PEDIATRIC THORACIC ANESTHESIA

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This article focuses on the intraoperative anesthetic care of infants and children undergoing noncardiovascular thoracic surgery. Surgical disorders afflicting infants and children are described, with an emphasis on features impacting anesthetic care. Techniques for performing single-lung ventilation in pediatric patients are summarized. Anesthetic management, including regional anesthetic techniques, are reviewed.

SURGICAL LESIONS OF THE CHEST

Neonates and Infants

A variety of congenital intrathoracic lesions for which surgery is required may present during the newborn period or within the first year of life. These include lesions of the trachea and bronchi, lung parenchyma, and diaphragm (Table 1).

Tracheal Stenosis

Tracheal stenosis may be acquired or congenital. Tracheal stenosis occurs most commonly because of prolonged tracheal intubation, often in neonates with infant respiratory distress syndrome associated with prematurity. Ischemic injury of the tracheal mucosa may occur because of a tight-fitting endotracheal tube (ETT) at the level of the cricoid

Text continued on page 155
<table>
<thead>
<tr>
<th>Lesion</th>
<th>Preoperative Evaluation</th>
<th>Surgical Treatment</th>
<th>Anesthetic Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracheal stenosis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acquired</td>
<td>Laryngoscopy/bronchoscopy</td>
<td>Cricoid split</td>
<td>TIVA</td>
</tr>
<tr>
<td>Congenital</td>
<td>Laryngoscopy/bronchoscopy</td>
<td>Laryngotraceoplasty</td>
<td>TIVA, postoperative ventilation</td>
</tr>
<tr>
<td>Pulmonary sequestration</td>
<td>CT, MRI</td>
<td>Resection</td>
<td>Avoid N₂O</td>
</tr>
<tr>
<td>Congenital cystic lesions</td>
<td>CT, MRI</td>
<td>Resection</td>
<td>Minimize inflating pressure, avoid N₂O</td>
</tr>
<tr>
<td>Congenital lobar emphysema</td>
<td>CT, MRI</td>
<td>Resection</td>
<td>Minimize inflating pressure, avoid N₂O</td>
</tr>
<tr>
<td>Congenital diaphragmatic hernia</td>
<td>CXR</td>
<td>Replace abdominal contents, close defect</td>
<td>Hyperventilation, minimize inflating pressure, avoid N₂O</td>
</tr>
<tr>
<td>Tracheoesophageal fistula</td>
<td>CXR</td>
<td>Ligation of fistula, esophageal anastomosis</td>
<td>Nitrous oxide, HFOV, ECMO</td>
</tr>
</tbody>
</table>

FOB = Fiberoptic bronchoscopy, TIVA = total intravenous anesthesia, CT = computed tomography, MRI = magnetic resonance imaging, N₂O = nitrous oxide, CXR = chest radiography, HFOV = high-frequency oscillatory ventilation, ECMO = extracorporeal membrane oxygenation, ETT = endotracheal tube.
cartilage, which becomes scarred and constricted. Subglottic stenosis may develop, resulting in stridor following tracheal extubation. Reintubation may be required because of oxygen desaturation and hypercarbia.

Fiberoptic bronchoscopy is used to evaluate the severity of the stenosis and exclude other causes of stridor (e.g., vocal cord paralysis or laryngomalacia). When general anesthesia is required, inhalational anesthesia may be administered through a face mask, with the fiberoptic bronchoscope (FOB) inserted through an adapter in the mask and into the nasopharynx. This is usually performed with the patient breathing spontaneously.70

A cricoid split procedure may be performed for infants with acquired subglottic stenosis. Following diagnostic bronchoscopy, the patient is intubated with an ETT or a rigid bronchoscope is left in place during the operation. Anesthesia may be maintained with inhalational agents or an intravenous anesthetic technique, such as propofol and remifentanil.49 Typically, an ETT one-half size larger than the original tube is placed following the repair.

For patients with severe, congenital tracheal stenosis, a laryngotra- cheoplasty may be performed. This procedure involves the placement of a costal, auricular, or laryngeal cartilage graft into the anterior or posterior trachea.129 In some cases, a stent may be positioned within the trachea. Patients may remain intubated and ventilated for a variable period of time postoperatively. In these cases, sedation, analgesia, and neuromuscular blockade are maintained following surgery.

**Pulmonary Sequestrations**

Pulmonary sequestrations result from disordered embryogenesis producing a nonfunctional mass of lung tissue supplied by anomalous systemic arteries. Presenting signs include cough, pneumonia, and failure to thrive, and often present during the neonatal period, usually before the age of 2 years. Diagnostic studies include computerized tomographic (CT) scans of the chest and abdomen and arteriography. Magnetic resonance imaging (MRI) may provide high-resolution images, including definition of vascular supply. CT scans and MR images may obviate the need for angiography.129 Surgical resection is performed following diagnosis. Pulmonary sequestrations do not generally become hyperinflated during positive-pressure ventilation. Nitrous oxide administration may result in expansion of these masses, however, and should be avoided.

