AU1
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32

Anesthesia for Thoracic Surgery

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OUTLINE

s0025 ## INTRODUCTION

p0470 Thoracic surgery in children is performed for a wide variety of congenital, neoplastic, infectious, and traumatic lesions (Box 32.1). The patient may be a few hours old with a congenital cystic adenomatoid malformation (CCAM) and life-threatening respiratory distress, or an adolescent with an asymptomatic mediastinal tumor. Regardless of age or disease, four principles are common to all patients undergoing general anesthesia for thoracic surgery, as follows:

u0310 • Preoperative evaluation and preparation can minimize intraoperative problems and improve the safety of the anesthetic.

u0315 • The anesthesiologist must be aware of potential intraoperative problems.

u0320 • Modern monitoring techniques have increased safety with regard to anesthetic management.

u0325 • Surgical approaches and techniques are constantly changing as surgeons make efforts to use minimally invasive procedures.

p0495 A thorough preoperative evaluation is essential in caring for the pediatric patient scheduled for thoracic surgery. Appropriate imaging and laboratory studies should be performed preoperatively according to the lesion involved. Guidelines for fasting, choice of premedication, and preparation of the operating room are used as for other infants and children scheduled for major surgery. After induction of anesthesia, placement of an IV catheter, and tracheal intubation, arterial catheterization should be performed for most patients undergoing thoracotomy and for those with severe lung disease having thoracoscopic surgery. This facilitates monitoring of arterial blood pressure during manipulation of the lungs and mediastinum, as well as monitoring of arterial blood gas tensions during single-lung ventilation (SLV). For thoracoscopic procedures of relatively short duration in patients without severe lung disease, the insertion of an arterial catheter is not required (Rao et al. 1981). Placement of a central venous catheter is generally not indicated if peripheral IV access is adequate for projected fluid and blood administration.

p0500 Intravenous anesthetic agents have little effect on hypoxic pulmonary vasoconstriction (HPV), but HPV is attenuated by inhaled anesthetic agents (Lumb and Slinger 2015). Inhaled anesthetic agents are commonly administered in 100% O_2 during maintenance of anesthesia. Isoflurane may be preferred because there is less attenuation of HPV than with other inhaled agents, although this has not been studied in children (Benumof et al. 1987). Nitrous oxide is avoided. Use of IV opioids may facilitate a decrease in the concentration of inhaled anesthetics used and thereby limit impairment of hypoxic pulmonary vasoconstriction. Alternatively, total IV 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 it may also be beneficial for thoracoscopic procedures, especially when thoracostomy tube drainage, a source of significant postoperative pain, is used after 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 (see Chapter 24: AU2 Regional Anesthesia).

p0505 In awake patients, except for young infants, ventilation is normally distributed preferentially to dependent regions of the lung, so that there is a gradient of increasing ventilation from the most nondependent to the most dependent lung segments. Of note, in awake infants (until 18 months of age), ventilation is usually distributed preferentially to the nondependent regions (see Chapter 3: Respiratory Physiology AU3). Because of gravitational effects, perfusion normally follows a similar distribution, with increased blood flow to dependent lung segments; therefore ventilation and perfusion are normally well matched.

b0010

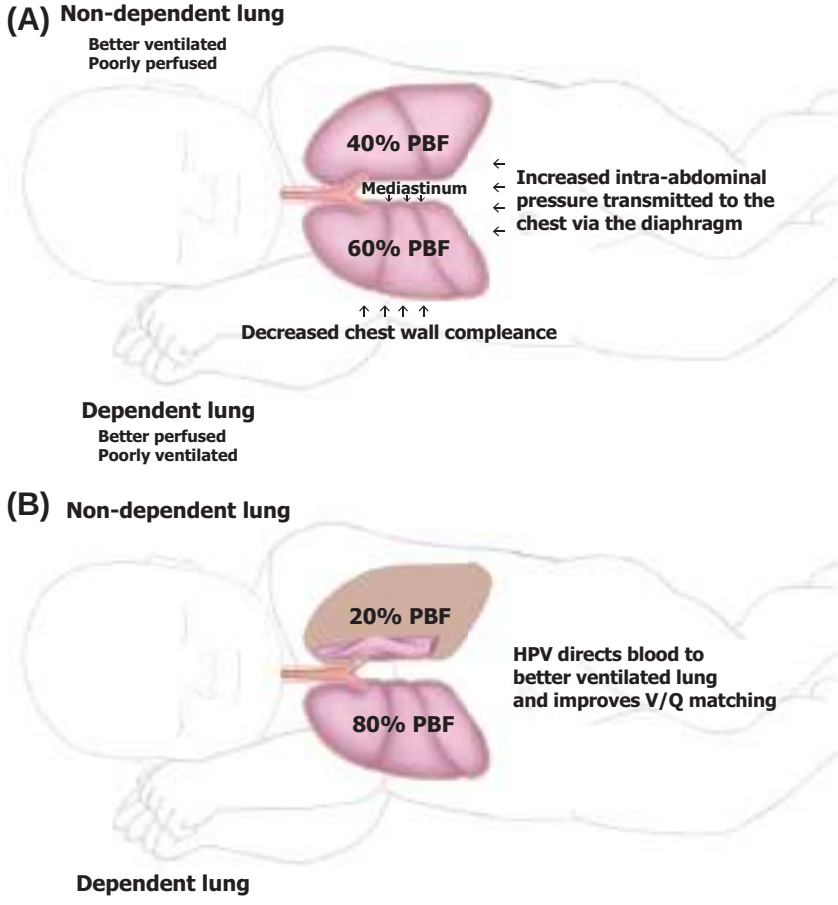
BOX 32.1 Childhood Lesions Requiring Thoracic Surgery

u0010 Empyema
u0015 Chest wall deformities
u0020 Chest wall masses
u0025 Lung abscess
u0030 Bronchiectasis
u0035 Lobar emphysema
u0040 Tumor (primary or metastatic)
u0045 Pulmonary sequestration
u0050 Congenital adenomatoid malformation
u0055 Congenital cysts of the lung
u0060 Bronchogenic cysts
u0065 Esophageal lesions
u0070 Mediastinal masses
u0075 Scoliosis

However, controlled ventilation under general anesthesia with decreased functional residual capacity (FRC) and absent diaphragmatic contractions results in a reverse distribution of ventilation (see Chapter 3, Respiratory Physiology). During thoracic surgery, these and other factors act to increase ventilation/perfusion (V/Q) mismatch. Compression of the dependent lung in the lateral decubitus position may cause atelectasis. Surgical retraction, SLV, or both result in collapse of the operative lung. Hypoxic pulmonary vasoconstriction, which acts to divert blood flow away from underventilated lung regions, thereby minimizing V/Q mismatch, may be diminished by the use of inhaled anesthetic agents and other vasodilating drugs. These factors apply similarly to infants, children, and adults. The overall effect of the lateral decubitus position on V/Q mismatch, however, differs in infants compared with older children and adults (see Fig. 32.1).

AU4 AU5

p0510 In adults with unilateral lung disease, oxygenation is optimal when the patient is placed in the lateral decubitus position with the healthy lung dependent (down) and the diseased lung nondependent (up) (Bachland et al. 1975; Remolina et al. 1981). Presumably, this is related



f0010 **Fig. 32.1 Effects of Lateral Positioning on the Redistribution of Pulmonary Blood Flow and V/Q Mismatch in an Anesthetized Patient.** In the lateral position **(A),** there is a decrease in compliance and functional residual capacity in the dependent lung from external compression by the mediastinum, an increase in intraabdominal pressure transmitted to the chest via the diaphragm, and a decrease in chest wall compliance. Lateral positioning also leads to an increase in perfusion to the dependent lung, which receives 60% of the pulmonary blood flow, and the nondependent lung received 40% of the pulmonary blood flow. With SLV **(B),** collapse and atelectasis in the nondependent lung activate hypoxic pulmonary vasoconstriction, directing blood toward the better-ventilated lung, thereby improving V/Q matching. *HPV*, Hypoxic pulmonary vasoconstriction; *SLV*, single-lung ventilation; *PBF*, pulmonary blood flow; *V/Q*, ventilation/perfusion. (From Templeton, T. W., Piccioni, F., & Chatterjee, D. 2021. An update on one-lung ventilation in children. *Anesthesia and Analgesia, 132*(5), 1389–1399.)

AU29 AU30

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

p0515 In infants with unilateral lung disease, however, oxygenation is better with the healthy lung up (Heaf et al. 1983). 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, especially in the lower lung, is closer to or at residual volume, making airway closure likely to occur in the dependent lung even during tidal breathing (Mansell et al. 1972) (see AU6 Chapter 3: Respiratory Physiology).

p0520 Finally, the infant's increased oxygen requirement, coupled with a small functional residual capacity, predisposes the patient to hypoxemia. Infants normally consume 6 to 8 mL of O_2/kg per minute, compared with a normal O_2 consumption in adults of 2 to 3 mL/kg per minute (Dawes 1973). For these reasons, infants are at increased risk for significant oxygen desaturation during surgery in the lateral decubitus position.

p0525 Perioperative ventilation strategies for lung protection during single lung ventilation are inconclusive. Although Lee and colleagues (2019) have shown lung protection ventilation decreased postoperative pulmonary complications compared with conventional ventilation in AU7 children, the lack of positive end-expiratory pressure (PEEP) in the control group may have influenced their findings.

s0030 THORACOSCOPY

p0530 During the past decade, the use of video-assisted thoracoscopic surgery has dramatically increased in both adults and children (see Videos 32.1 through 32.9). As with laparoscopy, reported advantages of thoracoscopy include smaller chest incisions, reduced postoperative pain, more rapid postoperative recovery, fewer musculoskeletal sequelae, and better cosmetic outcome (Weatherford et al. 1995; Angelillo Mackinlay et al. 1996; Mouroux et al. 1997).

p0535 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 abscess, bullous disease, sequestrations, lobar emphysema, CCAM, and neoplasms. Thoracoscopic procedures used in infants and children are listed in Box 32.2.

p0540 Thoracoscopy can be performed while both lungs are being ventilated using CO_2 insufflation and a retractor to displace lung tissue in the operative field. However, SLV is extremely desirable during thoracoscopy, because lung deflation improves visualization of thoracic contents and may reduce lung injury caused by the retractors (Benumof 1995).

s0035 SURGERY FOR CHEST WALL DEFORMITIES

p0545 Pectus excavatum (funnel chest) (Fig. 32.2) and the less common pectus carinatum (pigeon breast) deformities are congenital abnormalities of the sternum, ribs, and costal cartilages. These deformities are usually minimal at birth but progress with age. A higher incidence of both deformities occurs in children with Marfan syndrome or congenital heart disease, and in families in which other children have the defect (Shamberger and Welch 1987; Robicsek and Lobato 2000). These children often appear asymptomatic but occasionally have cardiac or pulmonary abnormalities related to the deformity (Malek et al. 2003). Patients with pectus excavatum generally present with normal or modestly reduced forced vital capacity and total lung capacity and, in severe cases, V/Q mismatch. The heart is displaced to the left and compressed, lending to arrhythmias, right-axis deviation on electrocardiogram, a functional murmur, and reduced stroke volume—most noticeable in the standing position and during exercise, explaining the mild exercise intolerance experienced by some patients. The cardiac and pulmonary abnormalities are in most instances benign and may worsen as the child ages but may be improved by surgical repair. There also is an increased incidence of mitral valve prolapse in patients with pectus deformities (Shamberger et al. 1987).

p0550 Preoperative assessment focuses on exercise tolerance and other signs of cardiopulmonary compromise, such as lung infections. Laboratory evaluation includes a chest radiograph; pulmonary function tests, arterial blood gases, and electrocardiogram are added only if there is clinical evidence of significant underlying disease. Echocardiography is now commonly performed to detect the presence of mitral valve prolapse. Patients are often emotionally distressed by the appearance of a chest deformity and may benefit from preoperative counseling and, if needed, premedication. A Haller index is calculated from preoperative CT scans and measures the ratio of the horizontal

BOX 32.2 Thoracoscopic Procedures in Infants and Children b0020

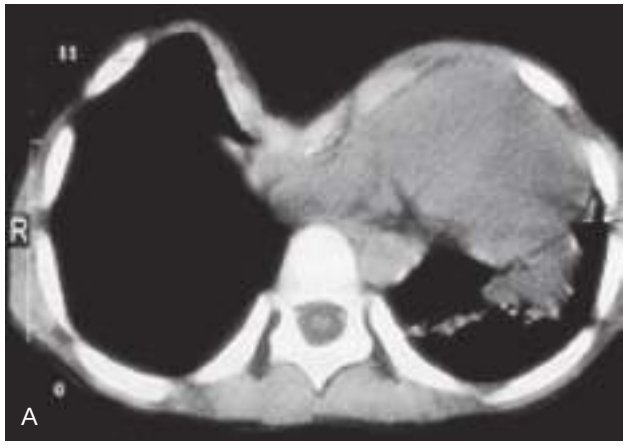
Anterior spinal fusion	u0080
Aortopexy	u0085
Biopsy	u0090
• Abscess	u0095
• Interstitial lung disease	u0100
• Mass	u0105
Cyst excision	u0110
Decortication or debridement of empyema	u0115
Diaphragmatic plication	u0120
Diaphragmatic hernia repair	u0125
Drainage	u0130
• Abscess	u0135
• Cyst	u0140
Esophageal atresia repair	u0145
Exploration	u0150
• Infection	u0155
• Mass	u0160
• Trauma	u0165
Foregut duplication resection	u0170
Hiatal hernia repair	u0175
Lobectomy	u0180
Mediastinal mass excision	u0185
Patent ductus arteriosus ligation	u0190
Segmentectomy	u0195
Sequestration resection	u0200
Sympathectomy	u0205
Tracheoesophageal fistula ligation	u0210
Thymectomy	u0215
Thoracic duct ligation	u0220

