0889–8537/02 $16.00 + .00

PEDIATRIC THORACIC ANESTHESIA

Gregory B. Hammer, MD

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 contined on page 155

From the Department of Anesthesia, Stanford University Medical Center, Palo Alto, California

Table 1. LESIONS OF THE AIRWAYS AND LUNGS IN NEONATES

Lesion	Preoperative Evaluation	Surgical Treatment	Anesthetic Considerations
Tracheal stenosis			
Acquired	Laryngoscopy/bronchoscopy	Cricoid split	TIVA
Congenital	Laryngoscopy/bronchoscopy	Laryngotracheoplasty	TIVA, postoperative ventilation
Pulmonary sequestration	CT, MRI	Resection	Avoid N_2O
Congenital cystic lesions	CT, MRI	Resection	Minimize inflating pressure, avoid N_2O
Congenital lobar emphysema	CT, MRI	Resection	Minimize inflating pressure, avoid N_2O
Congenital diaphragmatic hernia	CXR	Replace abdominal contents, close defect	Hyperventilation, minimize inflating pressure, avoid N_2O Nitrous oxide, HFOV, ECMO
Tracheoesophageal fistula	CXR	Ligation of fistula, esophageal anastomosis	Minimize inflating pressure, occlude fistula with ETT, blocker if possible

FOB = Fiberoptic bronchoscopy, TIVA = total intravenous anesthesia, CT = computed tomography, MRI = magnetic resonance imaging, N_2O = 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 laryngotracheoplasty 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 categories[73]: (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.[111] 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.[114]

Congenital Lobar Emphysema

Congenital lobar emphysema often presents with respiratory distress shortly after birth.[104] 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.[81] 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.

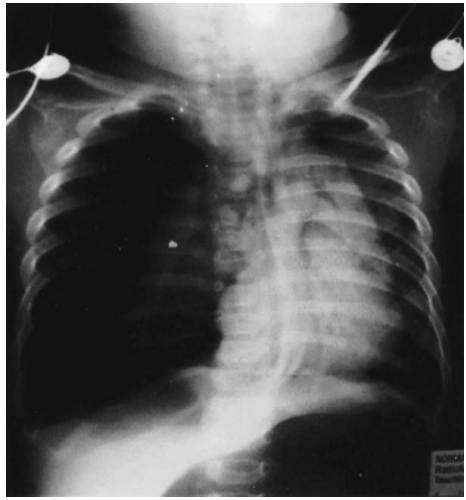

Figure 1. Congenital lobar emphysema. The radiographic appearance may be confused with tension pneumothorax or decreased lung volume (e.g., atelectasis) on the contralateral side.

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.[101] 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. 2*A*). Right-sided hernias (Fig. 2*B*) 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.[61, 63, 90, 107, 122] High-frequency oscillatory ventilation (HFOV) has been used with pulmonary vasodilator therapy

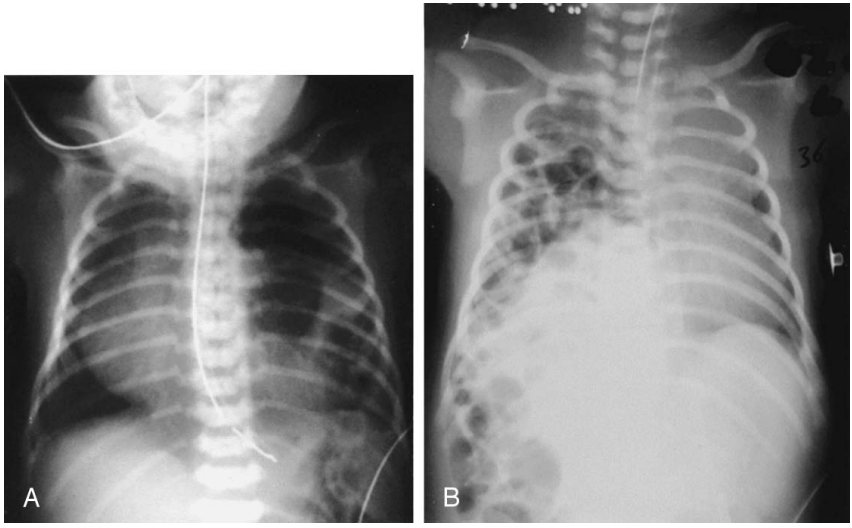

Figure 2. Congenital diaphragmatic hernia. This lesion occurs more commonly on the left side *(A)*, but may also occur on the right *(B)*.

to improve oxygenation prior to surgery.[96] 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.[37]

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.[1, 54] Prognosis has also been correlated with pulmonary compliance and radiographic findings.[32, 40, 67]

Surgical correction through a subcostal incision with ipsilateral chest tube placement may be performed prior to or during ECMO.[27, 126] 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.[19,79] 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.[30, 56] 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.[8] 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. 4*A*). 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. 4*B*).[16] ''Antegrade'' occlusion of a TEF has also been reported with a balloon-tipped catheter advanced through the trachea into the fistula (Fig. 4*C*).[34] Preoperative evaluation should be performed to diagnose associated anomalies, particularly cardiac, musculoskeletal, and gastrointestinal defects, which occur in 30% to 50% of patients.[58] Poorer prognosis in infants with TEF and esophageal atresia