**Congenital Cystic Lesions**

Congenital cystic lesions in the thorax may be classified into three categories73: (1) Bronchogenic cysts result from abnormal budding or branching of the tracheobronchial tree. They may cause respiratory distress, recurrent pneumonia, or atelectasis caused by lung compression. (2) Dermoid cysts are clinically similar to bronchogenic cysts but differ histologically because they are lined with keratinized, squamous
epithelium rather than respiratory (ciliated columnar) epithelium. They usually present later in childhood or adulthood. (3) Cystic adenomatoid malformations (CAM) are structurally similar to bronchioles but lack the associated alveoli, bronchial glands, and cartilage. Because these lesions communicate with the airways, they may become overdistended because of gas trapping, leading to respiratory distress in the first few days of life. When they are multiple and air filled, CAM may resemble congenital diaphragmatic hernia (CDH) radiographically. Treatment is surgical resection of the affected lobe. As with CDH, prognosis depends on the amount of remaining lung tissue, which may be hypoplastic because of compression in utero.

**Congenital Lobar Emphysema**

Congenital lobar emphysema often presents with respiratory distress shortly after birth. This lesion may be caused by “ball-valve” bronchial obstruction in utero, causing progressive distal overdistention with fetal lung fluid. The resultant emphysematous lobe may compress the lung bilaterally, resulting in a variable degree of hypoplasia. Congenital cardiac deformities are present in about 15% of patients. Radiographic signs of hyperinflation may be misinterpreted as tension pneumothorax or atelectasis on the contralateral side (Fig. 1). Positive-pressure ventilation may exacerbate lung hyperinflation. Nitrous oxide is contraindicated, and isolation of the lungs during anesthesia is desirable.

![Figure 1](image_url). Congenital lobar emphysema. The radiographic appearance may be confused with tension pneumothorax or decreased lung volume (e.g., atelectasis) on the contralateral side.
Congenital Diaphragmatic Hernia

Congenital diaphragmatic hernia is a life-threatening condition occurring in approximately 1 in 2000 live births. Failure of a portion of the fetal diaphragm to develop allows abdominal contents to enter the thorax, interfering with normal lung growth. In 70% to 80% of diaphragmatic defects, a portion of the left posterior diaphragm fails to close, forming a triangular defect known as the foramen of Bochdalek. Hernias through the foramen of Bochdalek occurring early in fetal life usually cause respiratory failure immediately after birth because of pulmonary hypoplasia. Distention of the gut postnatally with bag-and-mask ventilation exacerbates the ventilatory compromise by further compressing the lungs. The diagnosis is often made prenatally, and fetal surgical repair has been performed. Neonates present with tachypnea, a scaphoid abdomen, and absent breath sounds over the affected side. Chest radiography typically shows bowel in the left hemithorax with deviation of the heart and mediastinum to the right and compression of the right lung (Fig. 2A). Right-sided hernias (Fig. 2B) may occur late in childhood and present with milder signs. In the presence of significant respiratory distress, bag-and-mask ventilation should be avoided and tracheal intubation should be performed immediately.

Because pulmonary hypertension with right-to-left shunting contributes to severe hypoxemia in neonates with CDH, a variety of vasodilators have been used. These include tolazoline, prostacyclin, dipyridamole, and nitrous oxide. High-frequency oscillatory ventilation (HFOV) has been used with pulmonary vasodilator therapy.

Figure 2. Congenital diaphragmatic hernia. This lesion occurs more commonly on the left side (A), but may also occur on the right (B).
to improve oxygenation prior to surgery. In cases of severe lung hypoplasia and pulmonary hypertension refractory to these therapies (e.g., arterial oxygen saturation <50 mm Hg with inspired oxygen fraction 1.0), extracorporeal membrane oxygenation (ECMO) should be initiated early to avoid progressive lung injury. Improved outcomes have been associated with early use of ECMO followed by delayed surgical repair.

A particularly poor prognosis is predicted if CDH is associated with cardiac deformities, preoperative alveolar-to-arterial oxygen gradient greater than 500 mm Hg, or severe hypercarbia despite vigorous ventilation. Prognosis has also been correlated with pulmonary compliance and radiographic findings.

Surgical correction through a subcostal incision with ipsilateral chest tube placement may be performed prior to or during ECMO. In patients undergoing surgical repair of ECMO, pulmonary hypertension is the major cause of morbidity and mortality. Hyperventilation to induce a respiratory alkalosis and 100% oxygen should be administered to decrease pulmonary vascular resistance. The anesthetic should be designed to minimize sympathetic discharge, which may exacerbate pulmonary hypertension (e.g., a high-dose opioid technique). Infants should be ventilated with small tidal volumes and low inflating pressures to avoid pneumothorax on the contralateral (usually right) side. Both nitrous oxide and HFOV have been used during surgical repair. A high index of suspicion of right-sided pneumothorax should be maintained, and a thoracostomy tube should be placed in the event of acute deterioration of respiratory or circulatory function. It is also imperative that normal body temperature, intravascular volume, and acid–base status be maintained. Mechanical ventilation is continued postoperatively in nearly all cases.

Failure of the central and lateral portions of the diaphragm to fuse results in a retrosternal defect, the foramen of Morgagni. This usually presents with signs of bowel obstruction rather than respiratory distress. Repair is usually performed through an abdominal incision.

**Tracheoesophageal Fistula**

Tracheoesophageal fistula (TEF) or esophageal atresia occurs in approximately 1 in 4000 live births. In 80% to 85% of infants, this lesion includes esophageal atresia with a distal esophageal pouch and a tracheal fistulous connection. The fistula is usually located one or two tracheal rings above the carina. Afflicted neonates present with spillover of pooled oral secretions from the pouch and may develop progressive gastric distention and tracheal aspiration of acidic gastric contents through the fistula. A common association is the VACTERL complex, consisting of vertebral, anorectal, cardiac, tracheoesophageal, renal, and limb defects. Esophageal atresia is confirmed when an orogastric tube passed through the mouth cannot be advanced more than approximately
7 cm (Fig. 3). The tube should be secured and placed on continuous suction, after which a chest radiograph is diagnostic.

