occurs in the ventilated lung during OLV. The matching of ventilation and perfusion is now even more dependent on HPV.

Paediatric pulmonary physiology[4-7] predisposes to further mismatch and an increased tendency towards hypoxaemia during OLV in the LDP. The FRC is reduced in paediatric patients and oxygen consumption is 6–8 $ml.kg^{-1}min^{-1}$ compared to 3.5 $ml.kg^{-1}min^{-1}$ in adults, both resulting in a smaller oxygen reserve and susceptibility to desaturation during OLV in children. In adults, placing the sick lung in the non-dependent position (as is the case during surgery on the sick lung) offers considerable advantages to V/Q matching. This is not the case in small children due to a variety of factors. The compressible rib cage of the infant cannot fully support the dependent lung, resulting in atelectasis during tidal breathing. Due to their smaller size, the hydrostatic pressure gradient between the two lungs in the LDP is less in small children than in adults, resulting in a less pronounced increased perfusion to the dependent lung in the LDP. As a result of the compressible nature of the infant lung, the FRC is closer to the residual volume (RV) and airway closure can occur even during tidal breathing. The dependent diaphragm in adults has a mechanical advantage due to the increased abdominal pressure gradient, resulting in increased ventilation in the dependent lung. This pressure gradient is absent in infants.

Apart from the physiological effects, anatomical considerations further result in a higher susceptibility to hypoxaemia. Smaller diameter airways necessitate smaller diameter tubes with higher resistance to airflow and an increased tendency to block. Shorter airways result in easier displacement of airway devices.

Techniques of lung isolation in children[1–2,4–5,8–9]

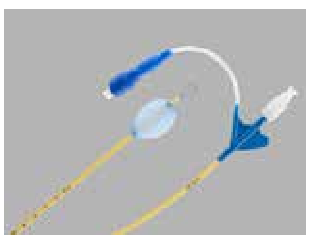
Although VATS can be performed during two-lung ventilation with CO_2 insufflation and retraction of lung tissue from the operating field, OLV is highly desirable. There are several techniques for OLV in children, each with advantages and disadvantages (Table II). The age and size of the child will determine the devices available for use (Table III).

1. Single-lumen endotracheal tube

A conventional single lumen endotracheal tube (ETT) may be placed in the ipsilateral mainstem bronchus. Half a size smaller than for tracheal use is selected. When intubating the left mainstem bronchus, the bevel of the ETT is rotated through 180˚ and the patient's head turned to the right. To place the ETT in the right mainstem bronchus, it is simply advanced deeper than for endotracheal use. The ETT is advanced until breath sounds disappear on the operative side. Placement may be assisted or confirmed with a fibre optic bronchoscope (FOB) passed through or alongside the ETT. Fluoroscopy-guided placement has also been described. When a cuffed tube is used, the distance from the proximal part of the cuff to the tip of the ETT should not exceed the length of the bronchus in order to prevent obstruction of the contralateral bronchial opening or trachea. An uncuffed tube may result in inadequate seal with failure of lung collapse and risk of contaminating the healthy lung. Suctioning of the operative lung is not possible and in small children with short bronchi, the risk of occlusion of the upper lobe bronchus is high. Independent intubation of both main bronchi with small ETTs have been described where one ETT is placed, after which the second ETT is advanced over a FOB into the other bronchus. This allows independent ventilation of the two lungs but is difficult to place, can potentially cause trauma and the thin lumens cause high airflow resistance and propensity for obstruction.

2. Balloon-tipped bronchial blockers

Bronchial blockers (BB) can be used for a variety of paediatric ages (Tables III and IV). Fogarty embolectomy catheters (Edward Lifesciences, Irvine, CA, USA) are placed with FOB guidance and completely seal the bronchus with good lung isolation. Their closed tips preclude suctioning and continuous positive airway pressure (CPAP) to the operative lung. The use of end-hole catheters (Arrow International Corp, Redding, PA) could overcome these problems. They are placed by first inserting a single-lumen ETT into one bronchus, advancing a guidewire through the tube, removing the tube and railroading the catheter over the guidewire. An ETT is then placed in the trachea alongside the catheter. Suctioning is possible (the lumen is too small to suction secretions but suctioning aids in lung collapse) and CPAP is possible to the operative lung. The Arndt Endobronchial Blocker® (Cook Critical Care, Bloomington, IN, USA) can be used for children older than two years (ETT ≥ 4.5). A three-port adapter accompanies the blocker and attaches to the ETT. The blocker is passed through one of the adapter lumens, the FOB through the second and the third is connected to the anaesthetic breathing circuit. The blocker is hooked around the FOB and advanced under vision.