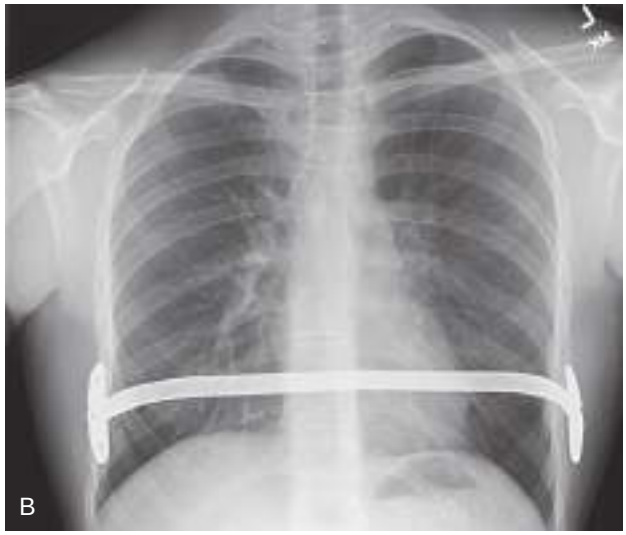
(Data from Abdullah, F., & Harris, J. 2016. Pectus excavatum: More than a matter of aesthetics. *Pediatric Annals, 45*(11), e403–e406; Erdos, G., & Tzanova, I. 2009. Perioperative anaesthetic management of mediastinal mass in adults. *European Journal of Anaesthesiology, 26*(8), 627–632; Guruswamy, V., Roberts, S., Arnold, P. & Potter, F. 2005. Anaesthetic management of a neonate with congenital cyst adenoid malformation. *British Journal of Anaesthesia, 95*(2), 240–242.)

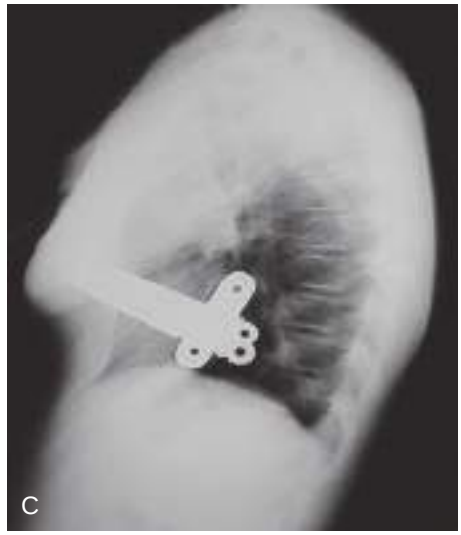
f0020 **Fig. 32.2 Pectus Excavatum Deformity Becomes Most Obvious When the Child is in the Sitting Position.** (From Davenport, K. P., & Kane, T. D. 2012. Surgery. In B. J. Zitelli, S. C. McIntire, & N. J. Nowalk (Eds.), *Zitelli and Davis' atlas of pediatric physical diagnosis* (6th ed.). Philadelphia: Saunders.)

diameter inside of the ribcage and the anteroposterior diameter between the vertebrae and sternum. A normal Haller index is approximately 2.5. Values greater than 3.2 are considered severe and may be considered for surgical repair (Abdullah and Harris 2016).

p0555 Classic operative repair involves extrapleural excision of the sternocostal cartilages and mobilization of the sternum and ribs (the Ravitch procedure). The Ravitch procedure is generally reserved for the more severe cases of pectus excavatum. For the majority of patients, a minimally invasive technique (i.e., the Nuss procedure) is used in which the costal cartilages are preserved and the sternum is elevated with a bar used to correct the deformity. Under direct vision and through a thorascope, a transmediastinal tunnel is created and a prebent bar is passed behind the sternum with the convex side down. The bar is then rotated 180 degrees to elevate the sternum (Fig. 32.3) (Nuss et al. 1998, 2002). Borowitz and colleagues showed that static pulmonary function and ventilatory response to exercise was normal both before and after surgery, thereby suggesting that placement of the bar does not result in an increased chest wall restriction (Borowitz et al. 2003). In addition, Lawson and colleagues noted that the surgical repair of the pectus excavatum after the Nuss procedure had a positive impact on the patient's physical and emotional well-being (Lawson et al. 2003). Complications of this minimally invasive approach include atelectasis, subcutaneous emphysema, pericardial and pleural effusions, myocardial perforation, diaphragmatic perforation, and dislocation of the stabilizing bar (Willekes et al. 1999; Hebra et al. 2000;







f0030 **Fig. 32.3** CT scan of a patient undergoing the Nuss procedure (**A**). Anterior-posterior (**B**) and lateral (**C**) radiographs of a patient with a Nuss bar in place.

Molik et al. 2001; Moss et al. 2001; Hosie et al. 2002; Uemura et al. AU8 2003; Notrica 2019). Postoperative pain after the Nuss procedure is significant.

p0560 The most common complications of operative repair are pneumothorax, flail chest, and postoperative atelectasis; blood loss is usually minimal to moderate. Intraoperative monitoring includes temperature, blood pressure, pulse, heart and breath sounds, airway pressure, and oxygen saturation or tension. Capnography is also useful, but arterial catheterization is needed only if there is a specific indication. General anesthesia with controlled ventilation is the method of choice, with no agents specifically indicated or contraindicated because of the operation itself. Oxygen by face mask is administered in the recovery room, but it is usually not needed after the patient fully awakens.

p0565 Postoperative pain management is a challenge in these patients. Though the procedure is "minimally invasive," the postoperative pain is intense and generally lasts days to weeks. Although patient-controlled analgesia is commonly used for postoperative analgesia, intercostal nerve blocks, paravertebral blocks, and thoracic epidural analgesia have become increasingly popular for children undergoing pectus repair (Robicsek 2000; Muhly et al. 2014; Loftus et al. 2016; AU9 AU10 Bryskin et al. 2017; Harbaugh et al. 2018; Pilkington et al. 2018; Singhal AU11 and Lerman 2019). A thoracic epidural catheter provides more reliable analgesia to the operative area than a lumbar epidural that has been threaded a great distance. However, thoracic epidural catheters are not as easy to insert as lumbar catheters, and many clinicians are not comfortable with their routine use. Although a technique using electrocardiographic guidance and insertion from the caudal space has been described, it is not widely used (Tsui et al. 2002). An additional issue with thoracic catheters is the safety of their insertion under general anesthesia (Horlocker et al. 2003; Walker et al. 2018). Although some children allow insertion before induction (McBride et al. 1996), many younger children are not likely to remain cooperative for the procedure, mandating insertion after induction (Hammer 2002; Birmingham et al. 2003). Moreover, several centers have actively and successfully used thoracic epidural techniques in anesthetized children for thoracic and cardiac procedures without complications related to insertion after induction (Cassady et al. 2000; Birmingham et al. 2003). Solutions of local anesthetic alone, local anesthetic with fentanyl, and fentanyl alone have been used successfully, including in the patient-controlled mode for appropriately mature children (Caudle et al. 1993; AU12 Birmingham et al. 2003) (see Chapter 24: Regional Anesthesia). Thoracic epidural analgesia for 2 to 3 days, followed by oral opioid and nonsteroidal antiinflammatory drug therapy, is a frequently used technique as reported in a web-based survey sent to representatives from pediatric hospitals in the United States, Europe, Asia, and Australia. Thoracic epidurals were used for analgesic management in 91% of the institutions (Muhly et al. 2014). Though used less frequently in patients undergoing the Nuss procedure, Hall-Burton and Boretsky (2014) reported on the equal analgesic efficiency of paravertebral catheters to epidural catheters.

s0040 THORACOTOMY, LOBECTOMY, AND PNEUMONECTOMY

p0570 Thoracotomy in the infant or child may be indicated for congenital abnormalities (cysts), tumors (mediastinal teratomas), trauma (gunshot wounds), or infective lesions (bronchiectasis). Subsegmental resection is used for biopsy and removal of metastatic tumors, whereas lobectomy is most commonly used for removal of congenital anomalies and extensive tumor metastasis. Pneumonectomy in children is done for various tumors, congenital abnormalities, and inflammatory lesions such as bronchiectasis. Lung resection may be performed via thoracoscopy in selected centers, though open resection remains the standard. Perioperative management differs dramatically depending on both the indication for surgery and the surgical approach.

Surgical Lesion

s0045

p0575 If a space-occupying lesion is present, the patient is examined for signs of decreased cardiac output, diminished lung volume and reserve, and airway compression (Keon 1981). History focuses not only on general exercise tolerance but also on signs of intermittent airway obstruction (stridor, cyanosis, or wheezing). Physical examination includes checking for a shift in the trachea, asymmetric chest movement, wheezing, and any signs of respiratory distress. Laboratory assessment should include a chest radiograph, but additional studies such as tomography, angiography, or computed tomography often provide more exact data about vascular or airway compression and compromise. It is crucial to determine the extent of airway compression and physiologic compromise, because impairment may worsen with induction of anesthesia as sympathetic and muscular tones are reduced.

p0580 If the intrathoracic lesion is a primary or metastatic tumor, the history should focus on previous treatment (Baldeyrou et al. 1984), especially chemotherapy and radiation. Special attention is given to anthracycline (cardiac toxicity), bleomycin (pulmonary toxicity), and steroid (adrenal suppression) therapy. If there is any question about functional disability caused by this treatment, consultation with the child's oncologist is useful. Anemia, thrombocytopenia, and malnutrition are common in these patients and should be evaluated before surgery (Beattie 1984). A special consideration is the immunocompromised patient with an unknown pulmonary infiltrate. This is usually assumed to be an opportunistic infection, but because it may represent metastasis, a biopsy is occasionally requested. These patients may be in poor general condition and may require postoperative ventilatory support, especially if they had only marginal compensation before surgery (Imoke et al. 1983; Prober et al. 1984).

Assessment

s0050

p0585 General assessment of the child starts with vital signs and overall appearance. Because children tolerate the loss of large amounts of usable lung tissue without obvious distress, the appearance of dyspnea or diminished exercise tolerance is an ominous sign. The history in older children focuses on complaints of dyspnea, cyanosis, wheezing, coughing, and weight loss. Infants often show less specific signs, such as poor feeding, irritability, choking, or change in sleep habits. If the child has had previous surgery, the perioperative course should be examined. The chest is inspected for asymmetric expansion and use of accessory muscles and then is auscultated for wheezes, rales, rhonchi, and absent breath sounds in both the supine and sitting positions. Physical assessment of the cardiovascular system concentrates on the presence of a gallop, murmurs, arrhythmias, and adequate peripheral pulses.

Preparation

s0055

p0590 Preparation for surgery starts with a discussion of the proposed anesthetic with the parents and, if appropriate, with the child. The anesthetic plan is discussed, including monitoring, possible complications, and potential for postoperative ventilation. It is best to delay surgery until any infection or bronchospasm has been brought under optimal medical control with antibiotics, chest physiotherapy, and bronchodilators, as needed. It may be difficult or impossible to eradicate infections or bronchospasm completely in destructive lesions such as bronchiectasis. If this is the case, it is acceptable to proceed after reasonable medical therapy has optimized the patient's status so that no further improvement is anticipated.

s0060
Monitoring

p0595 At a minimum, thoracotomy requires monitoring of inspired oxygen, blood pressure, heart and breath sounds, airway pressure, and temperature, as well as an electrocardiogram. Oxygen saturation by pulse oximeter or, less commonly, by transcutaneous oxygen tension (Po_2) monitor is vital for detection of sudden changes in oxygenation from lung compression or kinking of the airway. Capnography is particularly useful for detecting sudden changes in effective ventilation. Arterial cannulation for pressure and arterial blood samples is useful and is needed if extensive blood loss or resection of lung tissue is expected or if the child is already critically ill with abnormal oxygenation and ventilation requirements. Percutaneous arterial cannulas (24 gauge for neonates and infants, 22 gauge for children up to 8 to 10 years of age, and 20 gauge for preadolescents and older) can be inserted in children and should be used whenever indicated. Central venous monitoring is used less commonly but can be helpful for guiding extensive volume replacement. Urinary drainage is a consideration for particularly long procedures.

s0065
Positioning

p0600 Positioning of the patient has often been used to minimize spillage of lung contents because double-lumen tubes (DLTs) are impractical in smaller patients (Conlan et al. 1986). Suction through the endotracheal tube (ETT) may not be adequate to control the large quantities AU13 of pus freed during surgical manipulation. The prone and lateral positions are the most commonly used. Positioning can cause significant ventilatory changes in children. FRC decreases during general anesthesia (Motoyama et al. 1982), and it decreases dramatically once the pleura is opened (Larsson et al. 1987). The practical problems of dislodgment of the ETT with movement and adequate padding in these positions are especially important in children. Open-celled foam with adhesive backing (Reston; 3M, St. Paul, MN) can be applied to the thorax, pelvic rim, and other pressure points to minimize the effects of positioning. Also, the tube position must be rechecked each time the patient is moved.