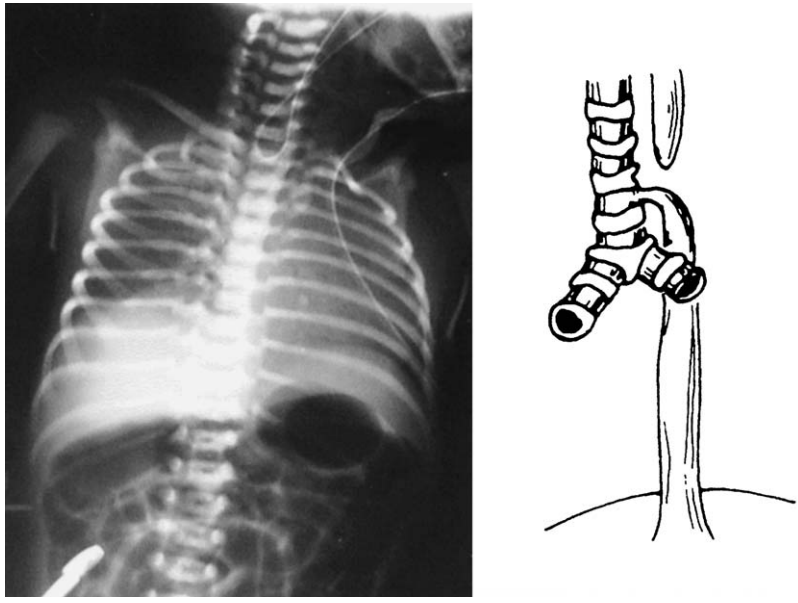

Figure 3. Tracheoesophageal fistula. The most common variants of this lesion include esophageal atresia and a distal fistula.

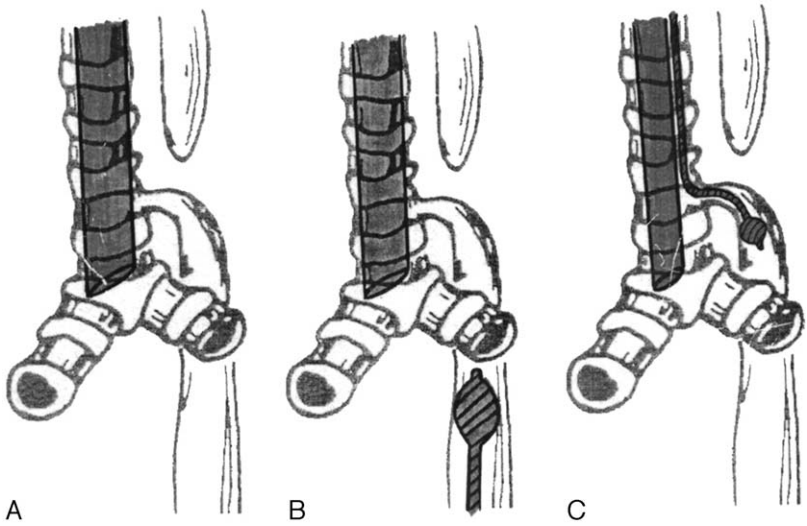

Figure 4. Methods for minimizing gastric insufflation in infants with a tracheoesophageal fistula. The tip of the ETT may be placed distal to the fistula in many cases *(A)*. Alternatively, a balloon-tipped catheter may be placed in the fistula by way of the gastrostomy *(B)* or the trachea *(C)*.

is correlated with prematurity and underlying lung disease as well as coexistence of other congenital anomalies.[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.[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.[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.[45]

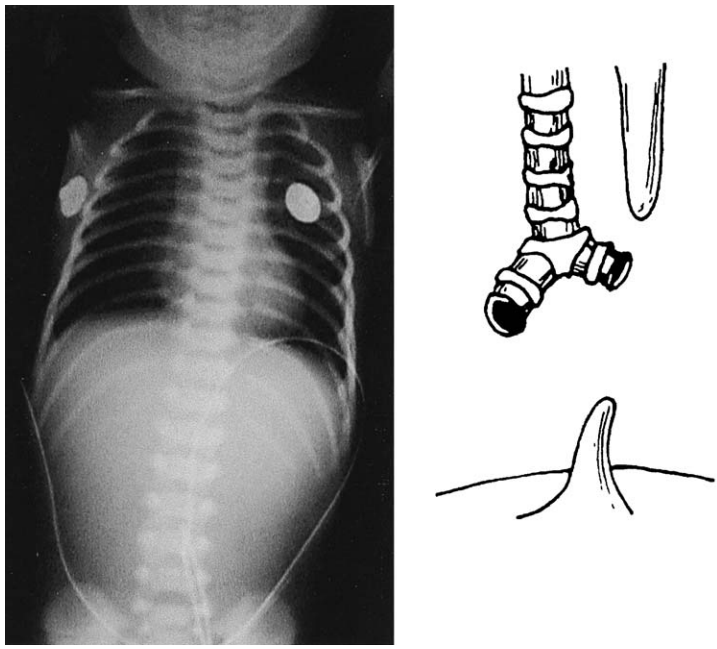

Figure 5. Esophageal atresia without a tracheoesophageal fistula.

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.[36] 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).[5, 6] Induction of anesthesia in patients with anterior mediastinal masses may be associated with severe airways and circulatory collapse.[69, 103] 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 contined on page 164

Table 2. LESIONS OF THE LUNGS AND CHEST IN CHILDREN

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

CT = Computerized tomography, MRI = magnetic resonance imaging, VATS = video-assisted thoracoscopic surgery, PFTs = pulmonary function tests, SLV = single lung ventilation.