Mask ventilation and tracheal intubation are avoided prior to surgery, if possible, because they may exacerbate gastric distention and respiratory compromise. When the trachea is intubated, an attempt is made to occlude the tracheal orifice of the fistula with the tracheal tube. The tip of the tracheal tube is positioned just above the carina by auscultation of diminished breath sounds over the left axilla as the tube is advanced into the right main-stem bronchus, after which the tube is retracted until breath sounds are increased (Fig. 4A). A small fiberoptic bronchoscope may be passed through the tracheal tube to confirm appropriate placement. Occasionally, emergency gastrostomy is performed because of massive gastric distention. Placement of a balloon-tipped catheter in the fistula through the gastrostomy may be performed under guidance with a fiberoptic bronchoscope to prevent further gastric distention or to enable effective positive-pressure ventilation in cases of significant lung disease (Fig. 4B). “Antegrade” occlusion of a TEF has also been reported with a balloon-tipped catheter advanced through the trachea into the fistula (Fig. 4C). Preoperative evaluation should be performed to diagnose associated anomalies, particularly cardiac, musculoskeletal, and gastrointestinal defects, which occur in 30% to 50% of patients. Poorer prognosis in infants with TEF and esophageal atresia

Figure 3. Tracheoesophageal fistula. The most common variants of this lesion include esophageal atresia and a distal fistula.
is correlated with prematurity and underlying lung disease as well as coexistence of other congenital anomalies.\textsuperscript{56}

Surgical repair usually involves a right thoracotomy and extrapleural dissection of the posterior mediastinum. In most cases, the fistula is ligated and primary esophageal anastomosis is performed ("short gap atresia"). In cases wherein the esophageal "gap" is long, the proximal segment is preserved for subsequent staged anastomosis, with or without intestinal interposition.\textsuperscript{56} The trachea may be intubated with the patient breathing spontaneously or during gentle positive-pressure ventilation with small tidal volumes to avoid gastric distention. If a gastrostomy tube is in place, occlusion of the fistula may be confirmed by cessation of bubbling through an underwater tubing connected to the gastrostomy or appearance of carbon dioxide by gas analysis.\textsuperscript{115} Alternatively, the tracheal tube may be positioned in the main-stem bronchus opposite the side of the thoracotomy incision until the fistula is ligated.

Esophageal atresia without connection to the trachea occurs much less commonly. These lesions are generally diagnosed by radiography after the inability to pass an orogastric tube, at which time an absence of gas in the abdomen may be noted (Fig. 5). So-called H-type TEF without esophageal atresia is relatively rare. Patients with H-type lesions may present later in childhood or adulthood with recurrent pneumonias or gastric distention during positive-pressure ventilation.\textsuperscript{45}
Childhood

Some of the lesions just described may not be diagnosed until childhood. These include pulmonary sequestration, cystic lesions, and lobar emphysema. Other disorders for which thoracic surgery is performed in children, either for definitive treatment or diagnostic purposes, include neoplasms, infectious diseases, and musculoskeletal deformities (Table 2).

Neoplasms of the lung, mediastinum, and pleura may be primary or metastatic. Primary tumors of the chest are uncommon in children. Perhaps the most common are lymphoblastic lymphoma, a form of non-Hodgkin’s lymphoma, and Hodgkin’s disease. These neoplasms usually present as an anterior mediastinal (thymic) mass with pleural effusion, dyspnea caused by airway obstruction, pain, or superior vena cava syndrome (swelling of the upper arms, face, and neck) (Fig. 6). Induction of anesthesia in patients with anterior mediastinal masses may be associated with severe airways and circulatory collapse. Accordingly, institutions should have an algorithm in place for the evaluation of these patients, including preoperative CT scanning, echocardiography, and flow–volume studies, as well as for treatment (Fig. 7). Careful consideration should be given to performing a biopsy under local anesthesia or initiating chemotherapy or limited radiation therapy prior to subjecting

Text continued on page 164
<table>
<thead>
<tr>
<th>Lesion</th>
<th>Preoperative Evaluation</th>
<th>Surgical Treatment</th>
<th>Anesthetic Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neoplasms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lymphoma</td>
<td>CT, MRI, PFTs</td>
<td>Needle versus open biopsy</td>
<td>Respiratory, circulatory collapse for lesions in anterior mediastinum</td>
</tr>
<tr>
<td>Neuroblastoma</td>
<td>CT, MRI</td>
<td>VATS versus thoracotomy</td>
<td>SLV, occasional sympathetic discharge</td>
</tr>
<tr>
<td>Osteogenic sarcoma</td>
<td>CT, MRI</td>
<td>VATS versus thoracotomy</td>
<td>SLV; effects of prior chemotherapy, radiation therapy on heart, lungs</td>
</tr>
<tr>
<td>Ewing’s sarcoma</td>
<td>CT, MRI</td>
<td>VATS versus thoracotomy</td>
<td>SLV; effects of prior chemotherapy, radiation therapy on heart, lungs</td>
</tr>
<tr>
<td>Rhabdomyosarcoma</td>
<td>CT, MRI, angiography</td>
<td>VATS versus thoracotomy</td>
<td>SLV; may be very vascular (bleeding)</td>
</tr>
<tr>
<td>Germ cell tumors</td>
<td>CT, MRI</td>
<td>VATS versus thoracotomy</td>
<td>SLV</td>
</tr>
<tr>
<td>Empyema</td>
<td>CXR, pleurocentesis</td>
<td>VATS</td>
<td>SLV</td>
</tr>
<tr>
<td>Interstitial lung disease</td>
<td>CXR, alveolar lavage</td>
<td>VATS versus thoracotomy</td>
<td>SLV; severe hypoxemia during surgery</td>
</tr>
<tr>
<td>Pectus excavatum</td>
<td>CXR, CT, PFTs</td>
<td>Sternal resection versus retrosternal “strut”</td>
<td>Postoperative analgesia</td>
</tr>
<tr>
<td>Kyphoscoliosis</td>
<td>CXR, PFTs</td>
<td>Anterior/posterior spinal fusion</td>
<td>Anterior fusion may be done with VATS, requiring SLV</td>
</tr>
</tbody>
</table>