s0070
Anesthesia

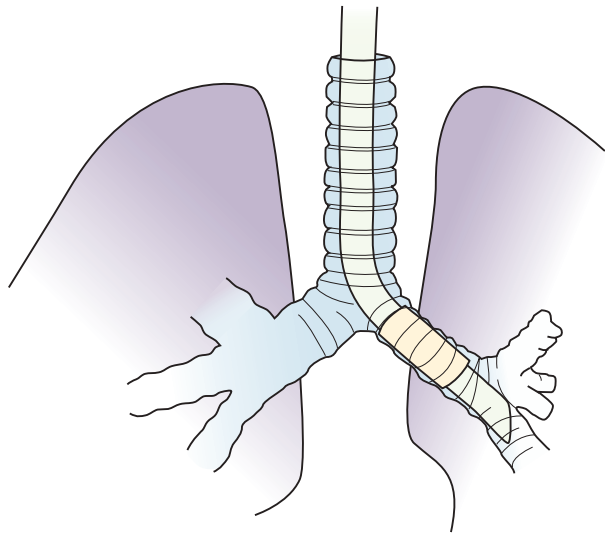
p0605 General endotracheal anesthesia presents various challenges to the anesthesiologist. A quiet, smooth inhalation induction is often used in infants and smaller children, whereas an IV induction is used in the older child. If there is concern about spillage of lung contents, rapid securing of the airway with IV induction is preferred to minimize coughing. The choice of appropriate anesthetic agents depends on both the patient's status and the surgical lesion. Nitrous oxide can accumulate in cysts with air-fluid levels and should be avoided in these patients or in patients requiring a high fraction of inspired oxygen (Fio_2). Volatile agents are especially useful in patients with bronchospastic disorders. The rate of rise of inhalational anesthetics may be slowed in the presence of intrapulmonary shunting. Precipitous hypotension is another potential problem with volatile agents in patients with low cardiac reserve. Muscle relaxants are routinely used along with controlled ventilation employing humidified gases. Although mechanical ventilators are usually acceptable, manual ventilation may provide useful information to the anesthesiologist about changes in compliance or airway resistance, especially in infants or in procedures in which there is recurrent obstruction of the airway.

s0075
SINGLE-LUNG VENTILATION TECHNIQUES

p0610 Single-lung ventilation (SLV) during thoracic surgery in infants and children is performed in order to (1) provide optimal surgical exposure by causing collapse of the operative lung and (2) minimize the risk for contamination of the nonoperative lung with blood and infected material from the surgical site. Although a publication by Dingemann and colleagues (2013) did not show improved outcomes with SLV compared with double-lung ventilation during thoracoscopic surgery in children, SLV is routinely used in many pediatric centers in the United States and around the world. Techniques and equipment for single lung ventilation have been reviewed by Templeton and colleagues (2020) and by Letal and Theam (2017).

s0080
Single-Lumen Endotracheal Tube

p0615 The simplest means of providing SLV is to intentionally intubate the desired main stem bronchus with a conventional single-lumen ETT (Baraka 1987; Kubota et al. 1987; Rowe et al. 1994) (Video 32.1). There are some anatomic implications for performing single lung ventilation: (1) the left lung mainstem bronchus is smaller than the right mainstem; (2) the left upper lobe take-off is further from the carina AU14 than the right upper lobe take-off; (3) the right upper lobe take-off in patients less than 8 years of age is generally within 1 cm of the carina; and (4) the cricoid and left mainstem bronchus diameters increase with age, height, and weight, but the ratio of cricoid to the left mainstem bronchus remains constant (Wani et al. 2016, 2018; Szelloe et al. 2017; Kuo et al. 2018; Templeton et al. 2020). When the left bronchus is to be intubated, the bevel of the ETT is rotated 180 degrees after passing the vocal cords and the patient's head is turned to the right (Bloch 1986; Kubota et al. 1987). The ETT is advanced into the bronchus until breath sounds on the operative side disappear. A fiberoptic bronchoscope (FOB) may be passed through or alongside the ETT to confirm or guide placement (Watson et al. 1982). Intubating the right bronchus is less challenging because the natural angle of the right bronchus facilitates right main stem intubation. Fiberoptic guidance can facilitate positioning of the ETT so that the take-off of the right upper lobe is not occluded. If the ETT is passed beyond the right upper lobe take-off, the ETT can be rotated to place the Murphy eye (if present) over the right upper lobe take-off to allow ventilation. 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 that the ETT does not occlude the upper lobe bronchus (Lammers et al. 1997) (Fig. 32.4). This technique is simple and requires no special equipment other than an FOB. This may be the preferred technique of SLV in emergency situations such as airway hemorrhage or contralateral



f0040 **Fig. 32.4** Obstruction of the Left Upper Lobe Bronchus With a Cuffed Endotracheal Tube Used for Left-Sided, Single-Lung Ventilation.

tension pneumothorax. Placement of a single-lumen ETT can also be done using fluoroscopic guidance.

p0620 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 it may fail to protect the healthy ventilated lung from contamination by purulent material from the contralateral lung. The operative lung cannot be suctioned using this technique. Hypoxemia may occur because of obstruction of the upper lobe bronchus, especially when the short right main stem bronchus is intubated.

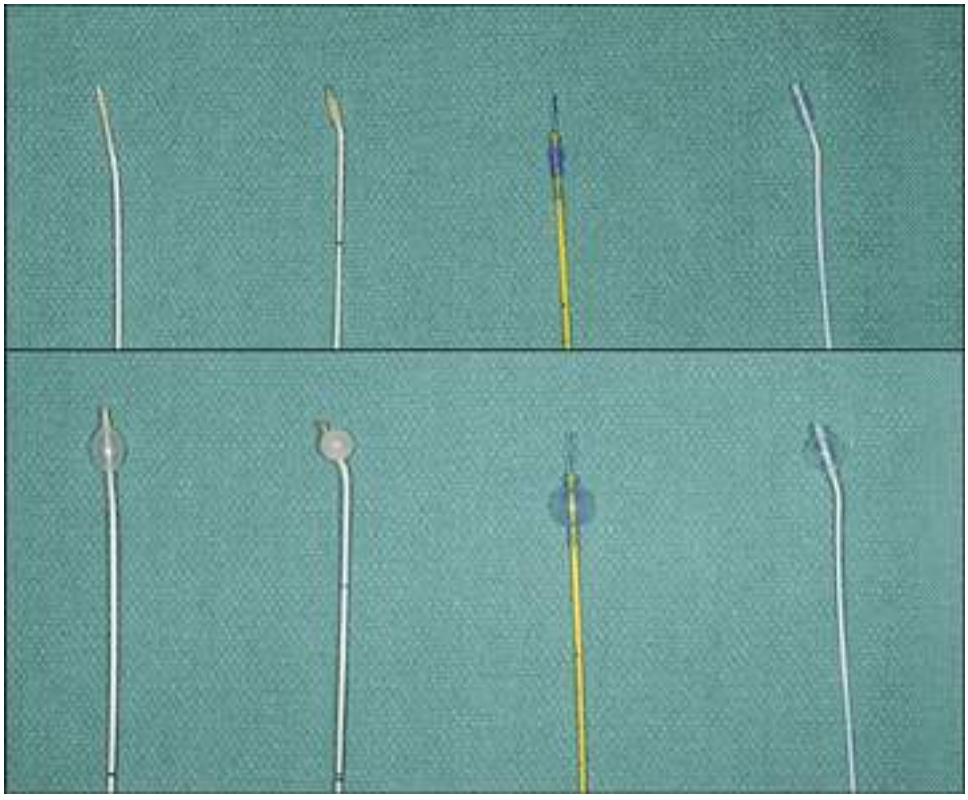
s0085 Balloon-Tipped Bronchial Blocker

p0625 A Fogarty embolectomy catheter or an end-hole, balloon-wedge catheter (Videos 32.2 and 32.3) may be used for bronchial blockade to provide SLV (Fig. 32.5) (Ginsberg 1981; Lin and Hackel 1994; Hammer et al. 1996; Turner et al. 1997). Placement of a Fogarty catheter is facilitated by bending the tip of its stylet toward the bronchus on the operative side. An FOB is 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 alongside the blocker catheter. The catheter balloon is positioned in the proximal main stem bronchus under fiberoptic visual guidance. With an inflated blocker balloon, the airway is completely sealed, providing a more predictable lung collapse and better operating conditions than with an ETT in the contralateral bronchus. A variety of other techniques have been described for catheter placement outside of the ETT (Peeters et al. 2014; Templeton et al. 2016, 2018a, 2018b, 2020; Guo et al. 2018).

p0630 The use of bronchial blockers has been associated with a high rate of success of thoracoscopic surgery in children (Seong et al. 2013). However, a potential problem with this technique is dislodgment of the blocker balloon into the trachea. The inflated balloon then blocks ventilation to both lungs or prevents collapse of the operated lung, or both. The balloons of most catheters currently used for bronchial blockade have low-volume, high-pressure properties, and overdistention can damage or even rupture the airway (Borchardt et al. 1998). One study, however, reported that bronchial blocker cuffs produced lower cuff-to-tracheal pressures than DLTs (Guyton et al. 1997). When closed-tip bronchial blockers are used, the operative lung cannot be suctioned, and continuous positive airway pressure (CPAP) cannot be provided to the operative lung if needed.

p0635 When a bronchial blocker is placed outside the ETT, care must be taken to avoid injury caused by compression and resultant ischemia of the tracheal mucosa. The sum of the catheter diameter and the outer diameter of the ETT should not exceed the tracheal diameter. Diameters for pediatric ETTs are shown in Table 32.1.

p0640 Adapters have been used that facilitate ventilation during placement of a bronchial blocker through an indwelling ETT (Arndt et al. 1999; Takahashi et al. 2000). For use in children, a 5-F endobronchial blocker designed with a multiport adapter and FOB has been described (Cook Critical Care, Bloomington, IN) (Hammer 2001; Hammer et al. 2002). The balloon is elliptical, so it conforms to the bronchial lumen when inflated. The blocker catheter has a maximal outer diameter of 2.5 mm (including the deflated balloon), a central lumen with a diameter



f0050 **Fig. 32.5** Different Types of 5 Fr Bronchial Blockers Deflated (*top*) and Inflated (*bottom*) With 2 mL of Air-Balloon Inflation Pressures (cm H_2O). *From left to right:* Folgary embolectomy catheter (710), Miller atrial septostomy catheter (690), Arndt bronchial blocker (340), Fuji Uniblocker (330). (Letal, M., & Theam, M. 2017. Paediatric lung isolation. *BJA Education, 17*(2), 61.)

t0010

TABLE 32.1 Diameters of Pediatric Endotracheal Tubes

Inner Diameter (mm)	Outer Diameter* (mm)
3	4.3
3.5	4.9
4	5.5
4.5	6.2
5	6.8
5.5	7.5
6	8.2
6.5	8.9
7	9.6

From Sheridan Tracheal Tubes, Kendall Healthcare, Mansfield, MA.
*Cuffed tubes add approximately 0.5 mm to the outer diameter.

of 0.7 mm, and a distal balloon with a capacity of 3 mL. The balloon has a length of 1.0 cm, corresponding to the length of the right main stem bronchus in children approximately 2 years of age (Scammon 1923). The blocker is placed coaxially through a dedicated port in the adapter, which also has a port for passage of an FOB and ports for connection to the anesthesia breathing circuit and ETT (Fig. 32.6). The FOB port has a plastic sealing cap, whereas the blocker port has a Tuohy-Borst connector, which locks the catheter in place and maintains an airtight seal. Because oxygen can be administered during passage of the blocker and FOB, the risk for hypoxemia during blocker placement is diminished, and repositioning of the blocker may be performed with fiberoptic guidance during surgery (Bird et al. 2007).

p0645 When placement of a bronchial blocker inside the ETT is guided by an FOB, both the blocker catheter and the FOB must pass through the indwelling ETT. The inner diameter of the ETT through which the catheter and FOB are to be placed must be larger than the sum of the outer diameters of the catheter and the FOB. The 5-F blocker catheter and an FOB with a 2.2-mm diameter, for example, may be inserted through an ETT as small as 5.0 mm in inner diameter. For children with an indwelling ETT smaller than 5.0 mm in inner diameter, a blocker catheter can be positioned under fluoroscopy (Fig. 32.7). Another device for bronchial blockers involves the EZ-blocker (Teleflex Inc., Wayne, PA). The device is a 7-foot shaft with two separate occlusive balloons coming off the shaft to form a Y configuration. Extraluminal placement of this device has been described by Piccioni and colleagues (2015) (See Figure Templeton 2018 Pediatric Anesthesia 2018b;28:347 (Fig. 32.8). AU15