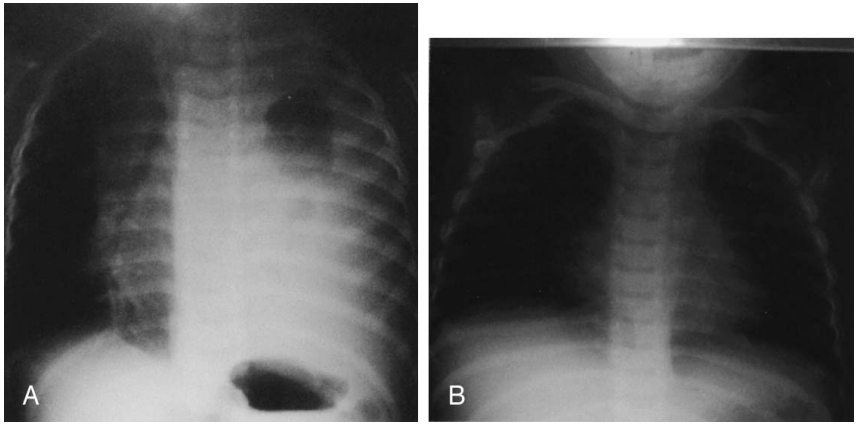

Figure 6. Anterior mediastinal mass caused by lymphoma with associated pleural effusion before *(A)* and after *(B)* treatment with corticosteroids.

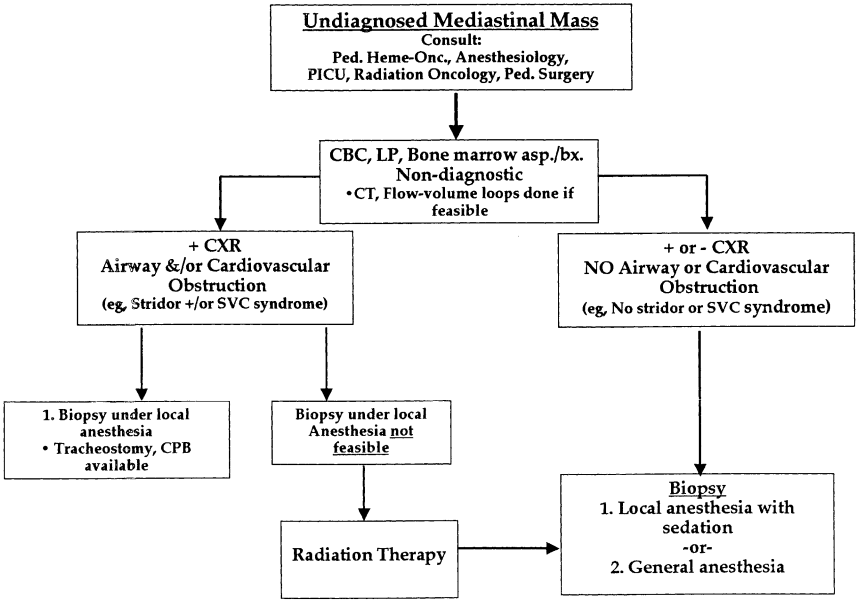

Figure 7. Evaluation and treatment of children with anterior mediastinal masses.

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”).[105] 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.”[55] 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.[89] 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.[31] 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.[2,100,131] 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.[12] 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.[109] When the left bronchus is to be intubated, the bevel of the ETT is rotated 180° and the head turned to the right.[74] 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.[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.[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).[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.[17] A recent study, however, reported that bronchial blocker cuffs produced lower ''cuff-to-tracheal'' pressures than double-lumen

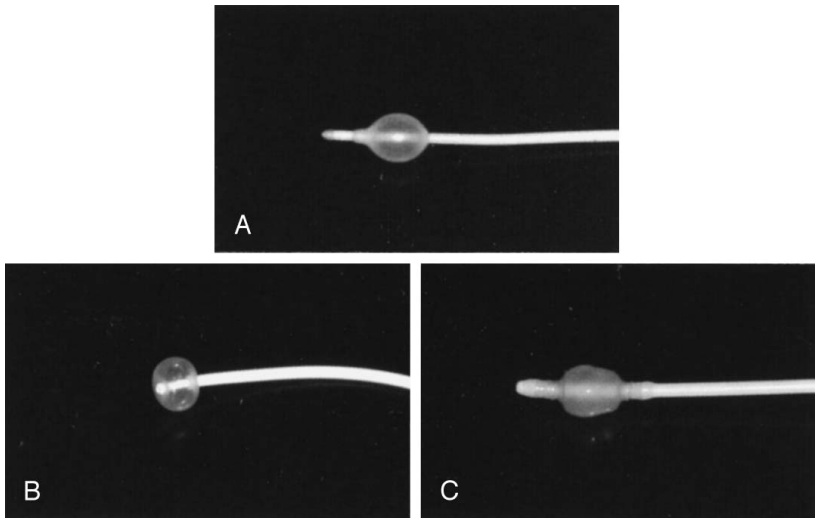

Figure 8. Balloon-tipped catheters for bronchial blockade. *A*, The Fogarty embolectomy catheter has a stylette but no end-hole (Baxter Healthcare Corp., Irvine, CA). *B*, The Arrow balloon wedge catheter has a spherical balloon (Arrow International Corp., Reading, PA). *C*, The Cook bronchial blocker has a cylindrical balloon designed specifically to conform to the bronchus in children (Cook, Inc., Bloomington, IN).

tubes (DLTs).[48] 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.[3, 123] 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).[51] 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.[39, 64, 66] 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.[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.[120] The Univent tube's blocker balloon has low-volume, high-pressure characteristics, so mucosal injuries can occur during normal inflation.[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[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.[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.[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.[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.[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%

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
From Hammer GB, Fitzmaurice BG, Brodsky JB: Methods for single lung ventilation in pediatric patients. Anesth Analg 89:1426–1429, 1999; with permission

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.[10] 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.[20] Intraoperative placement of an intercostal catheter for post-thoracotomy pain relief has also been described.[28, 106] 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.[82] Complications associated with paravertebral block include spinal, epidural, and intravascular injections.