CT = Computerized tomography, MRI = magnetic resonance imaging, VATS = video-assisted thoracoscopic surgery, PFTs = pulmonary function tests, SLV = single lung ventilation.
Figure 6. Anterior mediastinal mass caused by lymphoma with associated pleural effusion before (A) and after (B) treatment with corticosteroids.

Figure 7. Evaluation and treatment of children with anterior mediastinal masses.
the child to general anesthesia to effect a decrease in tumor mass and life-threatening airway or vascular occlusion.

VENTILATION AND PERFUSION DURING THORACIC SURGERY

Ventilation is normally distributed preferentially to dependent regions of the lung, so there is a gradient of increasing ventilation from the most non-dependent to the most dependent lung segments. Because of gravitational effects, perfusion normally follows a similar distribution, with increased blood flow to dependent lung segments. As a result, ventilation and perfusion are normally well matched. During thoracic surgery, several factors act to increase ventilation perfusion (V/Q) mismatch. General anesthesia, neuromuscular blockade, and mechanical ventilation cause decreases in functional residual capacities of both lungs. Compression of the dependent lung in the lateral decubitus position may cause atelectasis. Surgical retraction or single lung ventilation results in collapse of the operative lung. Hypoxic pulmonary vasoconstriction, which acts to divert blood flow away from the underventilated lung, thereby minimizing V/Q mismatch, may be diminished by inhalational anesthetic agents and other vasodilating drugs. These factors apply equally to infants, children, and adults. The overall effect of the lateral decubitus position on V/Q mismatch, however, is different in infants compared with older children 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 non-dependent ("up"). Presumably, this is related to an increase in blood flow to the dependent, healthy lung and a decrease in blood flow to the non-dependent, 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, however, oxygenation is improved with the healthy lung "up." 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. 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 non-dependent and dependent lungs. Consequently, the favorable increase in perfusion to the dependent, ventilated lung is reduced in infants.
Finally, the infant’s increased oxygen requirement, coupled with a small functional residual capacity, predisposes to hypoxemia. Infants normally consume 6 to 8 mL of oxygen kg/minute compared with a normal oxygen consumption in adults of 2 to 3 mL/kg/minute. For these reasons, infants are at increased risks of significant oxygen desaturation during surgery in the lateral decubitus position.

INDICATIONS AND TECHNIQUES FOR SINGLE LUNG VENTILATION (SLV) IN INFANTS AND CHILDREN

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 with thoracotomy. Recent advances in surgical techniques as well as technology, including high-resolution microchip cameras and smaller endoscopic instruments, have facilitated the application of VATS in smaller patients.

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 (CAM), and neoplasms. In select centers, more advanced procedures have been reported, including closure of patent ductus arteriosus, repair of hiatal hernias, and anterior spinal fusion.

Video-assisted thoracoscopic surgery 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. Single lung ventilation (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. Several techniques can be used for SLV in children.

Single-Lumen Endotracheal Tube

The simplest means of providing SLV is to intentionally intubate the ipsilateral main stem bronchus with a conventional single-lumen ETT. When the left bronchus is to be intubated, the bevel of the ETT is rotated 180° and the head turned to the right. The ETT is advanced
into the bronchus until breath sounds on the operative side disappear. A fiberoptic bronchoscope may be passed through or alongside the ETT to confirm or guide placement. When a cuffed ETT is used, the distance from the tip of the tube to the distal cuff must be shorter than the length of the bronchus so the cuff is not entirely in the bronchus.\(^\text{75}\)

This technique is simple and requires no special equipment other than a fiberoptic bronchoscope. This may be the preferred technique of SLV in emergency situations such as airway hemorrhage or contralateral tension pneumothorax.

Problems can occur when using a single-lumen ETT for SLV. If a smaller, uncuffed ETT is used, it may be difficult to provide an adequate seal of the intended bronchus. This may prevent the operative lung from adequately collapsing or fail to protect the healthy, ventilated lung from contamination by purulent material from the contralateral lung. The surgeon is unable to suction the operative lung using this technique. Hypoxemia may occur because of obstruction of the upper lobe bronchus, especially when the short right main stem bronchus is intubated.

Variations of this technique have been described, including intubation of both bronchi independently with small ETTs.\(^\text{29,94,130,136}\) One main stem bronchus is initially intubated with an ETT, after which another ETT is advanced over a fiberoptic bronchoscope into the opposite bronchus.

### Balloon-Tipped Bronchial Blockers

A Fogarty embolectomy catheter or an end-hole, balloon wedge catheter may be used for bronchial blockade to provide SLV (Fig. 8).\(^\text{42, 52, 80, 127}\) Placement of a Fogarty catheter is facilitated by bending the tip of its stylette 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.