Univent Tube

s0090

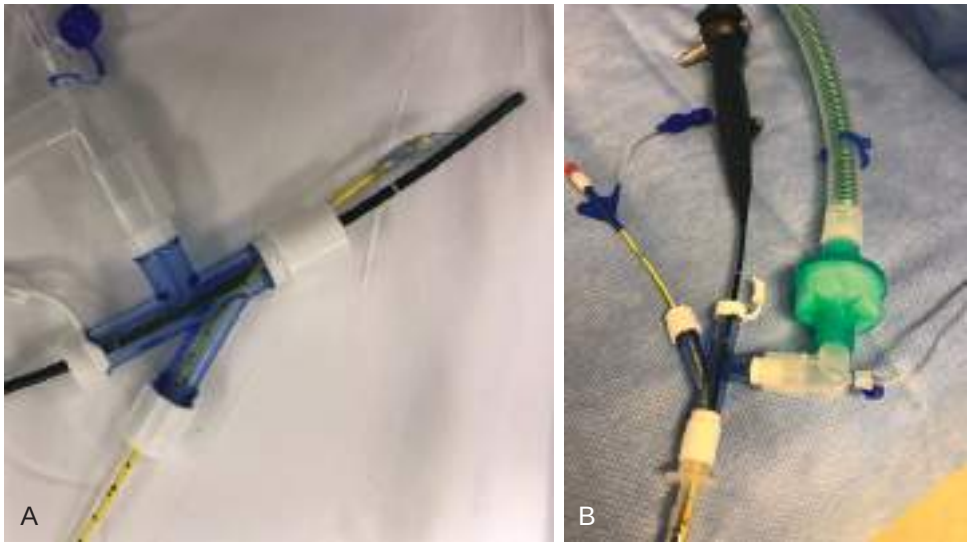
p0650 The Univent tube (Fuji Systems Corp., Tokyo, Japan) is a single-lumen ETT with a second lumen containing a small blocker catheter that can be advanced into a bronchus (Fig. 32.9) (Kamaya and Krishna 1985; Karwande 1987; Gayes 1993). A balloon located at the distal end of this small tube serves as a blocker. Univent tubes require an FOB for successful placement. Univent tubes are now available in sizes as small as 3.5- and 4.5-mm inner diameter for use in children older than 6 years of age (Tables 32.2 and 32.3) (Hammer et al. 1998). 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 of the 4.5-mm Univent tube has a small lumen, which allows egress of gas and can be used to insufflate oxygen or to suction the operated lung.

p0655 A disadvantage of the Univent tube is the large amount of cross-sectional area occupied by the blocker channel, especially in the smaller-sized tubes. Smaller Univent tubes have a disproportionately high resistance to gas flow (Slinger and Lesiuk 1998). The Univent tube's blocker balloon has low-volume, high-pressure characteristics, so mucosal injury can occur during normal inflation (Benumof et al. 1992; Kelley et al. 1992).

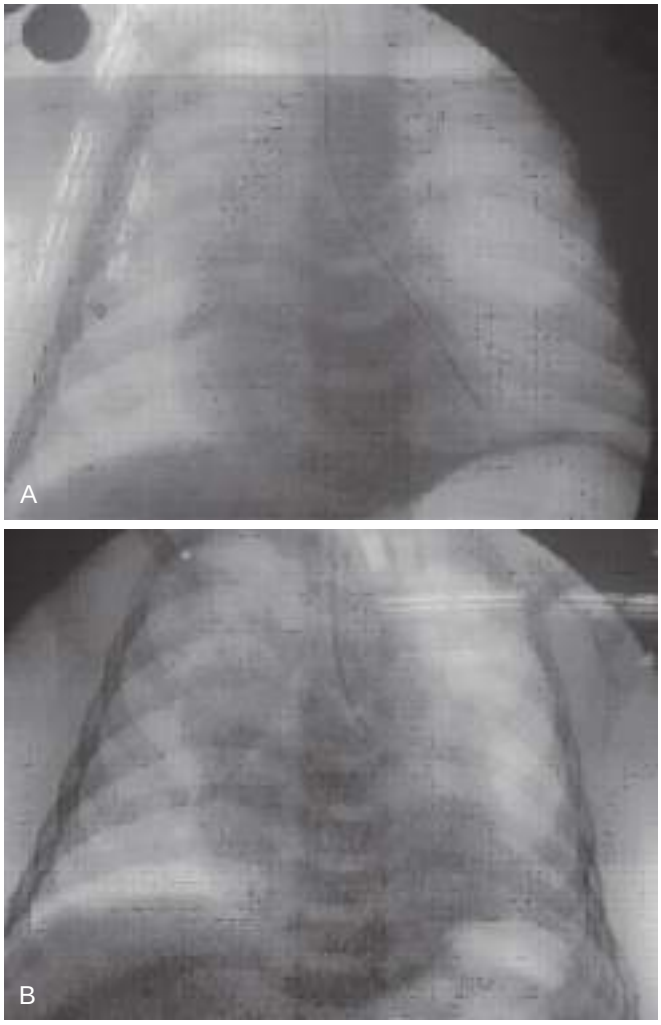
Double-Lumen Tube

s0095

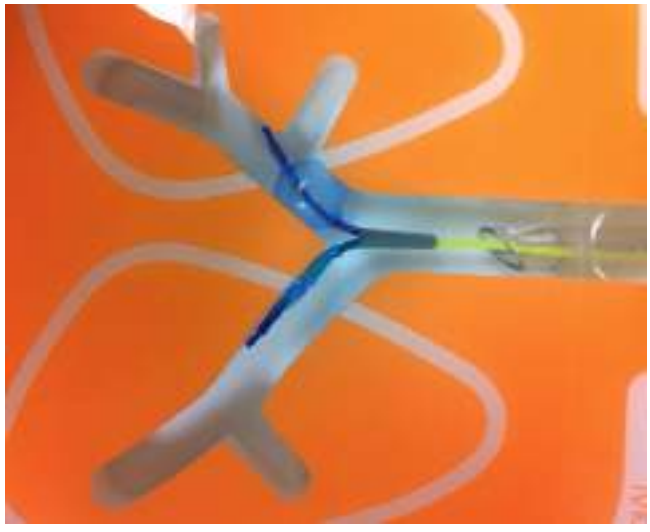
p0660 All DLTs are essentially two tracheal tubes of unequal length molded longitudinally together. The shorter tube ends in the trachea, and the longer tube ends in the bronchus. Marraro described a bilumen tube for infants (Marraro 1994; Pawar and Marraro 2005). DLTs for older children and adults have cuffs located on the tracheal and bronchial lumens. The tracheal cuff, when inflated, allows positive pressure



f0060 **Fig. 32.6 A,** Arndt endobronchial blocker. The wire loop is coupled to the fiberoptic bronchoscope prior to inserting the device into the endotracheal tube. **B,** The different ports on the multiport airway adapter include: blocker port, fiberoptic port, and ventilator port. (Cook Medical.)



f0070 **Fig. 32.7 Positioning a Bronchial Blocker Under Fluoroscopy. A,** The catheter has been advanced into a segmental bronchus on the *left.* **B,** The catheter has been pulled back so that the balloon is in the left main stem bronchus.



f0080 **Fig. 32.8 EZ Blocker (Rusch, Teleflex) Has Two Distal Limbs Each With a Blocker-Balloon That are Positioned in Each Mainstem Bronchus.** (From Slinger, P., & Campos, J. H. 2020. Anesthesia for thoracic surgery. In M. A. Gropper (Ed.), *Miller's anesthesia* (9th ed.). Philadelphia: Elsevier.)

f0090 **Fig. 32.9 The Univent Tube is a Single-Lumen Endotracheal Tube With a Second Lumen Containing a Small Blocker Catheter.** (From Fuji Systems, Tokyo, Japan.)

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.

p0665 Conventional plastic DLTs, once available only in adult sizes (35-F, 37-F, 39-F, and 41-F), are now available in smaller sizes (Tables 32.2 and 32.4). The smallest cuffed DLT is 26-F (Rusch, Duluth, GA) and may be used in children as young as 8 years of age. DLTs are also available in sizes 28-F and 32-F (Mallinckrodt Medical, St. Louis, MO), which are suitable for children 10 years of age and older.

p0670 DLTs are inserted in children using the same technique used in adults (Brodsky and Mark 1983). The tip of the tube is inserted just past the vocal cords, and the stylet is withdrawn. The DLT is rotated 90 degrees 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 (Brodsky et al. 1996). No equivalent measurements are yet available in children. If fiberoptic bronchoscopy is to be used to confirm tube placement, an FOB with a small diameter and sufficient length must be available (Slinger 1989).

p0675 A DLT offers the advantage of ease of insertion and 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 (Benumof et al. 1987). Right DLTs are more difficult to accurately position because of the greater risk for right upper lobe obstruction. DLTs 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 Tables 32.2 and 32.4. There is significant variability in overall size and airway dimensions among children, particularly among teenagers, and these recommendations are based on average values for airway dimensions. Larger DLTs may be safely used in adult-sized teenagers. The smallest double lumen tube is a 26F with an AU16 external diameter between 8.7 and 9.3 mm, which corresponds to a 6.5 ETT. In adolescents, the DLT size depends on sex and height. Females shorter than 160 cm will require a 35F DLT, whereas females taller than 160 cm will need a 37F. For males less than 170 cm, a 39 DLT can be used, whereas males taller than 170 cm will require a 41F (Seefelder et al. 2014; Slinger and Con 2014). AU17

0020

AU32
AU33

TABLE 32.2 Age and Device Selection for Single-Lung Ventilation in Infants and Young Children

Age	Mainstem Bronchus Diameter (mm)*		Standard UC ETT Size for Endobronchial Intubation (OD mm)†		Standard C ETT Size for Endobronchial Intubation (OD mm)†		5F Arndt BB	7F Arndt BB	9F Arndt BB	3F Fogarty	4F Fogarty	5F Fuji	9F Fuji	EZ-Blocker	3.5 Univent	4.5 Univent	26F DLT
	R	L	R	L	R	L											
0–3 mo	4.4*	3.6*	3.0 (4.2)	2.5 (3.6)	3.0 (4.3)	–	E	–	–	E	E	E	–	–	–	–	–
3–6 mo	4.7*	3.9*	3.0 (4.2)	2.5 (3.6)	3.0 (4.3)	–	E	–	–	E	E	E	–	–	–	–	–
6–12 mo	5.4*	4.2*	3.5 (4.9)	3.0 (4.2)	3.5 (4.9)	3.0 (4.3)	E	–	–	E	E	E	–	–	–	–	-
1–2 y	5.4‡	5.6‡	4.0 (5.5)	3.5 (4.9)	4.0 (5.6)	3.5 (4.9)	E	–	–	E	E	E	–	–	–	–	–
2–4 y	7.4‡	6.6‡	4.5 (6.2)	3.5 (4.9)	4.5 (6.2)	3.5 (4.9)	E/I	E	–	E/I	E/I	E/I	–	–	–	–	–
4–6 y	8.3‡	7.3‡	4.5 (6.2)	4.0 (5.5)	4.5 (6.2)	4.0 (5.6)	E/I	E	–	E/I	E/I	E/I	–	–	–	–	
6–8 y	8.9‡	7.8‡	5.5 (7.5)	5.0 (6.9)	5.5 (7.5)	5.0 (6.9)	E/I	E/I	–	–	–	E/I	–	E	+	–	–
8–10 y	9.9‡	8.8‡	–		6.0 (8.2)	5.0 (6.9)	–	E/I	E/I	–	–	–	E/I	E/I	+	+	+

Summary of bronchial diameters and recommended lung isolation device or ETT size for lung isolation. ETT outer diameters can vary significantly by manufacturer, so care must be taken to evaluate the outer diameter of a given ETT when planning to use it for endobronchial intubation and OLV.

BB, bronchial blocker; *C,* cuffed; *CT,* computed tomography; *DLT,* double-lumen tube; *E,* extraluminal; *ETT,* endotracheal tube; Fuji Uniblocker; *I,* intraluminal; *L,* left; *OD,* outer diameter; *R,* right; *UC,* uncuffed.

*Median bronchial diameter measured by high resolution CT (Downard, M. G., Johnson, A. L., Heald, C. J., Anthony, E. Y., Singh, J., & Templeton, T. W., unpublished data, April 2019).

†Measurement of outer diameter is for Shiley endotracheal tubes.

AU34 ‡Median bronchial diameter measured by high resolution CT.[3,2]

t0030

TABLE 32.3 Univent Tube Diameters

Inner Diameter (mm)	Outer Diameter* (mm)
3.5	7.5/8.0
4.5	8.5/9.0
6	10.0/11.0
6.5	10.5/11.5
7	11.0/12.0
7.5	11.5/12.5
8	12.0/13.0
8.5	12.5/13.5
9	13.0/14.0

*Sagittal/transverse.

t0040

TABLE 32.4 Tube Selection for Single-Lung Ventilation in Children

Age of Child (Yr)	ETT (mm, Inner Diameter*)	BB (F)	Univent‡	DLT (F)
0.5–1	3.5–4.0	2†	—	—
1–2	4.0–4.5	3†	—	—
2–4	4.5–5.0	5§	—	—
4–6	5.0–5.5	5§	—	—
6–8	5.5–6	5§	3.5	—
8–10	6.0 cuffed	5§	3.5	—
10–12	6.5 cuffed	5§	4.5	26‖ to 28¶
12–14	6.5–7.0 cuffed	5§	4.5	32¶
14–16	7.0 cuffed	5§	6	35¶
16–18	7.0–8.0 cuffed	9§	7	35¶

BB, Bronchial blocker; *DLT,* double-lumen tube; *ETT,* endotracheal tube; *F,* French; *Yr,* year.
*Sheridan Tracheal Tubes, Kendall Healthcare, Mansfield, MA.
†Edwards Lifesciences LLC, Irvine, CA.
‡Fuji Systems Corporation, Tokyo, Japan.
§Cook Critical Care, Inc., Bloomington, IN.
‖Rusch, Duluth, GA.
¶Mallinckrodt Medical, Inc., St Louis, MO.

s0100

Minimizing Injury

p0680

Collapse and subsequent reexpansion of lung tissue during SLV has been associated with an increase in proinflammatory markers and alveolar damage (Yin et al. 2007; Kozian et al. 2008). In a study of 28 children undergoing SLV for thoracic surgery, a preoperative dose of methylprednisolone 2 mg/kg IV resulted in a decrease in IL-6 levels and respiratory resistance and an increase in concentrations of tryptase and the antiinflammatory cytokine, IL-10. Three of 15 children in the placebo group and none of the 13 children in the treatment group experienced clinically significant intraoperative and postoperative respiratory complications (Theroux et al. 2015). Another potentially therapeutic intervention to mitigate lung injury associated with SLV is the administration of surfactant. Surfactant instilled into the subsequently deflated lung reduced the concentration of inflammatory cytokines in a piglet model of SLV (Bhatie et al. 2011). A more clinically practical method of reducing lung injury during SLV is to minimize the Fio_2 and utilize a lung-protective strategy during the procedure. The use of 50% O_2 compared with 100% O_2 was shown to cause less lung injury in animals subjected to SLV for 3 hours (Fisher et al. 2012). Piglets mechanically ventilated with a lung-protective strategy using a tidal volume 5 mL/kg and PEEP 5 cm H_2O demonstrated less lung injury than those ventilated with a tidal volume of 10 mL/kg and no PEEP (Theroux et al. 2010). Anesthesiologists should consider the use of the lowest Fio_2 needed to produce an acceptable oxygen saturation as well as low tidal volumes and adequate levels of PEEP in the ventilated lung during SLV in order to minimize lung injury. Preoperative administration of corticosteroids should also be considered.