The use of intrapleural anesthesia in children was first described in 1988.[93] 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 $\mu g\ mL^{-1}$. 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.[41] 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 $\mu g\ mL^{-1}$, 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.[33, 95, 108, 116] In a randomized prospective, double-blind study, epidural hydromorphone provided superior analgesia compared with intrapleural bupivacaine following thoracotomy.[38]

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 sufentanil[71] 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

Another (ref)	Indication	Age (years)	Epidural Solution	Infusion Rate
Gunter (46)	Thoracic/abdominal surgery	1–10	Bupiv 0.125% + Epi 1:200,000	0.15 $mL.kg^{-1}.hr^{-1}$
Cassidy (25)	Spinal fusion	11–18	Bupiv 0.125% Fent 0.025 $mg.mL^{-1}$	0.28 $mL.kg^{-1}.hr^{-1}$
Hammer (53)	Cardiac surgery	1–6	Bupiv 0.1% + HM .003 $mg.mL^{-1}$	0.30 $mL.kg^{-1}.hr^{-1}$
Tobias (124)	Thoracic surgery	.25–18	Bupiv 0.1% + Fent .017–.025 $mg.mL^{-1}$	0.30 $mL.kg^{-1}.hr^{-1}$

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

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

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.

References

1. Adelman S, Benson CD: Bochdalek hernias in infants: Factors determining mortality. J Pediatr Surg 11:569–573, 1976
2. Angelillo MacKinlay TA, Lyons GA, Chimondeguy DJ, et al: VATS debridement versus thoracotomy in the treatment of loculated postpneumonia empyema. Ann Thorac Surg 61:1626–1630, 1996
3. Arndt GA, De Lessio ST, Kranner PW, et al: One-lung ventilation when intubation is difficult–presentation of a new endobronchial blocker. Acta Anaesthesiol Scand 43: 356–358, 1999
4. Attia J, Ecoffy C, Sandouk P, et al: Epidural morphine in children: Pharmacokinetics and CO2 sensitivity. Anesthesiology 65:590–594, 1986
5. Azarow KS, Pearl RH, Zurcher R, et al: Primary mediastinal masses: A comparison of adult and pediatric populations. J Thorac Cardiovasc Surg 106:67–72, 1993
6. Azizkhan RG, Dudgeon DL, Colombani PM, et al: Life-threatening airway obstruction as a complication to the management of mediastinal masses in children. J Pediatr Surg 20:816–822, 1985
7. Bardsley H, Gristwood R, Baker H, et al: A comparison of the cardiovascular effects of levobupivacaine and rac-bupivacaine following intravenous administration to healthy volunteers. Br J Clin Pharmacol 46:245–249, 1998
8. Barry JE, Auldist AW: The VATER association: One end of a spectrum of anomalies. Am J Dis Child 128:769–771, 1974
9. Benumof JL: Anesthesia for Thoracic Surgery, ed. 2 Philadelphia, WB Saunders, 1995
10. Benumof JL, Augustine SD, Gibbons JA: Halothane and isoflurane only slightly impair arterial oxygenation during one-lung ventilation in patients undergoing thoracotomy. Anesthesiology 67:910–914, 1987
11. Benumof JL, Gaughan SD, Ozaki GT: The relationship among bronchial blocker cuff inflation volume, proximal airway pressure, and seal of the bronchial blocker cuff. J Cardiothorac Vasc Anesth 6:404–408, 1992
12. Benumof JL, Partridge BL, Salvatierra C, et al: Margin of safety in positioning modern double-lumen endotracheal tubes. Anesthesiology 67:729–738, 1987
13. Berde CB: Pediatric postoperative pain management. Pediatr Clin North Am 36: 921–940, 1989
14. Berde CB, Beyer JE, Bournaki MC, et al: A comparison of morphine and methadone for prevention of postoperative pain in 3 to 7 year old children. J Pediatr 119: 136–141, 1991
15. Berde CB, Sethna NF, Holtzman RS, et al: Pharmacokinetics of methadone in children and adolescents in the perioperative period. Anesthesiology 67:A519, 1987
16. Bloch EC, Filston HC: A thin fiberoptic bronchoscope as an aid to occlusion of the fistula in infants with tracheoesophageal fistula. Anesth Analg 67:791–793, 1988
17. Borchardt RA, LaQuaglia MP, McDowall RH, et al: Bronchial injury during lung isolation in a pediatric patient. Anesth Analg 87:324–325, 1998
18. Bosenberg AT, Bland BA, Schulte-Steinberg O, et al: Thoracic epidural anesthesia via the caudal route in infants. Anesthesiology 69:265–269, 1988
19. Bouchut JC, Dubois R, Moussa M, et al: High frequency oscillatory ventilation during repair of neonatal congenital diaphragmatic hernia. Paediatr Anaesth 10:377–379, 2000
20. Bricker SRW, Telford RJ, Booker PD: Pharmacokinetics of bupivacaine following intraoperative nerve block in neonates and infants less than 6 months. Anesthesiology 66:832–834, 1987
21. Bridenbaugh PO: Complications of local anesthetic neural blockade. *In*: Cousins MJ, Bridenbaugh PO, (eds): Neural Blockade in Clinical Anesthesia and Management of Pain. Philadelphia, JB Lippincott, 1988, 705–709