A potential problem with this technique is dislodgement of the blocker balloon into the trachea. The inflated balloon will then block ventilation to both lungs or prevent 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.\(^\text{17}\) A recent study, however, reported that bronchial blocker cuffs produced lower “cuff-to-tracheal” pressures than double-lumen
Figure 8. Balloon-tipped catheters for bronchial blockade. A, The Fogarty embolectomy catheter has a stylette but no end-hole (Baxter Healthcare Corp., Irvine, CA). B, The Arrow balloon wedge catheter has a spherical balloon (Arrow International Corp., Reading, PA). C, The Cook bronchial blocker has a cylindrical balloon designed specifically to conform to the bronchus in children (Cook, Inc., Bloomington, IN).

tubes (DLTs). When closed-tip bronchial blockers are used, the operative lung cannot be suctioned and continuous positive airway pressure cannot be provided to the operative lung if needed.

Recently, adapters have been used to facilitate ventilation during placement of a bronchial blocker through an indwelling ETT. Use of a new 5-Fr endobronchial blocker suitable for use in children with a multiport adapter and fiberoptic bronchoscope has been described (Cook, Bloomington, IN). The risk of hypoxemia during blocker placement is diminished, and repositioning of the blocker may be performed with fiberoptic guidance during surgery. Even with use of a FOB with a diameter of 2.2 mm, however, the indwelling 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.

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. A balloon located at the distal end of this small tube serves as a blocker. Univent tubes require a fiber optic bronchoscope 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.\textsuperscript{50} 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.

A disadvantage of the Univent tube is the large amount of cross-sectional area occupied by the blocker channel, especially in the smaller size tubes. Smaller Univent tubes have a disproportionately high resistance to gas flow.\textsuperscript{120} The Univent tube’s blocker balloon has low-volume, high-pressure characteristics, so mucosal injuries can occur during normal inflation.\textsuperscript{10, 68}

Double-Lumen Tubes (DLTs)

All DLTs are essentially two tubes of unequal lengths molded together. The shorter tube ends in the trachea and the longer tube in the bronchus. Marraro\textsuperscript{91} described a bilumen tube for infants. This tube consists of two separate uncuffed tracheal tubes of different lengths attached longitudinally. This tube is not available in the United States. DLTs for older children and adults have cuffs located on the tracheal and bronchial lumens. The tracheal cuff, when inflated, allows positive-pressure ventilation. The inflated bronchial cuff allows ventilation to be diverted to either or both lungs, and protects each lung from contamination from the contralateral side.

Conventional plastic DLTs, once only available in adult sizes (35, 37, 39, and 41 Fr), are now available in smaller sizes. The smallest cuffed DLT is 26 Fr (Rusch, Duluth, GA) which may be used in children as young as 8 years of age. Double-lumen tubes are also available in sizes 28 and 32 Fr (Mallinckrodt Medical, St Louis, MO), suitable for children 10 years of age and older.

Double-lumen tubes are inserted in children using the same technique as in adults.\textsuperscript{22} The tip of the tube is inserted just past the vocal cords and the stylette is withdrawn. The DLT is rotated 90° to the appropriate side and then advanced into the bronchus. In the adult population, the depth of insertion is directly related to the height of the patient.\textsuperscript{23} No equivalent measurements are available in children. If fiberoptic bronchoscopy is to be used to confirm tube placement, a FOB with a small diameter and sufficient length must be available.\textsuperscript{120}

A DLT offers the advantage of ease of insertion as well as the ability to suction and oxygenate the operative lung with CPAP. Left DLTs are preferred to right DLTs because of the shorter length of the right main bronchus.\textsuperscript{12} Right DLTs are more difficult to position accurately because of the greater risk of right upper lobe obstruction.

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.

Guidelines for selecting appropriate tubes (or catheters) for SLV in children are shown in Table 3. There are significant variabilities in overall size and airway dimensions in children, particularly in teenagers. The recommendations shown in Table 3 are based on average values for airway dimensions. Larger DLTs may be safely used in large teenagers.

### MONITORING AND ANESTHETIC TECHNIQUES

A thorough preoperative evaluation is essential in caring for the pediatric patient scheduled for thoracic surgery. As discussed previously, appropriate imaging and laboratory studies should be performed preoperatively, depending on the lesion involved. Guidelines for fasting, choice of premedication, and preparation of the operating room are followed as for other infants and children scheduled for major surgery. Following induction of anesthesia, placement of an intravenous catheter, tracheal intubation, and arterial catheterization should be performed for most patients undergoing thoracotomy as well as those with severe lung disease having VATS. This facilitates monitoring of arterial blood pressure during manipulation of the lungs and mediastinum as well as arterial blood gas tensions during SLV. For thoracoscopic procedures of relatively short durations in patients without severe lung disease, insertion of an arterial catheter is not required. Placement of a central venous catheter is generally not indicated if peripheral intravenous access is adequate for projected fluid and blood administration.