POSTOPERATIVE CARE

s0105

p0685

Tracheal extubation at the completion of surgery is often possible after simple subsegmental resection or lobectomy. However, the patient's underlying cardiopulmonary reserve, the course of the surgery, and the expected postoperative course may preclude extubation. Although postoperative pain can cause significant splinting, intercostal, epidural, or paravertebral blocks coupled with judicious parenteral opioids can minimize the discomfort (see Chapter 23: Acute Pain Management; Chapter 24: Regional Anesthesia). Whether in the operating room or in the intensive care area, before extubation, the patient must be awake, breathing well, able to cough and maintain an airway, and able to maintain acceptable oxygenation with no more than 40% inspired oxygen. A chest radiograph should be obtained as soon as possible after surgery to detect any significant pneumothorax or atelectasis. Atelectasis is common and usually responds to humidity, encouragement to cough, CPAP, and, if necessary, endotracheal suction. AU18

p0690

The expected postoperative course depends on both the surgical procedure and the underlying disease. After simple lobectomy, most children develop normally and have normal exercise tolerance (McBride et al. 1980). Children who have undergone pneumonectomy may have more problems (Buhain and Brody 1973). With time, overinflation of the remaining lung occurs, with a demonstrable decrease in forced vital capacity. These children may have significant exercise intolerance for a prolonged period after surgery.

THORACIC SURGICAL LESIONS

s0110

Congenital Lobar Emphysema

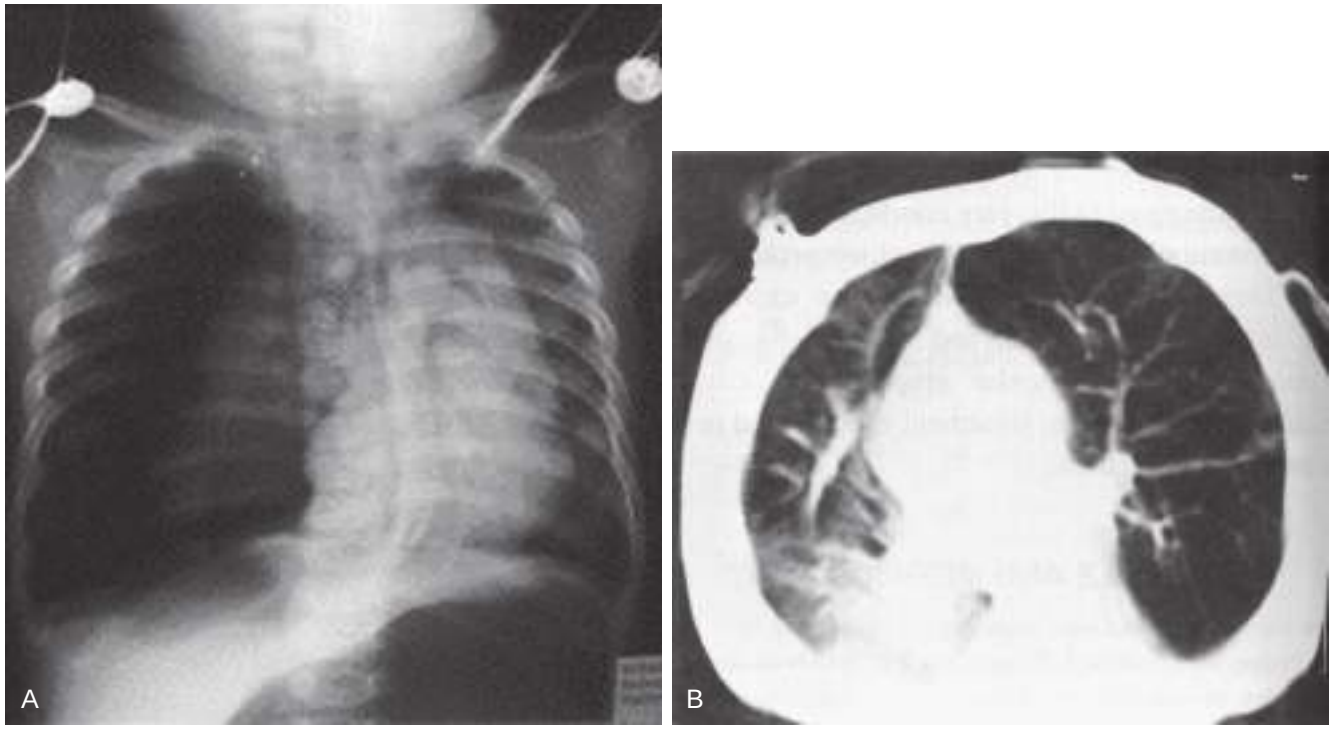
s0115

p0695

Congenital lobar emphysema is a rare cause of sudden respiratory distress in infants (Leape and Longino 1964; Raynor et al. 1967; Demir et al. 2019; Kunisaki et al. 2019). Hyperinflation and progressive air trapping cause expansion of the affected lobe, along with compression of other lung tissue, mediastinal shifting, and impaired venous return. The most commonly affected is the left upper lobe, followed by the right middle and upper lobes. Occasionally, more than one lobe is affected. The cause of the obstruction is unknown in most cases, although many show evidence of deficient and disordered bronchial cartilage. In some cases, there are identifiable causes of bronchial compression, such as aberrant blood vessels, bronchial cysts, and bronchial stenosis. Finally, some patients have widespread lung disease with poor elastic recoil throughout (Ryckman and Rosenkrantz 1985) (Video 32.4). AU19

p0700

Congenital lobar emphysema usually appears clinically between the newborn period and the first 6 months of life (Murray 1967) with tachycardia and retractions. The child may have rapid, progressive accumulation of gas in the affected lobe. Physical examination reveals asymmetric expansion of the thorax, wheezing, displacement of the cardiac impulse, hyperresonance to percussion, and diminished breath and heart sounds. Chest radiographs (Fig. 32.10) show overdistention of the affected lobe, mediastinal shift, and atelectasis in other lobes.



f0100 **Fig. 32.10** Right-Sided Congenital Lobar Emphysema. **A,** The right lung appears hyperinflated and lucent and may be mistaken for a pneumothorax. **B,** CT scan reveals a markedly hyperexpanded right lung, mediastinal shift to the left, and compression of the left lung.

The chest radiograph can help differentiate lobar emphysema from pneumothorax or congenital cysts by the presence of faint bronchovascular markings and herniation of the affected lobe across the midline.

p0705 Infants who show rapid deterioration constitute a surgical emergency to relieve the expanding lobe with its ventilatory and cardiac impairment. Many patients do not have a clear clinical picture, however, but rather have a vague history of intermittent cyanosis or respiratory distress, failure to thrive, or unusual respiratory distress with feeding or a cold. Lobar emphysema is also seen in preterm infants with respiratory distress who are undergoing mechanical ventilation, and it most frequently develops in the right upper lobe.

p0710 Preoperative evaluation depends on the degree of patient distress (Payne et al. 1984). If there is rapid deterioration, evaluation is limited. Chest tube placement, needle aspiration of the trapped air, and vigorous mechanical ventilation have been tried as palliative procedures but are associated with a much higher mortality than thoracotomy and lobectomy. If the patient is stable and there is any question about the diagnosis, procedures such as radioisotope perfusion scans, angiography, or CT imaging can be used before proceeding with definitive surgery. During preanesthesia evaluation, cardiopulmonary stability of the patient is the prime concern. The degree of distress, its progression, and the need for supplemental oxygen are key components of the examination. Cardiac evaluation is important because these patients have a higher incidence of congenital heart disease, especially ventricular septal defect. In addition to standard anesthetic monitors, invasive arterial pressure monitoring is indicated. Capnography wave forms are a useful diagnostic tool for detecting changes in airway compliance, resistance, and reactivity.

p0715 Induction of anesthesia in infants with congenital lobar emphysema is a critical phase in the management of anesthesia. The crying, struggling infant can increase the amount of trapped gas, whereas positive-pressure ventilation or positive airway pressure by the anesthesiologist can also increase the emphysema. A smooth inhalation induction with sevoflurane and oxygen is often used, with positive pressure ventilation minimized until the chest is open (Coté 1978). Controlled or assisted ventilation is added if unacceptable hypoventilation develops, whereas intubation is performed with or without muscle relaxants, depending on the patient's tolerance of positive pressure ventilation. High-frequency ventilation has been used successfully in infants with lobar emphysema (Goto et al. 1987) and should be considered if the practitioner is familiar with the technique. The low airway pressures are especially suitable for these patients. Nitrous oxide is avoided because it can expand the emphysematous areas (Payne et al. 1984). If the lobe expands suddenly, the surgeon should be ready to open the chest immediately and relieve the pressure. Raghavendran and colleagues described a technique involving a caudal epidural catheter threaded to the thoracic level in spontaneously breathing patients who were anesthetized with potent inhaled anesthetic agents (Raghavendran et al. 2001).

p0720 An alternative induction approach, especially for unstable infants, is sedation with IV ketamine (1 to 2 mg/kg) and local anesthetic infiltration of the incision site (Coté 1978). After the intrathoracic pressure has been relieved, general anesthesia can proceed with any technique appropriate to the patient's underlying status. Older children who are stable often undergo bronchoscopy before thoracotomy to rule out a foreign body or other correctable lesions. After induction with oxygen and a volatile agent, thorough topical anesthesia with 2% to 4% lidocaine (not more than 4 to 6 mg/kg) facilitates airway manipulation. As with the younger patient, rapid surgical decompression may be needed as the case proceeds.

p0725 In most patients, the trachea can be extubated at the end of the lobectomy. Humidity, coughing, and early increases in activity or ambulation minimize atelectasis in the immediate postoperative period.

These children do well clinically after surgery but have reduced forced vital capacity and delayed forced expiration, not only in the immediate postoperative period but throughout childhood (Eigen et al. 1976; McBride et al. 1980).