Embolectomy catheters (Photo: Newtech™ medical devices catalogue)	**Arndt bronchial blocker** (Photo: Cook Medical catalogue Arndt_Blocker_Balloon_ G44114_P_002) (Permission for use granted by Cook Medical, Bloomington, Indiana)
	

3. Univent tube

The Univent tube (Fuji Systems corporation, Tokyo, Japan) comprises a conventional ETT with a second lumen containing a small tube with a balloon tip which is advanced into a bronchus to serve as a blocker. The blocker lumen can be used for suctioning and insufflation of oxygen. Because the blocker is attached to the ETT, displacement is less likely than with other blockers. The blocker channel does, however, occupy a sizable portion of the cross-sectional area of the device which increases resistance to airflow. The device is placed in the same way as a conventional ETT, after which it is rotated through 90 ˚ so that the blocker sits on the appropriate side. The tube is secured and the blocker is advanced either blindly or under FOB guidance.

Univent tube (Photo: Sharn Anesthesia catalogue)

4. EZ blockers

The Rusch® EZ-Blocker™ (Teleflex International Corp, USA) is a BB catheter with a bifurcated distal end with an inflatable balloon at the end of each leg. It is placed through a conventional ETT. While inside the ETT, the legs are in close proximity, but deploy when exiting at the bottom of the ETT to form a Y-shape. Each leg enters one of the main bronchi and the two colour-coded balloons are independently inflated. A multiport is supplied with one port for the blocker, one for the FOB and the third connects to the breathing circuit. Cuff inflation is done under FOB guidance. The blocker is only available in one size with a 7Fr catheter (2.33 mm in diameter) and passes through ETT tubes ≥ size 7.

EZ-Blocker™ (Photo: Teleflex incorporated catalogue)

5. Double lumen tubes

Double lumen tubes (DLTs) (Mallinckrodt Medical, Inc, St Louis, MO, USA for 28-41 Fr and Rüsch, Duluth, GA, USA for 26 Fr) consist of two cuffed tubes of unequal length moulded together with the shorter tube ending in the trachea and the longer tube in either bronchus. The tube is placed through the vocal cords and the stylet is removed before it is rotated 90 ˚ towards the appropriate side and advanced until resistance is met. Placement is verified by auscultation ± FOB. The smallest available size is a 26 Fr which can be used in children from eight years of age.

Table II. Advantages and disadvantages of various lung isolation techniques

Technique	Advantages	Disadvantages
Single lumen tube in main bronchus	• Relatively easy to place • Cost-effective • No special equipment required • Can use through tracheostomy tube	• Poor seal if uncuffed (inability to deflate lung and possibility of soiling) • Easily occludes upper lobe bronchus • Unable to suction operative lung • No CPAP possible to operative lung • Slow conversion from OLV to two-lung ventilation and vice versa
Separate single lumen tube in each bronchus	• Independent ventilation of two lungs • Suction possible	• Technically difficult • Trauma • Small lumens (resistance to airflow, block easily)
Closed-tip bronchial catheters (Fogarty)	• Good seal • Relatively easy placement	• Inability to suction operative lung • No CPAP possible to operative lung • Tracheal occlusion if dislodges proximally • Slow lung collapse
End-hole bronchial blocker catheters (BB)	• Can be used when single lumen ETT already in place • Good seal • Good lung collapse • Suctioning possible • CPAP possible • No need to replace ETT at end of procedure • Selective lobar blockage possible • Can use through tracheostomy	• Tracheal occlusion if dislodges proximally • Slow conversion from two-lung to OLV • Independent lung management difficult or impossible (suctioning, FOB inspection, split lung ventilation in ICU) • Easily displaces