Inhalational anesthetic agents are commonly administered in 100%

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**Table 3. TUBE SELECTION FOR SINGLE LUNG VENTILATION IN CHILDREN**

| Age (years) | ETT (ID)* | BB (Fr) | Univent§ | DLT (Fr)||
|-------------|-----------|---------|-----------|--------|
| 0.5–1       | 3.5–4.0   | 5† 6‡   |           |        |
| 1–2         | 4.0–4.5   | 5† 6‡   |           |        |
| 2–4         | 4.5–5.0   | 5† 6‡   |           |        |
| 4–6         | 5.0–5.5   | 5† 6‡   |           |        |
| 6–8         | 5.5–6     | 5† 6‡   | 3.5       |        |
| 8–10        | 6.0 cuffed| 5† 6‡   | 3.5       | 26     |
| 10–12       | 6.5 cuffed| 5† 6‡   | 4.5       | 26–28  |
| 12–14       | 6.5–7.0 cuffed| 5† 6‡ | 4.5 | 32     |
| 14–16       | 7.0–7.5 cuffed| 9† 7‡ | 6.0 | 35     |
| 16–18       | 7.5–8.0 cuffed| 9† 7‡ | 7.0 | 35     |

*Sheridan® Tracheal Tubes, Kendall Healthcare, Mansfield, MA
†Cook, Inc, Bloomington, IN
‡Arrow International Corp, Redding, PA
§Fuji Systems Corporation, Tokyo, Japan
26 Fr—Rusch, Duluth, GA; 28–35 Fr—Mallinckrodt Medical Inc., St. Louis, MO
ID = internal diameter, Fr = French size, DLT = double-lumen tube
oxygen during maintenance of anesthesia. Isoflurane may be preferred because it offers less attenuation of hypoxic pulmonary vasoconstriction compared with other inhalational agents, though this has not been studied in children. Nitrous oxide is avoided. Use of intravenous opioids may facilitate a decrease in the concentration of inhalational anesthetics used, and therefore limit impairment of hypoxic pulmonary vasoconstriction. Alternatively, total intravenous anesthesia may be used with a variety of agents. The combination of general anesthesia with regional anesthesia and postoperative analgesia is particularly desirable for thoracotomy, but may also be beneficial for VATS, especially when thoracostomy tube drainage, a source of significant postoperative pain, is used following surgery. A variety of regional anesthetic techniques have been described for intraoperative anesthesia and postoperative analgesia, including intercostal and paravertebral blocks, intrapleural infusions, and epidural anesthesia.

Intercostal nerve blocks may be performed prior to skin incision or under direct vision by the surgeon prior to chest closure. Because of overlap of sensory dermatomes, nerves above and below the area of surgery must be blocked. This may require large doses and therefore high plasma concentrations of local anesthetic agents, especially in infants. Intraoperative placement of an intercostal catheter for post-thoracotomy pain relief has also been described. Paravertebral blocks provide analgesia comparable with intercostal blockade. Though not reported for post-thoracotomy pain in children, the use of continuous paravertebral block has been described in children undergoing renal surgery. Complications associated with paravertebral block include spinal, epidural, and intravascular injections.

The use of intrapleural anesthesia in children was first described in 1988. Though continuous infusions of bupivacaine of 1.25 mg.kg⁻¹.hr⁻¹ were not associated with clinical signs of toxicity in this report, plasma concentrations were as high as 7 μg mL⁻¹. Because a relatively large volume of local anesthetic solution is required to achieve satisfactory analgesia with this technique, the use of a more dilute bupivacaine solution has been described. In this study of eight children undergoing thoracotomy, bupivacaine 0.1% was infused up to 1 mL.kg⁻¹.hr⁻¹ following surgery. The maximum plasma bupivacaine concentration measured was 2.16 μg mL⁻¹, and no signs of toxicity were observed. Satisfactory analgesia was achieved in all children. Several studies in adult patients, however, have shown that intrapleural bupivacaine does not produce reliable post-thoracotomy analgesia. In a randomized prospective, double-blind study, epidural hydromorphone provided superior analgesia compared with intrapleural bupivacaine following thoracotomy.

Of the regional anesthesia techniques described, only epidural anesthesia facilitates excellent intraoperative anesthesia, a low risk of local anesthetic toxicity, and “titratable” postoperative analgesia.
Epidural Anesthesia

To attenuate the stress response associated with thoracic surgery as well as provide optimal postoperative analgesia, a combination of epidural opioids and local anesthetic agents may be used. Though local anesthetic agents may spread to thoracic dermatomes when administered through the caudal or lumbar epidural space, potentially toxic doses of local anesthetics are required to achieve thoracic analgesia.\(^{112, 113}\) When the epidural catheter tip is placed in proximity to the spinal segment associated with surgical incision (i.e., a thoracic epidural catheter is placed for thoracic surgery), segmental anesthesia may be achieved with lower doses of local anesthetic than those needed when the catheter tip is distant from the surgical site.

In infants, a catheter can usually be advanced from the caudal to the thoracic epidural space.\(^{18, 46}\) With the infant in the lateral decubitus position following the induction of general anesthesia, a 20-gauge epidural catheter may be inserted through an epidural needle or an 18-gauge intravenous catheter placed through the sacrococcygeal membrane. The epidural catheter is then advanced 16 to 18 cm to the mid-thoracic epidural space. Minor resistance to passage of the catheter may be overcome by simple flexion or extension of the spine. If continued resistance is encountered, no attempt should be made to advance the catheter further, as the catheter may become coiled within or may exit the epidural space.