s0120 p0730

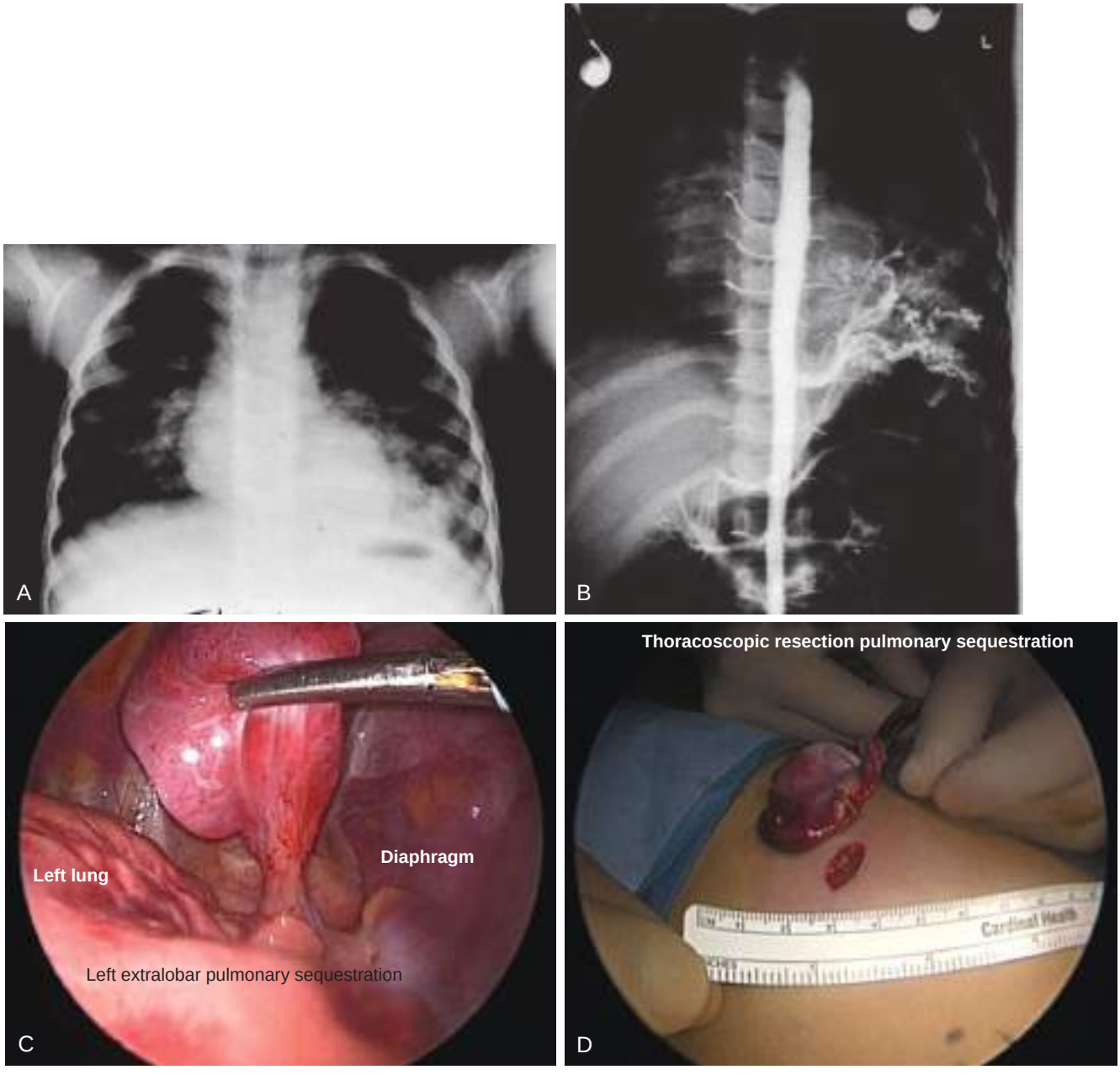
Pulmonary Sequestrations

Pulmonary sequestrations (Fig. 32.11) result from disordered embryogenesis producing a nonfunctional mass of lung tissue supplied by anomalous systemic arteries. Signs include cough, pneumonia, and failure to thrive, and they often appear during the neonatal period, usually before 2 years of age. Diagnostic studies include arteriography and CT scans of the chest and abdomen. Magnetic resonance imaging may provide high-resolution images, including definition of vascular supply. This may obviate the need for angiography. Surgical resection is performed after the 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.

s0125 p0735

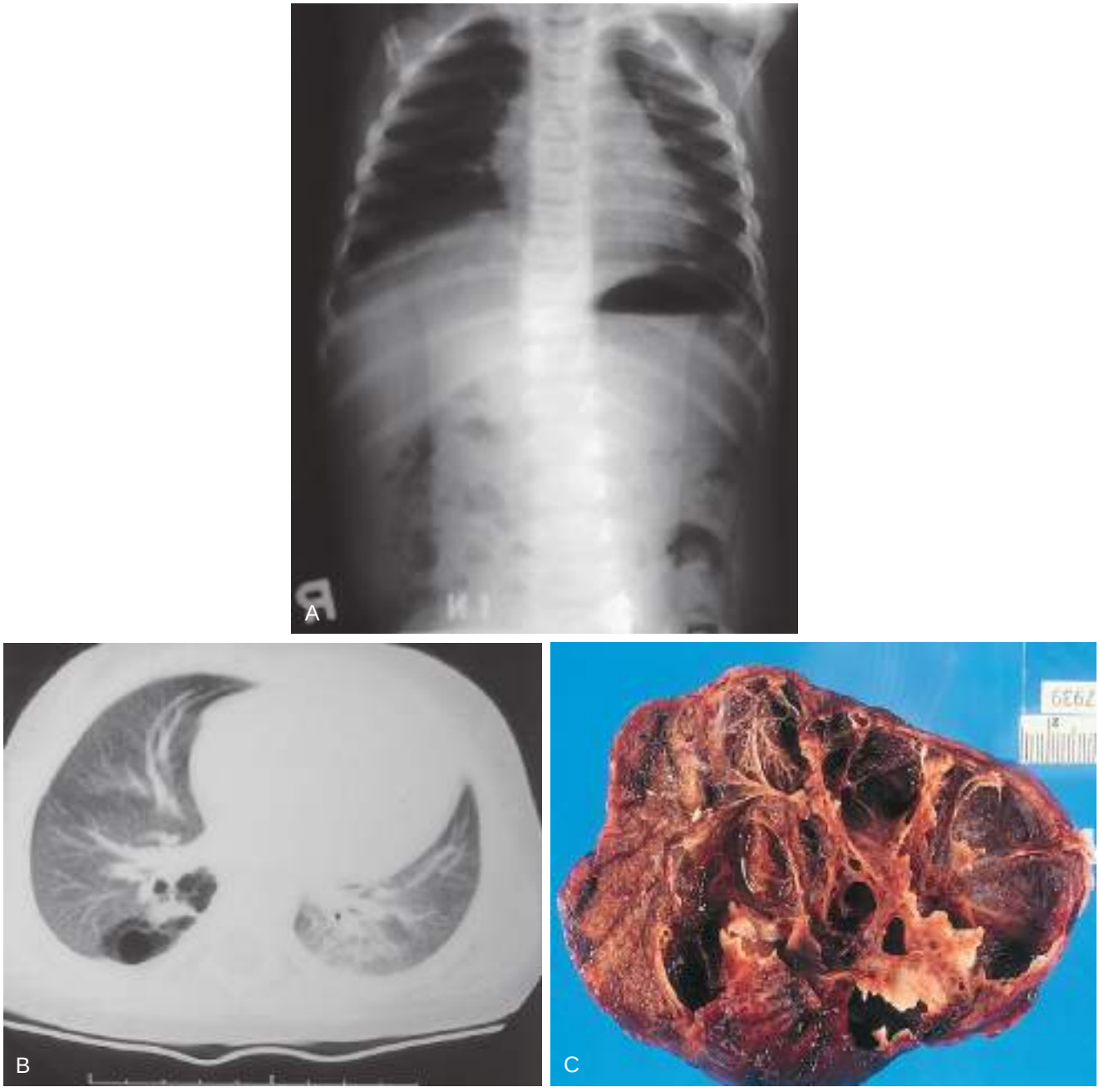
Congenital Cystic Lesions

Congenital cystic lesions in the thorax fall into three categories: bronchogenic, dermoid, and cystic adenomatoid malformations (Fig. 32.12) (Stocker et al. 1977; Nishibayashi et al. 1981; Kravitz 1994). Bronchogenic cysts result from abnormal budding or branching of the tracheobronchial tree. They may cause respiratory distress, recurrent pneumonia, or atelectasis due to lung compression.



f0110

Fig. 32.11 Extralobar Pulmonary Sequestration. **A,** Chest radiograph of pulmonary sequestration. **B,** Aortogram of pulmonary sequestration of arterial blood supply coming from aorta. **C,** Thoracoscopic resection of sequestration. **D,** Resected sequestration. (From Zitelli, B. J., & Davis, H. W. (Eds.). 2002. *Atlas of pediatric physical diagnosis* (4th ed., p. 539). St Louis: Mosby.)



f0120

Fig. 32.12 Microcystic adenomatoid malformation seen on plain radiograph (**A**), CT scan (**B**), and surgical specimen (**C**). (From Zitelli, B. J., & Davis, H. W. (Eds.). 2002. *Atlas of pediatric physical diagnosis* (4th ed., p. 565). St Louis: Mosby.)

Dermoid cysts are clinically similar to bronchogenic cysts but differ histologically, as they are lined with keratinized, squamous epithelium rather than respiratory (ciliated columnar) epithelium. They usually appear later in childhood or adulthood. CCAMs are structurally similar to bronchioles but lack associated alveoli, bronchial glands, and cartilage (Ryckman and Rosenkrantz 1985). Because these lesions communicate with the airways, they may become overdistended as a result of gas trapping, leading to respiratory distress in the first few days of life. When they are multiple and air-filled, CCAMs may resemble congenital diaphragmatic hernia radiographically. Fluid may drain from a CCAM during resection and lung isolation may be required to minimize expansion of the lesion and soiling of the contralateral lung (Guruswamy et al. 2005). Treatment is surgical resection of the affected lobe. Although thoracoscopic resection is performed in stable patients in selected centers, open resections are more common. As with the diaphragmatic hernia, prognosis depends on the amount of remaining lung tissue, which may be hypoplastic because of compression in utero (Adelman and Benson 1976; Schwartz and Ramachandran 1997).

SURGICAL DISEASES OF THE MEDIASTINUM

s0130

Surgical problems of the mediastinum fall into three major categories: masses, infections, and pneumomediastinum. The mediastinum is functionally divided into anterior, middle, and posterior segments (Fig. 32.14). This classification is useful diagnostically in evaluating

p0740

t0050

TABLE 32.5 Mediastinal Masses

Location	Masses
Anterior division	Lymphomas
	Lymphangiomas (cystic hygromas)
	Teratomas
	Thymomas and thymic cysts
Middle division	Bronchogenic cysts
	Granulomas
	Lymphomas
Posterior division	Enteric cysts, duplications
	Neuroblastomas
	Ganglioneuromas, neurofibromas
Superior division	Cystic hygromas
	Bronchogenic cysts
	Neurally based tumors
	Rare vascular lesions

defects, because of the propensity of lesions to develop primarily in only one of the divisions (Table 32.5).

p0745 Masses in the anterior portion of the mediastinum tend to be lymphomas, lymphangiomas (cystic hygromas), and teratomas (Videos 32.5 and 32.6). Thymomas and thymic cysts can appear here but are rare in childhood. Lymphomas are primarily of the Hodgkin type, and biopsies of them are done only for diagnostic purposes. The survival of the child with mediastinal lymphoma depends on the systemic spread of the tumor and not on the amount of lymphoma present in the mediastinum. Lymphangiomas are often extensions of cystic hygromas from the cervical region into the mediastinum. If all of the lymphangioma is not removed at the initial resection, further extension may occur. Anterior mediastinal masses can appear in various ways. Although they may be asymptomatic and detected incidentally on a chest radiograph, they may also present as compression of pulmonary or vascular structures. Superior vena cava syndrome, cardiac tamponade, and both tracheal and lung compression can be prominent characteristics (Levin et al. 1985; Northrip et al. 1986).

p0750 Bronchogenic cysts result from abnormal budding from the perimeter of the trachea after it has differentiated from the foregut. They are the most frequent cysts of the mediastinum, accounting for approximately 60% of these lesions. The cyst's inner lining is composed of ciliated pseudostratified respiratory epithelium interspersed with goblet cells. Bronchial communication is rare, and cysts are most commonly an incidental finding on chest radiography. Bronchogenic cysts usually appear as air filled, with or without an air-fluid level (Fig. 32.13). They may be asymptomatic or exhibit symptoms of airway obstruction or recurrent pulmonary infection. Bronchogenic cysts can produce sudden, life-threatening airway obstruction at any age. Lesser degrees of obstruction appear initially as wheezing, stridor, or unilateral obstructive emphysema (Azizkhan et al. 1985; Azarow et al. 1993; Birmingham et al. 1993; Landsman et al. 1994).

p0755 In the posterior division, enteric cysts and tumors of neurogenic origin (neuroblastoma, ganglioneuroma, neurofibroma) predominate (Videos 32.7, 32.8, and 32.9). Enteric cysts and duplications are lined with secretory epithelium and can enlarge rapidly and cause dysphagia, ulceration, or bleeding. In rare cases, they can ulcerate directly into the tracheobronchial tree. Neurogenic tumors are usually asymptomatic and detected on a routine chest radiograph, although they can be responsible for tracheobronchial compression, recurrent pneumonias, and, rarely, stigmata of pheochromocytoma.