22. Brodsky JB, Mark JBD: A simple technique for accurate placement of double-lumen endobronchial tubes. Anesth Rev 10:26–30, 1983
23. Brodsky JB, Macario A, Mark JBD: Tracheal diameter predicts double-lumen tube size: A method for selecting left double-lumen tubes. Anesth Analg 82:861–864, 1996
24. Bromage PR, Benumof JL: Paraplegia following intracord injection during attempted epidural anesthesia under general anesthesia. Reg Anesth Pain Med 23:104–107, 1998
25. Cassidy JF, Lederhaas G, Cancel DD, et al: A randomized comparison of the effects of continuous thoracic epidural analgesia and intravenous patient-controlled analgesia after posterior spinal fusion in adolescents. Reg Anesth Pain Med 25:246–253, 2000
26. Chaplan R, Duncan SR, Brodsky JB, et al: Morphine and hydromorphone epidural analgesia. Anesthesiology 77:1090–1094, 1992
27. Clark RH, Hardin WD Jr, Hirschl RB: Current surgical management of congenital diaphragmatic hernia: A report from the Congenital Diaphragmatic Hernia Study Group. J Pediatr Surg 33:1004–1009, 1998
28. Cooper MG, Seaton HL: Intraoperative placement of intercostal catheter for post-thoracotomy pain relief in a child. Paediatr Anaesth 2:165–167, 1992
29. Cullum AR, English CW, Branthwaite MA: Endobronchial intubation in infancy. Anaesthesia 28:66–70, 1973
30. Cumming WA: Esophageal atresia and tracheoesophageal fistula. Radiol Clin North Am 13:277–295, 1975
31. Dawes GS: Fetal and Neonatal Physiology. Chicago, Yearbook Medical, 1973
32. Donnelly LF, Sakurai M, Klosterman LA: Correlation between findings on chest radiography and survival in neonates with congenital diaphragmatic hernia. Am J Roentgenol 173:1589–1593, 1999
33. Ferrante FM, Chan VW, Arthur GR, et al: Interpleural analgesia after thoracotomy. Anesth Analg 72:105–109, 1991
34. Filston HC, Chitwood WR Jr, Schkolne B, et al: The Fogarty balloon catheter as an aid to management of the infant with esophageal atresia and tracheoesophageal fistula complicated by severe RDS or pneumonia. J Pediatr Surg 17:149–151, 1982
35. Flandin-Blety C, Barrier G: Accidents following extradural analgesia in children. The results of a retrospective study. Paediatr Anaesth 5:41–46, 1995
36. Franken EA Jr, Smith JA, Smith WL: Tumors of the chest wall in infants and children. Pediatr Radiol 6:13–18, 1977
37. Frenckner B, Ehren H, Granholm T: Improved results in patients who have congenital diaphragmatic hernia using preoperative stabilization, extracorporeal membrane oxygenation, and delayed surgery. J Pediatr Surg 32:1185–1189, 1997
38. Gaeta RR, Macario A, Brodsky JB, et al: Pain outcomes after thoracotomy: Lumbar epidural hydromorphone versus intrapleural bupivacaine. J Cardiothorac Vasc Anesth 9:534–537, 1995
39. Gayes JM: The Univent tube is the best technique for providing one-lung ventilation. Pro: One-lung ventilation is best accomplished with the Univent endotracheal tube. J Cardiothorac Vasc Anesth 7:103–105, 1993
40. Geary MP, Chitty LS, Morrison JJ: Perinatal outcome and prognostic factors in prenatally diagnosed congenital diaphragmatic hernia. Ultrasound Obstet Gynecol 12: 107–111, 1998
41. Giaufre E, Bruguerolle B, Rastello C, et al: New regimen for interpleural block in children. Paediatr Anaesth 5:125–128, 1995
42. Ginsberg RJ: New technique for one-lung anesthesia using a bronchial blocker. J Thorac Cardiovasc Surg 82:542–546, 1981
43. Goldman LJ: Complications in regional anesthesia. Paediatr Anaesth 5:3–9, 1995
44. Goodarzi M: Comparison of epidural morphine, hydromorphone and fentanyl for postoperative pain control in children undergoing orthopaedic surgery. Paediatr Anaesth 9:419–422, 1999
45. Grant DM, Thompson GE: Diagnosis of congenital tracheoesophageal fistula in the adolescent and adult. Anesthesiology 49:139–140, 1978
46. Gunter JB, Eng C: Thoracic epidural anesthesia via the caudal approach in children. Anesthesiology 76:935–938, 1992
47. Gunter JB, McAuliffe J, Gregg T, et al: Continuous epidural butorphanol relieves