In older children, a thoracic epidural catheter may be inserted under general anesthesia directly between T4 and T8 to provide intraoperative neuraxial block and postoperative analgesia. Though the safety of placing epidural catheters in anesthetized patients has been questioned,\(^{24}\) this technique is widely used by pediatric anesthesia practitioners.\(^{72}\) The incidence of neurologic sequelae related to epidural catheterization in pediatric patients is unknown. Flandin-Blety and Barrier\(^{35}\) reported five cases of serious neurologic injury in a retrospective review of 24,005 regional anesthetics performed in France and Belgium over a 10-year period. All these patients were infants under 3 months of age, and the causes of neurologic injuries and associations with epidural anesthesia were unknown. In a separate retrospective survey of 119 pediatric hospitals, including more than 150,000 epidural blocks, there were no reports of permanent neurologic injuries, epidural hematomas, infections, or deaths.\(^{43}\) The authors concluded that the risk of a major complication was less than approximately 1:10,000. This complication rate is consistent with that observed in adult patients,\(^{21, 65}\) who are usually awake and able to report pain or paresthesias during needle and catheter placement.

A variety of local anesthetic agents have been used to provide epidural anesthesia and analgesia in infants and children, including chloroprocaine,\(^{125}\) lidocaine,\(^{92, 134}\) bupivacaine,\(^{99, 117}\) and ropivacaine.\(^{60, 99}\) Advantages of lidocaine are that it has less cardiotoxicity than bupivacaine, and blood concentrations can be readily measured in most hospital laboratories. Nevertheless, the majority of reports of the use of thoracic
epidural anesthesia and analgesia in children include the use of bupivacaine.25, 46, 51, 124, 134 A new agent, levobupivacaine (Chirocaine, Purdue Pharma, LP/8), causes less cardiovascular toxicity than racemic bupivacaine in adults, but no study in children has been published.7, 57

Clearance and protein binding for local anesthetics are reduced in neonates and young infants, causing the potential for drug accumulation during continuous infusion and increased central nervous system and cardiovascular toxicities.76, 84, 97 Maximum infusion rates for lidocaine of 1 mg.kg.hr⁻¹ (e.g., 1 mg.kg.hr⁻¹ of a 0.1% solution) have been recommended for young infants.134 Plasma concentrations of lidocaine and its principal active metabolite, monoethylglycinexylidide, should be measured twice daily in infants, if possible, because both compounds are epileptogenic.97 Maximal bupivacaine infusion rates of 0.2 to 0.3 mg.kg.hr⁻¹ should be used when prolonged epidural infusion is planned in infants under 3 months of age.

Epidural opioids are often combined with local anesthetic agents to provide maximal pain relief and to minimize tachyphylaxis. The concomitant use of opioids allows the use of lower concentrations of local anesthetics and decreases the risk of local anesthetic toxicity. Epidural morphine,88, 119 hydromorphone,44 fentanyl,83 and sufentanil71 have been used in infants and children. Of these agents, morphine has the lowest lipid solubility, followed by hydromorphone, fentanyl, and sufentanil.110 Morphine has been associated with delayed respiratory depression and relatively high incidences of pruritus, nausea, and vomiting.4,132 By comparison, hydromorphone has been associated with rapid onset of analgesia, a low incidence of side effects, and a low risk of delayed respiratory depression.26, 51, 98, 102 More highly lipophilic drugs, such as fentanyl, spread minimally in the epidural space, and optimal postoperative analgesia is achieved only when the epidural catheter is placed at or near the level of surgery.78 In a recent study comparing side-effects with epidural morphine, hydromorphone, and fentanyl, hydromorphone was associated with the lowest incidences of pruritus, nausea, and vomiting.44 Regimens used for continuous thoracic epidural analgesia in children are shown in Table 4.

Suggested treatments for side effects related to spinal and epidural opioids are shown in Table 5.

Recent reports have described epidural administration of a number of other drugs to provide analgesia or decrease the side effects of epidural opioids. These include ketamine,62, 118 clonidine,60, 84 and butorphanol.47, 77 The roles of these agents in providing epidural anesthesia and analgesia for pediatric patients undergoing thoracic surgery remain to be defined.

For patients not receiving a regional anesthetic technique to provide postoperative analgesia, systemic opioids are used following thoracotomy. Though intermittent intramuscular and subcutaneous injections have been used widely in the past, these routes of administration are painful and are associated with unpredictable and erratic uptake and distribution. Intermittent intravenous injections with opioids of short or
Table 4. DOSING REGIMENS FOR CONTINUOUS THORACIC EPIDURAL ANALGESIA IN CHILDREN

<table>
<thead>
<tr>
<th>Another (ref)</th>
<th>Indication</th>
<th>Age (years)</th>
<th>Epidural Solution</th>
<th>Infusion Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gunter (46)</td>
<td>Thoracic/abdominal surgery</td>
<td>1–10</td>
<td>Bupiv 0.125% +</td>
<td>0.15 mL·kg⁻¹·hr⁻¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Epi 1:200,000</td>
<td></td>
</tr>
<tr>
<td>Cassidy (25)</td>
<td>Spinal fusion</td>
<td>11–18</td>
<td>Bupiv 0.125%</td>
<td>0.28 mL·kg⁻¹·hr⁻¹</td>
</tr>
<tr>
<td>Hammer (53)</td>
<td>Cardiac surgery</td>
<td>1–6</td>
<td>Bupiv 0.1% +</td>
<td>0.30 mL·kg⁻¹·hr⁻¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HM .003 mg·mL⁻¹</td>
<td></td>
</tr>
<tr>
<td>Tobias (124)</td>
<td>Thoracic surgery</td>
<td>.25–18</td>
<td>Bupiv 0.1% +</td>
<td>0.30 mL·kg⁻¹·hr⁻¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fent .017–.025 mg·mL⁻¹</td>
<td></td>
</tr>
</tbody>
</table>