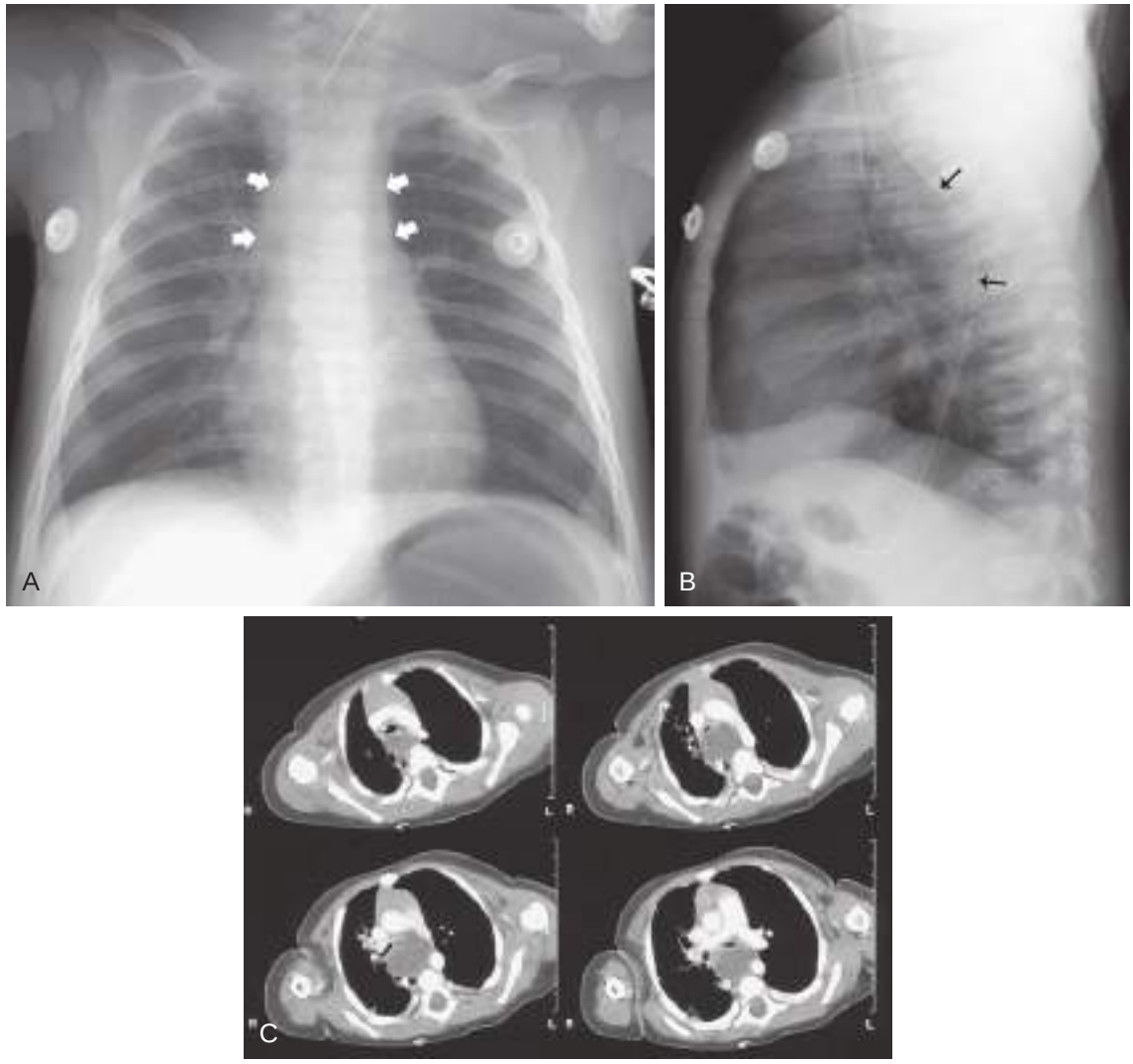
p0760 Mediastinal infections and inflammation are less common today than in the past (Campbell and Lilly 1983). Modern antibiotic therapy dramatically reduced the incidence of suppurative mediastinitis caused by *Staphylococcus* and other organisms, whereas the incidence of tuberculosis and other similar infections in the general population has diminished. Although mediastinitis can result from extension of cervical node infections or hematogenous spread, the more likely cause is perforation of the trachea or esophagus. Foreign bodies can be responsible for perforation of the larynx, trachea, or esophagus; instrumentation of the trachea (endotracheal intubation or suction) or esophagus (esophageal dilation) can also be responsible.

p0765 Pneumomediastinum is an accumulation of air, usually in the superior anterior division. This occurs in trauma patients and as a result of mechanical ventilation, especially in newborns who undergo long-term ventilation and children with severe asthma. Pneumomediastinum is usually asymptomatic, but it may be responsible for tamponade and hypotension. These patients need urgent decompression by thoracostomy. Pneumomediastinum can be accompanied by pneumopericardium, which may need to be drained urgently as well. The intrathoracic pressure generated by pneumomediastinum can impede venous drainage of the head and result in increased intracranial pressure.

p0770 Anesthetic management of children with mediastinal diseases demands careful preoperative evaluation (Mackie and Watson 1984). The location and nature of the disease are crucial to both preparation and management (Fig. 32.14). The airway is considered first (Todres et al. 1976; Keon 1981). If there is evidence of obstruction, the site and degree must be assessed. History and physical examination should focus not only on signs such as cyanosis and stridor but also on maneuvers or circumstances that change the signs. Orthopnea, coughing, or hoarseness are significant findings and may represent tracheal or vascular compression and risk of cardiovascular or airway complications on induction of anesthesia (Erdos and Tzanova 2009). The practitioner should determine whether sleep, excitement, position, movement of the head and neck, or coughing changes the degree of obstruction. Although chest radiographs and barium studies provide some information, CT scans are best at delineating the obstruction of vascular and airway structures (Anghelescu et al. 2007). These scans have the added advantage of demonstrating extension of infection or tumor into structures such as the pericardium.

p0775 Signs of lower airway disease can be caused by mediastinal tumors (Sibert et al. 1987). Compression of the lower airways and lung tissue can be responsible for wheezing, atelectasis, obstructive emphysema, and recurrent pneumonias (Fig. 32.15). This is important because wheezing caused by compression of lower airways and lung tissue usually does not respond to bronchodilators, nor will atelectasis caused by compression respond to chest physical therapy. Repeat chest radiographs or pulmonary function tests can help delineate the degree of functional impairment. In older, more cooperative children, maximal inspiratory and expiratory flow-volume loops obtained with the patient upright and supine can quantitate the functional degree of impairment and help distinguish fixed from variable obstructions (Fig. 32.16).

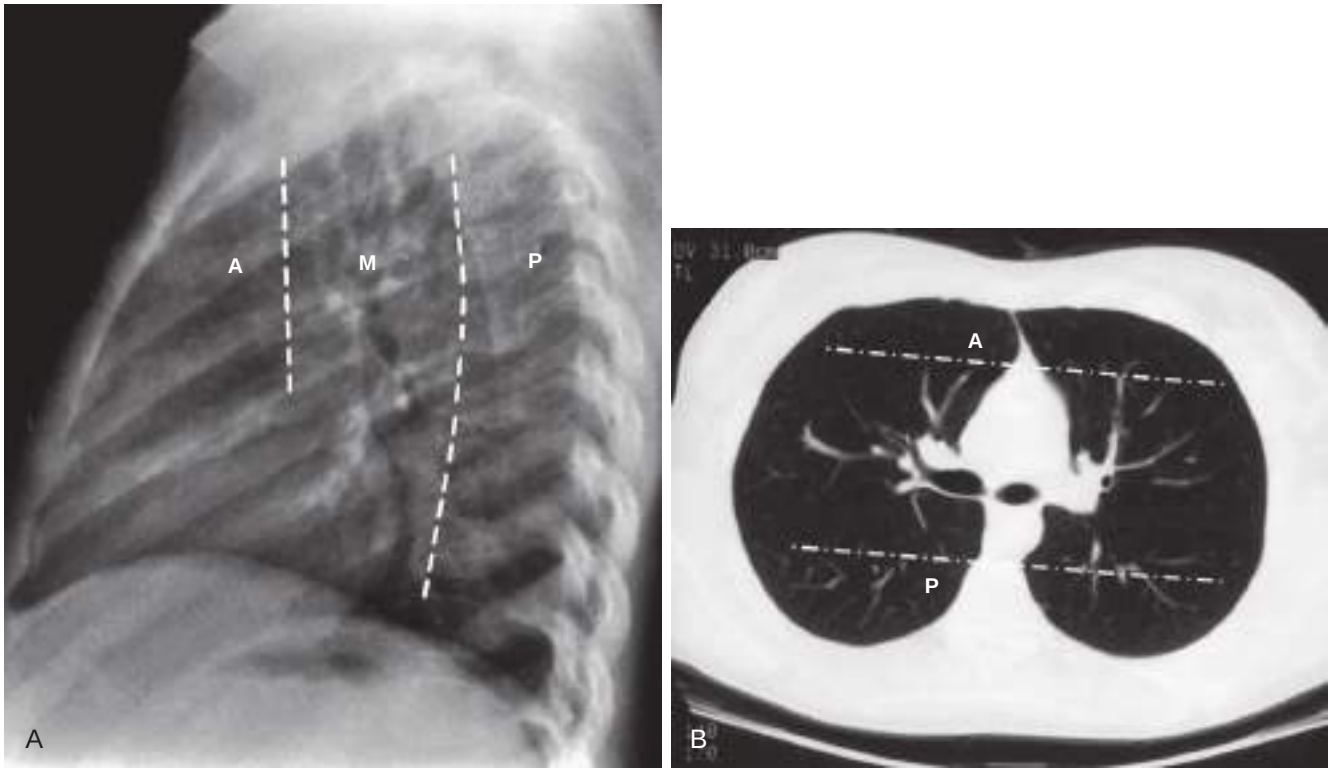
p0780 Cardiovascular involvement may be related to direct compression of the heart or of the great vessels. Echocardiography or CT scanning can delineate impingement. The important determination is assessment of functional impairment. If the child has arrhythmias, pulsus paradoxus, hypotension, or superior vena cava syndrome, the risk associated with general anesthesia increases. Life-threatening airway obstruction and cardiovascular collapse can occur with the administration of general anesthesia. During general anesthesia, lung volume



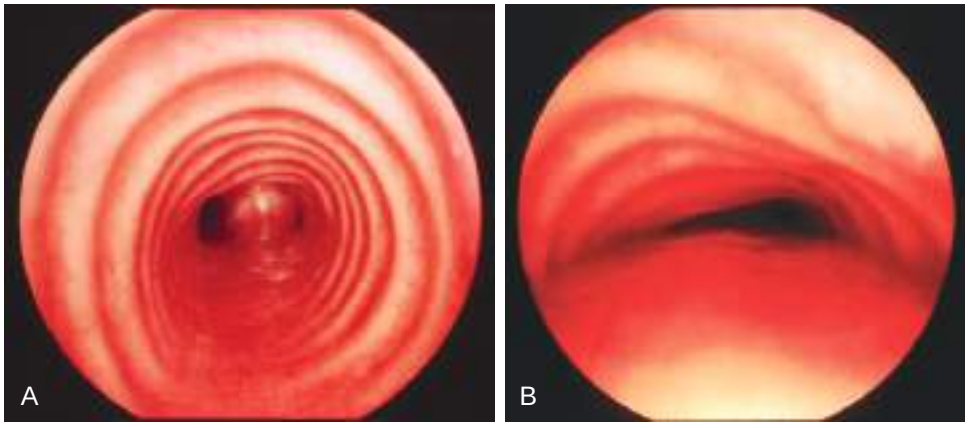
f0130 **Fig. 32.13 Bronchogenic Cyst in a 4-Month-Old Boy With Cough.** Anteroposterior (**A**) and lateral (**B**) chest radiographs show a central mediastinal mass *(white arrows)* displacing the esophagus (outlined by nasogastric tube, *black arrows*) posteriorly. **C,** Four contiguous axial computed tomography images of the chest show a retrotracheal and subcarinal mass with low density. (Courtesy Simon C. Kao, MD, Iowa City, IA.)

is reduced from loss of inspiratory muscle tone and from loss of the tethering effect of the expanded lung on the airway. The normal transpleural pressure gradient that distends the airway during inspiration is diminished, which further compromises the airway caliber. During spontaneous ventilation, the diaphragm moves caudad; however, when neuromuscular blocking agents are administered, the diaphragm shifts cephalad at the end of expiration. This change in the diaphragm further compromises the airway. Laminar gas flow through a narrow airway is best maintained with spontaneous ventilation. Positive-pressure ventilation (PPV) and airway obstruction disrupt laminar flow and increase the resistance to gas flow in the airways. An inspired mixture of helium and oxygen decreases airway resistance because of helium's lower density.

p0785 Induction of anesthesia may remove compensatory efforts by the patient (Neuman et al. 1984). The child's position, pattern of ventilation, or sympathetic tone while awake may have been responsible for maintaining adequate cardiopulmonary function (Bray and Fernandes 1982; Prakash et al. 1988). If the patient is symptomatic, the anesthesiologist and surgeon must determine the best patient position to perform the procedure and the anesthetic alternatives to obtaining a tissue diagnosis (Mackie and Watson 1984). Positional changes can markedly affect the patient's respiratory status, and the procedure should occur in the position that minimizes respiratory compromise. Oftentimes it is in the sitting position. In patients with an anterior medial mass, Shamberger and colleagues (1991) noted that in pediatric patients AU20 undergoing general anesthesia, respiratory compromise was more likely in patients with a tracheal cross-sectional area less than 50% of normal (as predicted by CT) and a peak expiratory flow rate less than 50% of predicted (Shamberger 1999). In these patients, biopsy of accessible lesions under local anesthesia should be considered. In extreme cases where patients are significantly compromised, radiation therapy can quickly shrink the tumor mass and thereby allow a biopsy to be done later with less risk to the patient (Piro et al. 1976). However, this approach may result in the inability to make a specific tissue diagnosis, which may ultimately affect therapy. If general anesthesia is used, the surgeon should be present at induction and prepared for interventions such as passage of a rigid bronchoscope or immediate release of a pneumomediastinum via subxiphoid thoracostomy. Of utmost importance is that the patient, family, pediatrician, and surgeon all understand the risk for cardiovascular and respiratory



f0140 **Fig. 32.14** Mediastinal compartmentalization on lateral radiograph (**A**) and CT scan (**B**). *A,* Anterior; *M,* middle; *P,* posterior. (From Blickman, J. G., Parker, R., & Barnes, P. D. 2009. *Pediatric radiology.* St Louis: Mosby.)