pruritus associated with epidural morphine infusions in children. Paediatr Anaesth 10:167–172, 2000
48. Guyton DC, Besselievre TR, Devidas M, et al: A comparison of two different bronchial cuff designs and four different bronchial cuff inflation methods. J Cardiothorac Vasc Anesth 11:599–603, 1997
49. Hammer GB, Lammers CR: Pediatric otolaryngology. *In*: Jaffe RA, Samuels SI, (eds): Anesthesiologist's Manual of Surgical Procedures. Philadelphia, Lippincott Williams & Wilkins, 1999, pp 872–875
50. Hammer GB, Brodsky JB, Redpath J, et al: The Univent tube for single lung ventilation in children. Paediatr Anaesth 8:55–57, 1998
51. Hammer GB, Harrison TK, Vricella LA, et al: Single lung ventilation using a new pediatric bronchial blocker. Paediatr Anaesth 2001 in press
52. Hammer GB, Manos SJ, Smith BM, et al: Single lung ventilation in pediatric patients. Anesthesiology 84:1503–1506, 1996
53. Hammer GB, Ngo K, Macario A: A retrospective examination of regional plus general anesthesia in children undergoing open heart surgery. Anesth Analg 90:1020–1024, 2000
54. Harrison MR, Bjordal RI, Langmark F, et al: Congenital diaphragmatic hernia: The hidden mortality. J Pediatr Surg 13:227–230, 1978
55. Heaf DP, Helms P, Gordon MB, et al: Postural effects on gas exchange in infants. N Engl J Med 28:1505–1508, 1983
56. Holder TM, Ashcraft KW, Sharp RJ, et al: Care of infants with esophageal atresia, tracheoesophageal fistula, and associated anomalies. J Thorac Cardiovasc Surg 94: 828–835, 1987
57. Huang YF, Pryor ME, Mather LE, et al: Cardiovascular and central nervous system effects of intravenous levobupivacaine and bupivacaine. Anesth Analg 86:797–804, 1998
58. Humphreys GH, Hogg BM, Ferrer J: Congenital atresia of the esophagus. J Thorac Surg 32:332–348, 1956
59. Ivani G, Bergendahl HT, Lampugnani E, et al: Plasma levels of clonidine following epidural bolus injection in children. Acta Anaesthesiol Scand 42:306–311, 1998
60. Ivani G, Mereto N, Lampugnani E: Ropivacaine in paediatric surgery: Preliminary results. Paediatr Anaesth 8:127–129, 1998
61. Ivy DD, Ziegler JW, Kinsella JP, et al: Dipyridamole attenuates rebound pulmonary hypertension after inhaled nitric oxide withdrawal in postoperative congenital heart disease. J Thorac Cardiovasc Surg 115:875–882, 1998
62. Johnston P, Findlow D, Aldridge LM, et al: The effect of ketamine on 0.25% and 0.125% bupivacaine for caudal epidural blockade in children. Paediatr Anaesth 9: 31–34, 1999
63. Kaapa P, Koivisto M, Ylikorlaka O, et al: Prostacyclin in the treatment of neonatal pulmonary hypertension. J Pediatr 107:951–953, 1985
64. Kamaya H, Krishna PR: New endotracheal tube (Univent tube) for selective blockade of one lung. Anesthesiology 63:342–343, 1985
65. Kane RE: Neurologic deficits following epidural or spinal anesthesia. Anesth Analg 60:150–161, 1981
66. Karwande SV: A new tube for single lung ventilation. Chest 92:761–763, 1987
67. Kavvadia V, Greenough A, Laubscher B: Perioperative assessment of respiratory compliance and lung volume in infants with congenital diaphragmatic hernia: Prediction of outcome. J Pediatr Surg 32:1665–1669, 1997
68. Kelley JG, Gaba DM, Brodsky JB: Bronchial cuff pressures of two tubes used in thoracic surgery. J Cardiothorac Vasc Anesth 6:190–194, 1992
69. Keon TP: Death on induction spore of anesthesia for cervical node biopsy. Anesthesiology 55:471–472, 1981
70. Khoo ST: Anaesthesia for fiberoptic bronchoscopy in children. Anaesthesia 45:248–249, 1990
71. Kokki H, Tuovinen K, Hendolin H: The effect of intravenous ketoprofen on postoperative epidural sufentanil analgesia in children. Anesth Analg 88:1036–1041, 1999