Univent tube	• Easy placement • Less displacement • Suctioning possible through lumen • CPAP possible through lumen • O_2 insufflation possible through lumen • Able to switch between OLV and two-lung ventilation	• High airflow resistance • Trauma possible • Balloon has low volume-high pressure characteristics predisposing to mucosal injury
EZ-Blocker™	• Easy placement • Placed through existing ETT • CPAP possible to collapsed lung	• Only available for ETT ≥ size 7 • Selective lobar blockage not possible
Double-lumen tubes (DLTs)	• Quick placement possible • Good lung isolation • FOB not imperative • Displacement less common than BBs • Independent lung management possible (suctioning, FOB inspection, split lung ventilation in ICU) • Quick conversion from OLV to two-lung ventilation and vice versa	• Trauma possible • Only possible in children older than 8 years (≥ 30-35 kg) • Needs to be replaced by single-lumen ETT at end of procedure • Not option in patients who cannot tolerate apnoeic period • Not possible to place through tracheostomy • Hard to place in difficult/abnormal airways • Cannot block selective lobes • Right-sided DLT can occlude the right upper bronchus

Table III. Device selection for lung isolation in children[4,8,10]

Age (years)	ETT (ID)$^{+}$	Fogarty catheter (Fr)§	BB (Fr)	Univent (ID)***	DLT (Fr)
0.5–1	3.5–4.0	3	2*		
1–2	4.0–4.5	3	3*		
24ʲ	4.5–5.0	3	5**		
4–6	5.0–5.5	4–5	5**		
6–8	5.5–6.0	4–5	5**	3.5	
8–10	6.0 cuffed	4–5	5**	3.5	26$^{\#}$
10–12	6.5 cuffed	4–5	5**	4.5	26$^{\#}$–28$^{\#\#}$
12–14	6.5–7.0 cuffed	5–6	7**	4.5	32$^{\#\#}$
14–16	7.0 cuffed	5–6	5,7**	6.0	35$^{\#\#}$
16–18	8.0–8.5 cuffed	5–6	7,9**	7.0	35$^{\#\#}$,37$^{\#\#}$

ETT = endotracheal tube; ID = internal diameter; BB = bronchial blocker; Fr = French; DLT = double lumen tube; $^{+}$ = Sheridan® tracheal tubes, Kendall Healthcare, Mansfield, MA;
§ = Edward Lifesciences, Irvine, CA, USA; * = Edwards Lifesciences LLC, Irvine, CA;
** = Cook Critical Care, Inc, Bloomington, IN; *** = Fuji Systems Corporation, Tokyo, Japan; $^{\#}$ = Rusch, Duluth, GA; $^{\#\#}$ = Mallinckrodt Medical, Inc, St. Louis, MO.

Table IV. Arndt blocker sizing for lung isolation in children[11,12]

Arndt size (Fr)	Patient age (years)	Smallest ETT (mm)	FOB size (mm)
5.0	< 8	4.5	2.8
7.0	8–12	6.5	3.6
9.0	> 12	8	4.2

Fr = French, ETT = endotracheal tube, FOB = fibre optic bronchoscope, mm = millimetres

Perioperative management of paediatric patients for VATS

Preoperative evaluation

Preoperative workup for thoracoscopy should be similar to the workup for thoracotomy since these patients will also be anaesthetised, might be in the LDP and will most probably be exposed to OLV. The focus of the workup is on pulmonary and cardiac reserve and function. A full history and examination is followed by special investigations which should routinely include a haematocrit, haemoglobin, serum-electrolytes and a chest X-ray. Pulmonary function tests (in older children), ECG and computerised tomography (CT) scans are done as indicated by the patient's specific pathology.

Patients should be optimised according to their pathology (mediastinal masses could be shrunk by radiation or chemotherapy) and their general condition should be optimised with adequate nutrition, chest physiotherapy, bronchodilator therapy, antibiotics, steroid supplementation and blood transfusion as indicated. As conversion to open thoracotomy is always a possibility and major vessel injury could occur, blood should be ordered on standby.

Anxiolytic premedication could be considered in children without respiratory compromise and could include midazolam

0.3–0.5 mg.kg^{-1} p.o or a suitable alternative. Antiemetics and H_2-antagonists should be administered in patients at risk of aspiration. Fasting times resemble guidelines for routine surgery.

Intraoperative management

Monitoring should include ECG, pulse oximetry, non-invasive blood pressure monitoring (NIBP), capnography, temperature monitoring and urinary output in longer cases. Neuromuscular and depth-of-anaesthesia monitoring are convenient optional modalities, the latter being especially useful when a total intravenous technique is chosen.