Bupiv = Bupivacaine, Epi = epinephrine, Fent = fentanyl, HM = hydromorphone

Moderate duration are also associated with periods of excessive sedation and inadequate analgesia. The use of methadone, which has a half-life of approximately 19 hours in children over the age of 1 year,14 may provide more continuous analgesia than shorter-acting agents.14 For moderate to severe pain, intermittent intravenous doses of methadone between 0.05 mg·kg⁻¹ and 0.08 mg·kg⁻¹ as needed may be given.13

Continuous analgesia may be achieved when opioids are administered by continuous intravenous infusion with or without patient-controlled analgesia (PCA) dosing. Morphine is the drug used most commonly for postoperative analgesia. In neonates less than 1 month of age, clearance is reduced and elimination half-life is prolonged—about three times that in adults.87 For continuous infusions of morphine, a loading dose of 0.025 to 0.075 mg·kg⁻¹ followed by infusion rates of 0.005 to 0.015 mg·kg·hour⁻¹ result in therapeutic plasma concentrations in neonates.86 Older infants and children require loading doses of 0.05 to 0.1 mg·kg⁻¹ followed by initial infusion rates of 0.01 to 0.03 mg·kg⁻¹/hour⁻¹. In children receiving PCA, dosing in the range of 0.01 to 0.03 mg·kg⁻¹ with a lock-out interval of 6 to 10 minutes with or without a continuous infusion has been recommended.134 In children at risk for morphine-induced histamine release, fentanyl (0.0005–0.001 mg·kg⁻¹·hr⁻¹ ± 0.0005–0.001 mg·kg⁻¹ PCA dose) or hydromorphone (0.003–0.005 mg·kg⁻¹ ± 0.003–0.005 mg·kg⁻¹ PCA dose) may be used.135

The side effects that may occur with intravenous opioid administration are similar to those described with epidural opioids, and may be treated similarly (see Table 5). With epidural or intravenous techniques, improved analgesia and a decrease in opioid dosing (and side effects) may be achieved with concomitant administration of nonopioid analgesic agents. The use of these adjuvant drugs, including acetaminophen and a variety of nonsteroidal anti-inflammatory drugs has been reviewed elsewhere.133
Table 5. TREATMENT FOR SIDE EFFECTS OF NEURAXIAL OPIOID ADMINISTRATION

<table>
<thead>
<tr>
<th>Side Effect</th>
<th>Treatment</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nausea/ vomiting</td>
<td>Metoclopramide 0.1–0.2 mg.kg⁻¹ dose iv Q 6 hr Maximum dose: 10 mg</td>
<td>Extrapyramidal reactions may occur but are uncommon</td>
</tr>
<tr>
<td></td>
<td>Droperidol 0.025–0.05 mg.kg⁻¹ iv Q 6 hr prn Maximum dose: 1.25 mg</td>
<td>Very sedating—avoid if somnolent</td>
</tr>
<tr>
<td></td>
<td>Diphenhydramine 0.5–1 mg.kg⁻¹ iv Q 6 hr prn Maximum dose: 50 mg</td>
<td>Very sedating—avoid if somnolent</td>
</tr>
<tr>
<td></td>
<td>Ondansetron 0.1–0.2 mg.kg⁻¹ iv Q 6 hr prn Maximum dose: 4 mg</td>
<td>May substitute other 5-HT3 antagonist; e.g., Granisetron</td>
</tr>
<tr>
<td></td>
<td>Nalbuphine 0.1 mg.kg⁻¹ iv Q 6 hr prn Naloxone 0.001–0.005 mg.kg⁻¹.hr⁻¹ infusion</td>
<td>Excessive doses may compromise analgesia</td>
</tr>
<tr>
<td>Pruritus</td>
<td>Diphenhydramine 0.5–1.0 mg.kg⁻¹ iv Q 6 hr prn Maximum dose: 50 mg</td>
<td>Very sedating—avoid if somnolent</td>
</tr>
<tr>
<td></td>
<td>Nalbuphine mg.kg⁻¹ iv Q 6 hr prn Naloxone 0.001–0.005 mg.kg⁻¹.hr⁻¹ infusion</td>
<td>Excessive doses may compromise analgesia</td>
</tr>
<tr>
<td>Somnolence</td>
<td>Decrease epidural opioid infusion Consider low-dose naloxone infusion (above)</td>
<td></td>
</tr>
<tr>
<td>Respiratory depression</td>
<td>Severe: Administer 100% through facemask Initiate positive-pressure ventilation prn Naloxone 0.001–0.01 mg.kg⁻¹ iv Stop epidural infusion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subsequent/Mild-moderate depression: Increase fractional inspired oxygen Reduce epidural opioid infusion Naloxone 0.001–0.005 mg.kg⁻¹.hr⁻¹ infusion</td>
<td></td>
</tr>
<tr>
<td>Urinary retention</td>
<td>Replace urinary catheter prn</td>
<td></td>
</tr>
</tbody>
</table>

SUMMARY

The anesthesiologist caring for infants and children undergoing thoracic surgery faces many challenges. An understanding of the primary underlying lesion as well as associated anomalies that may impact perioperative management is paramount. A working knowledge of respiratory physiology and anatomy in infants and children is required for the planning and execution of appropriate intraoperative care. Familiarity with a variety of techniques for SLV suited to the patient’s size will allow maximal surgical exposure while minimizing trauma to the lungs.
and airways. Finally, use of regional anesthetic techniques, including epidural anesthesia and analgesia, facilitates optimal postoperative pain control and pulmonary function.

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