72. Krane EJ, Dalens BJ, Murat I, et al: The safety of epidurals placed during general anesthesia. Reg Anesth Pain Med 23:433–438, 1998
73. Kravitz RM: Congenital malformations of the lung. Pediatr Clin North Am 41: 453–472, 1994
74. Kubota H, Kubota Y, Toshiro T, et al: Selective blind endobronchial intubation in children and adults. Anesthesiology 67:587–589, 1987
75. Lammers CR, Hammer GB, Brodsky JB, et al: Failure to isolate the lungs with an endotracheal tube positioned in the bronchus. Anesth Analg 85:944, 1997
76. Larsson BA, Lonnqvist PA, Olsson GL: Plasma concentrations of bupivacaine in neonates after continuous epidural infusion. Anesth Analg 84:501–505, 1997
77. Lawhorn CD, Stoner JM, Schmitz ML, et al: Caudal epidural butorphanol plus bupivacaine versus bupivacaine in pediatric outpatient genitourinary procedures. J Clin Anesth 9:103–108, 1997
78. Lejus C, Roussiere G, Testa S, et al: Postoperative extradural analgesia in children: Comparison of morphine with fentanyl. Br J Anaesth 72:156–159, 1994
79. Leveque C, Hamza J, Berg AE, et al: Successful repair of a severe left congenital diaphragmatic hernia during continuous inhalation of nitric oxide. Anesthesiology 80:1171–1175, 1994
80. Lin YC, Hackel A: Paediatric selective bronchial blocker. Paediatr Anaesth 4:391–392, 1994
81. Lincoln JC, Stark J, Subramanian S, et al: Congenital lobar emphysema. Ann Surg 173:55–62, 1971
82. Lonnqvist PA, Olsson GL: Paravertebral vs. epidural block in children. Effects on postoperative morphine requirement after renal surgery. Acta Anaesthesiol Scand 38: 346–349, 1994
83. Lovstad RZ, Halvorsen P, Raeder JC, et al: Post-operative epidural analgesia with low dose fentanyl, adrenaline and bupivacaine in children after major orthopaedic surgery. A prospective evaluation of efficacy and side effects. Eur J Anaesthesiol 14: 583–589, 1997
84. Luz G, Innerhofer P, Oswald E, et al: Comparison of clonidine 1 microgram kg-1 with morphine 30 micrograms kg-1 for post-operative caudal analgesia in children. Eur J Anaesthesiol 16:42–46, 1999
85. Luz G, Wieser C, Innerhofer P, et al: Free and total bupivacaine plasma concentrations after continuous epidural anesthesia in infants and children. Paediatr Anaesth 8: 473–478, 1998
86. Lynn AM, Opheim KE, Tyler DC: Morphine infusion after pediatric cardiac surgery. Crit Care Med 12:863–866, 1984
87. Lynn AM, Slattery JT: Morphine pharmacokinetics in early infancy. Anesthesiology 66:136–139, 1987
88. Malviya S, Pandit UA, Merkel S, et al: A comparison of continuous epidural infusion and intermittent intravenous bolus doses of morphine in children undergoing selective dorsal rhizotomy. Reg Anesth Pain Med 24:438–443, 1999
89. Mansell A, Bryan C, Levison H: Airway closure in children. J Appl Physiol 33: 711–714, 1972
90. Mariani G, Barefield ES, Carlo WA: The role of nitric oxide in the treatment of neonatal pulmonary hypertension. Curr Opin Pediatr 8:118–125, 1996
91. Marraro G: Selective bronchial intubation in paediatrics: The Marraro paediatric bilumen tube. Paediatr Anaesth 4:255–258, 1994
92. McBride WJ, Dicker R, Abajian JC, et al: Continuous thoracic epidural infusions for postoperative analgesia after pectus deformity repair. J Pediatr Surg 31:105–107, 1996
93. McIlvaine WB, Knox RF, Fennessey PV, et al: Continuous infusion of bupivacaine via intrapleural catheter for analgesia after thoracotomy in children. Anesthesiology 69: 261–264, 1988
94. McLellan I: Endobronchial intubation in children. Anaesthesia 29:757–758, 1974
95. Miguel R, Hubbell D: Pain management and spirometry following thoracotomy: A prospective, randomized study of four techniques. J Cardiothorac Vasc Anesth 7: 529–534, 1993
96. Miguet D, Claris O, Lapillonne A, et al: Preoperative stabilization using high-fre-

quency oscillatory ventilation in the management of congenital diaphragmatic hernia. Crit Care Med 22:77–82, 1994
97. Miyabe M, Kakiuchi Y, Kihara S, et al: The plasma concentration of lidocaine's principle metabolite increases during continuous epidural anesthesia in infants and children. Anesth Analg 87:1056–1057, 1998
98. Moon RE, Clements FM: Accidental epidural overdose of hydromorphone. Anesthesiology 63:238–239, 1985
99. Moriarty A: Postoperative extradural infusions in children: Preliminary data from a comparison of bupivacaine/diamorphine with plain ropivacaine. Paediatr Anaesth 9: 423–427, 1999
100. Mouroux J, Clary-Meinesz C, Padovani B, et al: Efficacy and safety of videothoracoscopic lung biopsy in the diagnosis of interstitial lung disease. Eur J Cardiothorac Surg 11:22–26, 1997
101. Mychaliska GB, Bullard KM, Harrison MR: In utero management of congenital diaphragmatic hernia. Clin Perinatol 23:823–841, 1996
102. Parker RK, White PF: Epidural patient-controlled analgesia: An alternative to intravenous patient-controlled analgesia for pain relief after cesarian delivery. Anesth Analg 75:245–251, 1992
103. Piro AH, Weiss DR, Hellman S: Mediastinal Hodgkin's disease: A possible danger for intubation anesthesia. Int J Radiat Oncol Biol Phys 1:415–419, 1976
104. Raynor AC, Capp MP, Sealy WC: Lobar emphysema of infancy: Diagnosis, treatment, and etiologic aspects. Ann Thorac Surg 4:374–385, 1967
105. Remolina C, Khan AU, Santiago TV, et al: Positional hypoxemia in unilateral lung disease. N Engl J Med 304:523–525, 1981
106. Richardson J, Sabanathan S, Mearns AJ, et al: Efficacy of preemptive analgesia continuous extra-pleural intercostal nerve block on post-operative pain and pulmonary mechanics. J Cardiovasc Surg 35:219–228, 1994
107. Roberts JD, Polaner DM, Lang P, et al: Inhaled nitric oxide in persistent pulmonary hypertension of the newborn. Lancet 340:818–819, 1992
108. Rosenberg PH, Scheinin M, Lepantalo M, et al: Continuous infusion of intrapleural of bupivacaine for analgesia after thoracotomy. Anesthesiology 67:811–813, 1987
109. Rowe R, Andropoulos D, Heard M, et al: Anesthestic management of pediatric patients undergoing thoracoscopy. J Cardiothorac Vasc Anesth 8:563, 1994
110. Roy SD, Flynn GL: Solubility and related physicochemical properties of narcotic analgesics. Pharm Res 5:580–586, 1988
111. Ryckman FC, Rosenkrantz JG: Thoracic surgical problems in infancy and childhood. Surg Clin North Am 65:1423–1454, 1985
112. Satoyoshi M, Kaniyama Y: Caudal anaesthesia for upper abdominal surgery in infants and children: A simple calculation of the volume of local anaesthesia. Acta Anaesthesiol Scand 28:57–60, 1984
113. Schulte-Steinberg O, Rahlfs VW: Spread of extradural analgesia following caudal injection in children. Br J Anaesth 49:1027–1034, 1982
114. Schwartz MZ, Ramachandran P: Congenital malformations of the lung and mediastinum—a quarter century of experience from a single institution. J Pediatr Surg 32:44–47, 1997
115. Schwartz N, Eisencraft JB: Positioning of the endotracheal tube in an infant with tracheoesophageal fistula. Anesthesiology 69:289–290, 1988
116. Scneider RF, Villamena PC, Harvery J, et al: Lack of efficacy of intrapleural bupivacaine for postoperative analgesia following thoracotomy. Chest 103:414–416, 1993
117. Scott DA, Beilby DS, McClymont C: Postoperative analgesia using epidural infusions of fentanyl with bupivacaine. A prospective analysis of 1,014 patients. Anesthesiology 83:727–737, 1995
118. Semple D, Findlow D, Aldridge LM, et al: The optimal dose of ketamine for caudal epidural blockade in children. Anaesthesia 51:1170–1172, 1996
119. Shayevitz JR, Merkel S, O'Kelly SW: Lumbar epidural morphine infusions for children undergoing cardiac surgery. J Cardiothorac Vasc Anesth 10:217–224, 1996
120. Slinger PD: Fiberoptic bronchoscopic positioning of double-lumen tubes. J Cardiothorac Vasc Anesth 3:486–496, 1989