Large-bore peripheral lines should be placed in the event of conversion to thoracotomy or massive bleeding. The literature regards arterial lines mostly as optional or indicated by specific pathological conditions, but the author prefers them in all patients undergoing OLV for both blood gas and electrolyte analysis and continuous blood pressure monitoring. When end-tidal CO_2 ($ETCO_2$) levels drop, a continuous blood pressure trace will differentiate between airway compression and compression of the heart or major vessels. When a central venous pressure catheter is indicated (for drug administration or central venous pressure monitoring), the catheter should be placed on the side of the thoracoscopy to prevent the eventuality of bilateral pneumothoraces.

Patient positioning should take meticulous care of pressure points as well as optimization of the effect of gravity on perfusion and subsequent matching of ventilation and perfusion. In the LDP, potential pressure points are the dependent eye and ear, acromion process, olecranon, ribs, iliac crest, greater trochanter, condyles and malleoli.[1] To optimise perfusion to the dependent lung (the ventilated lung) in the LDP, the patient needs to be perfectly perpendicular to the bed. Slight ventral or dorsal tilt will decrease the gravitational effect and reduce perfusion. When placing a patient in the LDP, the dependent arm is perpendicular to the body, the dependent knee flexed, padding placed under the ankles, between the knees, under the hip (for protection of the greater trochanter and iliac crest), behind the olecranon and between the arms. The dependent eye and ear should be free, the neck supported and in line with the body and a chest roll (just distal to the axilla) in place. The abdomen should be allowed unobstructed movement.[13]

Anaesthetic technique (local anaesthesia, regional anaesthesia or general anaesthesia) will depend on the age and pathology of the child. Local anaesthesia is rarely an option but could be considered in older children for short procedures without intrathoracic surgical manipulation or in moribund patients, especially where spontaneous breathing is paramount. Such patients are, however, often not able to withstand the required lung collapse for thoracoscopy in which case local anaesthesia is not a viable option. Regional techniques include epidural, paravertebral block or multi-level intercostal blocks, often supplemented with a stellate ganglion block to suppress the cough reflex.

For general anaesthesia, induction and maintenance are possible with inhalational or intravenous drugs. The effect of each drug on HPV (Table V) and cardiac output should be considered in addition to the pathology and general condition of the patient. The decision to extubate the patient in theatre or ventilate postoperatively, will also influence the choice of drugs. Muscle relaxants are commonly used, except in instances where spontaneous ventilation is mandatory, as is mostly the case with anterior mediastinal masses. A balanced anaesthetic with opioids and inhalants is probably advisable (see below). Nitrous oxide should be avoided when gas insufflation is used as it can enhance gas embolism. This is less of an issue when CO_2 is used (solubility of nitrous oxide and carbon dioxide are similar), but nitrous oxide is still best avoided.

OLV is achieved with one of the methods previously described. Especially in smaller children where lung isolation is impossible or suboptimal, CO_2 insufflation into the operative hemithorax facilitates lung collapse. At this point displacement of intrathoracic contents and tension pneumothorax can cause significant cardiovascular compromise due to increased left ventricular afterload or decreased venous return reducing cardiac output. Insufflation can also lead to bradycardia due to increased vagal tone caused by activation of pulmonary stretch receptors. Therefore, insufflation rate should not exceed 1 litre/minute and insufflation pressure should be between 4–6 mmHg. Insufflation of CO_2 directly into lung parenchyma is possible and could lead to sudden increase in $ETCO_2$, subcutaneous emphysema and gas embolism. CO_2 is used for insufflation because it is more soluble in blood than O_2 or air and poses a smaller risk for embolisation.[14] Methods described to monitor for gas embolism include transoesophageal echocardiography (detects 0.1 ml of gas), precordial Doppler (detects 0.5 ml) and capnometric end tidal nitrogen monitoring (for air embolism but not useful in detecting CO_2 emboli).[15] $ETCO_2$ monitoring is also useful to detect gas embolism. CO_2 insufflation could lead to hypothermia in small children and meticulous temperature management is mandatory.

Hypercarbia during VATS is more common in young children than in adults.[16,17] Possible causes include hypoventilation, CO_2 insufflation and malpositioning of airway devices.