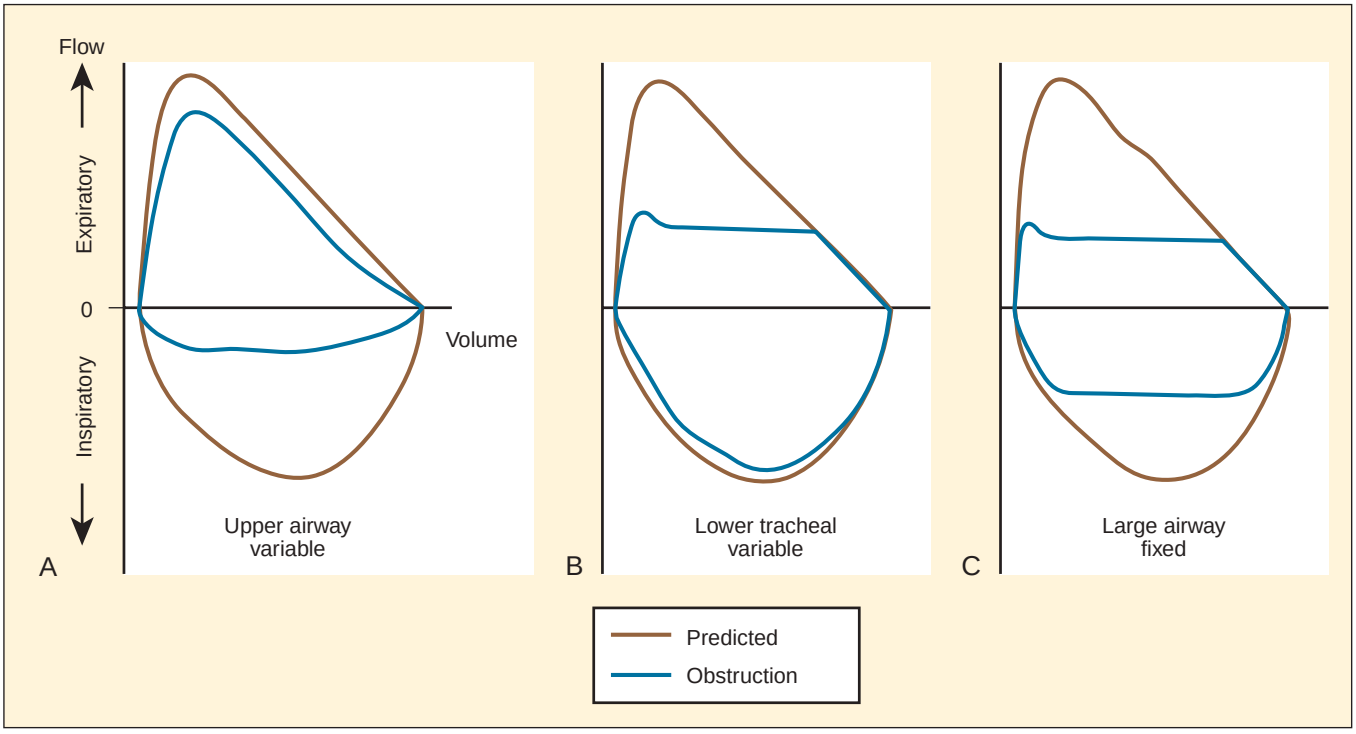


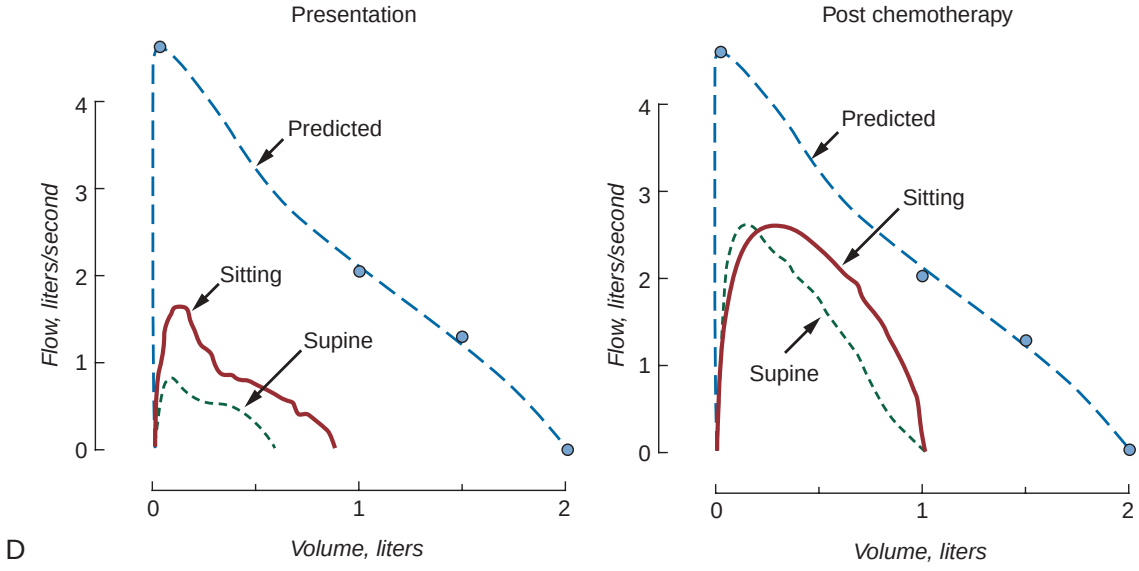
f0150 **Fig. 32.15** **A,** Normal trachea. **B,** Tracheal compression with tracheomalacia can occur by several causes including mediastinal masses, repaired trachea-esophageal fistula and vascular rings, and anomalies. (From Fraga, J. C., Jennings, R. W., & Kim, P. C. W. 2016. Pediatric tracheomalacia. *Seminars in Pediatric Surgery, 25*(3), 156–164.)

compromise that exists in performing tissue biopsies under general anesthesia (Fig. 32.17). For severely compromised patients, extracorporeal membrane oxygenation (ECMO) standby should be present. AU21

p0790 If general anesthesia is undertaken, either intravenous or inhalational induction with a volatile agent and 100% oxygen can be performed. If helium is available, then an oxygen helium admixture can be used to promote laminar flow and decrease airway resistance. Regardless of induction techniques, efforts to maintain spontaneous ventilation are paramount. In cases of severe airway compromise, local anesthetic administration coupled with judicious use of sedative agents may be necessary to perform the procedure. If cardiac compromise is present from vascular compression or pericardial effusion, then an anesthetic technique that maintains heart rate and preload should be administered (see Chapter 30: Anesthesia for Congenital Heart Disease). AU22

p0795 Nitrous oxide is avoided in all cases involving mediastinal masses, airway obstruction, pneumomediastinum, obstructive emphysema, and patients with significant V/Q abnormalities from lung compression (Mackie and Watson 1984). The role of nitrous oxide in patients with asymptomatic bronchogenic cysts, however, is unclear. Because these cysts are air filled, they may expand on exposure to nitrous oxide and cause airway compromise.

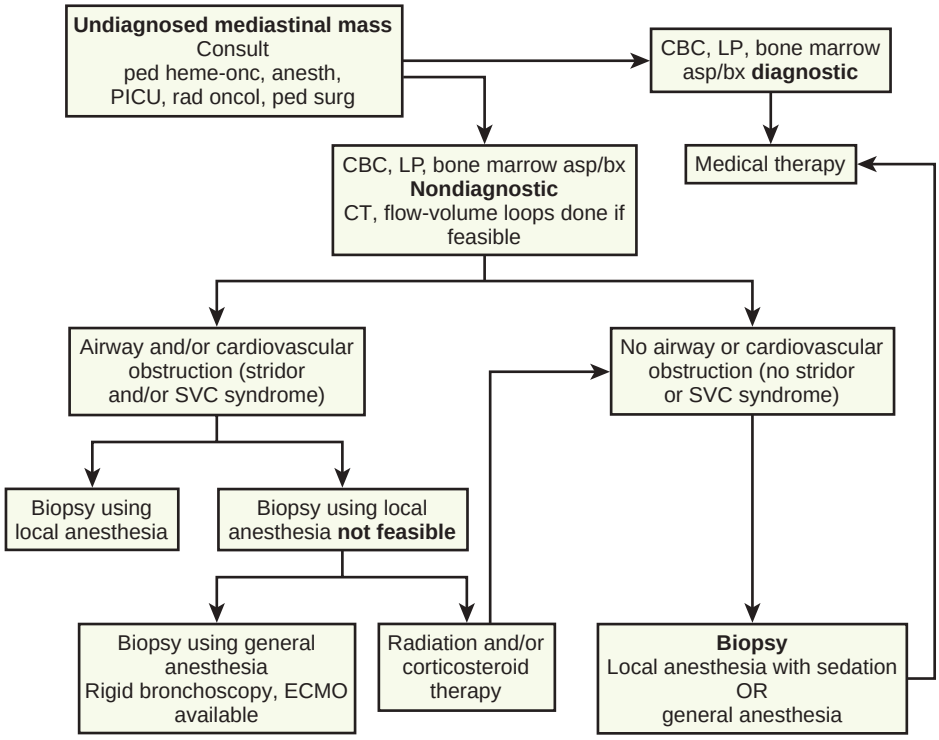




f0160

Fig. 32.16 Curves Showing Maximum Expiratory and Inspiratory Flow Versus Volume. **A,** Variable upper airway obstruction caused by papillomatosis of the larynx. **B,** Variable central (intrathoracic) airway obstruction caused by tracheomalacia. **C,** Fixed-type obstruction caused by tracheal stenosis. **D,** Expiratory flow volume loop in a patient with a mediastinal mass in both sitting and supine position before and 4 days after chemotherapy to reduce the mass. (A–C, from Motoyama, E. K. 1985. Physiologic alterations in tracheostomy. In E. N. Myers, S. E. Stool, & J. T. Johnson (Eds.), *Tracheostomy.* New York: Churchill Livingstone; D, from Shamberger, R. C., Holzman, R. S., Griscom, N. T., Tarbell, N. J., & Weinstein, H. J. 1991. CT quantitation of tracheal cross-sectional area as a guide to the surgical and anesthetic management of children with anterior mediastinal masses. *Journal of Pediatric Surgery, 26*(2), 138–142.)

p0800 Thoracotomy or thoracostomy is usually the operative procedure performed in patients with mediastinal disorders. Major complications include massive blood loss, further obstruction or perforation of the airway, and lung compression (Barash et al. 1976; Neuman et al. 1984). There continue to be sporadic reports of death during the induction and maintenance of anesthesia in children with mediastinal masses, emphasizing the need for meticulous preoperative evaluation and intraoperative care (see Box 32.3). After reviewing 44 pediatric patients with mediastinal masses, Ferrari and Bedford (1990) found that significant anesthesia-related problems occurred in patients who were symptomatic before surgery. They noted that general anesthesia could be administered with the



f0170

Fig. 32.17 Patient Care Algorithm for Mediastinal Mass.

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b0030

BOX 32.3 Anesthetic Considerations for Mediastinal Mass

s0010 **Preop Evaluation**

o0010 A. Patient assessment

u0225 Evaluate: signs and symptoms for orthopnea, coughing or hoarseness with lying flat, dyspnea at rest or on exertion, pulsus paradoxus, vena caval syndrome, wheezing, headache, and papilledema

o0015 B. Laboratory assessment

u0230 Review CT scan, echocardiogram, and pulmonary function tests (flow-volume loops if feasible)

s0015 **Anesthetic Management**

u0235 Premedication: dependent on patient anxiety and degree of respiratory compromise

u0240 Anesthetic monitors: standard anesthesia monitoring; consider preoperative arterial catheter

u0245 Anesthetic induction:

u0250 Asymptomatic patient and airway compression <50% on imaging studies

u0255 • Consider general anesthesia with inhaled or intravenous induction agents

u0260 • Determine optimal position of patient with regard to respiratory effort

u0265 • Avoid nitrous oxide

u0270 • Avoid neuromuscular blocking agents

u0275 • Maintain spontaneous ventilation

u0280 • Surgeon presence on induction of anesthesia

s0020 **Symptomatic Patient and Airway Compression >50% on Imaging Studies**

u0285 Determine optimal position of patient with regard to respiratory effort

u0290 • Consider bx with local anesthetic and minimal sedative agents

AU35 u0295 • Rigid bronchoscope immediately available

AU36 u0300 • Extracorporeal membrane oxygenation (ECMO) standby

u0305 • Surgeon presence

following caveats: spontaneous ventilation must be performed, induction of anesthesia should be in the sitting position, IV access should be in the lower upper extremity, and a rigid bronchoscope AU23 and experienced bronchoscopist must be available. The anesthesiologist not only must be prepared for each complication but also must notify the surgeon immediately if there is loss of airway, difficulty in ventilation, or sudden hypotension.

SUMMARY

s0135

p0805 Thoracic surgery involves a wide variety of lesions that can remarkably affect the patient's perioperative cardiovascular and pulmonary status. Though the surgical approach frequently "involves" minimally invasive surgery, the physiologic perturbations are anything but minimal. An understanding of the physiologic effects of positioning gas inflation of the chest coupled with the effects of single-lung ventilation are essential to good patient outcomes. Postoperative pain can be intense, especially if a chest tube is left in place. Thus the anesthesiologist needs to address not only the intraoperative management but also the patient's postoperative analgesic needs.

ACKNOWLEDGMENT

s0140

p0810 The author is grateful to Steven Hall, MD, for his contribution to this chapter in the eighth edition of *Smith's Anesthesia for Infants and Children.*

p0815 *For questions and answers on topics in this chapter, go to "Chapter Questions" at ExpertConsult.com.*

AU31

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p0820 *Complete references used in this text can be found online at Expert Consult.com.*

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