121. Slinger PD, Lesiuk L: Flow resistances of disposable double-lumen, single-lumen, and Univent tubes. J Cardiothorac Vasc Anesth 12:142–144, 1998
122. Sumner E, Frank JD: Tolazoline in the treatment of congenital diaphragmatic hernias. Arch Dis Child 56:350–353, 1981
123. Takahashi M, Horinouchi T, Kato M, et al: Double-access-port endotracheal tube for selective lung ventilation in pediatric patients. Anesthesiology 93:308–309, 2000
124. Tobias JD, Lowe S, O'Dell N, et al: Thoracic epidural anaesthesia in infants and children. Can J Anaesth 40:879–882, 1993
125. Tobias JD, Rasmussen GE, Holcomb GW, et al: Continuous caudal anaesthesia with chloroprocaine as an adjunct to general anaesthesia in neonates. Can J Anaesth 43: 69–72, 1996
126. Truog RD, Schena JA, Hershenson MB, et al: Repair of congenital diaphragmatic hernia during extracorporeal membrane oxygenation. Anesthesiology 72:750–753, 1990
127. Turner MWH, Buchanon CCR, Brown SW: Paediatric one lung ventilation in the prone position. Paediatr Anaesth 7:427–429, 1997
128. Vegunta RK, Teich S: Preoperative diagnosis of extralobar pulmonary sequestration with unusual vasculature: A case report. J Pediatr Surg 34:1307–1308, 1999
129. Vinograd I, Klim B, Efrati Y: Airway obstruction in neonates and children: Surgical treatment. J Cardiovasc Surg 35:7–12, 1994
130. Watson CB, Bowe EA, Burk W: One-lung anesthesia for pediatric thoracic surgery: A new use for the fiberoptic bronchoscope. Anesthesiology 56:314–315, 1982
131. Weatherford DA, Stephenson JE, Taylor SM, et al: Thoracoscopy versus thoracotomy: Indications and advantages. Ann Surg 61:83–86, 1995
132. White MJ, Berghaus EJ, Dumont SW, et al: Side effects during continuous infusion of morphine and fentanyl. Can J Anaesth 39:576–582, 1992
133. Yaster M: Nonsteroidal anti-inflammatory drugs. *In*: Yaster M, Krane EJ, Kaplan RF, et al (eds): Pediatric Pain Management and Sedation Handbook. St. Louis, Mosby, 1997, pp 19–28
134. Yaster M, Andresini J, Krane EJ: Epidural analgesia. *In*: Yaster M, Krane EJ, Kaplan RF, et al (eds): Pediatric Pain Management and Sedation Handbook. St. Louis, Mosby, 1997, pp 113–147
135. Yaster M, Billett C, Monitto C: Intravenous patient controlled analgesia. *In*: Yaster M, Krane EJ, Kaplan RF, et al (eds): Pediatric Pain Management and Sedation Handbook. St. Louis, Mosby, 1997, pp 89–111
136. Yeh TF, Pildes RS, Salem MR: Treatment of persistent tension pneumothorax in a neonate by selective bronchial intubation. Anesthesiology 49:37–38, 1978

Address reprint requests to

Gregory B. Hammer, MD
Department of Anesthesia
Room H3580
Stanford University Medical Center
300 Pasteur Drive
Stanford, CA 94305–5640