Hypoxaemia during OLV is not uncommon and several management strategies are described (see Table VI). Specific variables influence oxygenation during OLV and should be optimised in the event of hypoxaemia.[18] These are pulmonary shunt fraction (Qs/Q_T), haemoglobin concentration and the ratio between oxygen consumption and cardiac output (VO_2/Q_T). Reducing Qs/Q_T is achieved by optimising HPV in the non-dependent lung while minimising pulmonary vascular resistance in the dependent lung. This is mainly achieved by good lung isolation and selecting drugs with minimal effect on HPV. Haemoglobin should be optimal for patient age. Cardiac output should be optimal but injudicious use of inotropes will be contra-productive as increased Q_T could increase pulmonary artery pressure and reduce HPV and inotropes can directly reduce HPV. Inhalational agents will decrease VO_2 but will also reduce Q_T, negating the positive effect on oxygenation. It is therefore probably advisable to use a balanced anaesthetic technique with opioids and inhalants at concentrations of < 1 MAC, limiting the reduction in Q_T. Inhalants are good bronchodilators and their half-life is short, permitting extubation in theatre. Further strategies to manage hypoxaemia during OLV include increasing F_iO_2, maintaining adequate tidal volume (too low will cause atelectasis in the dependent lung with subsequent intrapulmonary shunt and hypoxaemia and too high (> 10 $ml.kg^{-1}$) will increase pulmonary vascular resistance in the dependent lung and will force blood to the nondependent lung which will also increase intrapulmonary shunting), apply positive end-expiratory pressure (PEEP) to the dependent lung and apply intermittent two-lung ventilation. Continuous positive airway pressure (CPAP) to the non-dependent lung is probably not advisable during thoracoscopy as this might compromise visibility.

Table V. Effects of drugs on hypoxic pulmonary vasoconstriction

Minimal effect on HPV	Reduces HPV
• Isoflurane < 1 MAC • Opioids • Propofol • Ketamine • Benzodiazepines • Barbiturates	• Vasodilators (nitroglycerine, dobutamine) • Beta-agonists (salbutamol) • Inhalants if > 1 MAC

HPV = hypoxic pulmonary vasoconstriction; MAC = minimum alveolar concentration

Table VI. Strategies to manage hypoxaemia during one-lung ventilation

- Check ETT tube positioning
- Suction airway
- Check cardiac output
- Check haemoglobin
- Consider drug effects on HPV – Table V
- Increase F_iO_2
- Optimise tidal volume
- PEEP to dependent lung (5 cmH_2O)
- No CPAP during VATS
- Intermittent two-lung ventilation

ETT = endotracheal tube; HPV = hypoxic pulmonary vasoconstriction; F_iO_2 = inspiratory fraction of oxygen; PEEP = positive end-expiratory pressure; CPAP = continuous positive airway pressure; VATS = video-assisted thoracoscopic surgery.

Analgesic requirements for VATS are less than for thoracotomy because of smaller incisions without splitting of serratus anterior and latissimus dorsi muscles and spreading of ribs.[1] Chest drains are, however, painful[4] and pleural procedures require more than simple analgesia. Analgesia is often achieved with paracetamol, nonsteroidal anti-inflammatory drugs, and intravenous opioids supplemented by local infiltration of the port sites or intercostal nerve blocks. Neuraxial local anaesthetic agents or opioids are reserved for open procedures.[2]

Apart from ventilation and perfusion challenges, intraoperative complications could include dysrhythmias, re-expansion pulmonary oedema and massive bleeding. Vigilance on the part of the anaesthetist is paramount.[1,2]

Postoperative care

Postoperative care for thoracoscopic procedures is not different from thoracotomies. Analgesia and chest physiotherapy are important and early chest radiographs should be done to exclude pneumothorax or severe atelectasis.[8] The perioperative team should focus on early detection and management of postoperative complications, including bleeding, lung herniation through the chest wall, Horner syndrome, persistent air leak, respiratory complications (atelectasis and pneumonia) and infection (wound infection, abscess or empyema).[1,2]

Thoracoscopy in children is less invasive than thoracotomy, but due to their smaller size with associated physiological and equipment difficulties, this is often more challenging than anaesthesia for thoracoscopy in adults. Paediatric thoracic anaesthetists should be well versed in the physiology of OLV and LDP as well as the various types of equipment available for lung isolation in children.

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