11 Anesthesia for Lung Cancers

Brent MacLellan and Peter Slinger

11.1 Introduction

Globally, lung cancer remains the most common cancer and the most common cause of cancer-related death [1, 2]. Smoking tobacco is the attributable etiology of 90% of lung cancer patients. Other carcinogens include asbestos and radon gas. Cessation of smoking reduces the risk of lung cancer with time but it never equates to that of non-smokers. With increasing incidence, death due to cancer shall surpass cardiac-related death in North America in this decade [2].

Most thoracic surgical procedures are performed for malignancy [3]. Given the variety of physiologic and anatomic implications of each lung cancer, the anesthesiologist must understand the patient's pathologic diagnosis obtained through bronchoscopy, mediastinoscopy, or trans-thoracic needle aspiration. Lung cancer is broadly divided into small cell and non-small cell lung cancers. The management strategies and outcomes differ among these types.

B. MacLellan (✉)
Department of Anesthesia, St. Joseph's Healthcare Hamilton, McMaster University, Hamilton, ON, Canada
e-mail: brent.maclellan@medportal.ca

P. Slinger
Department of Anesthesia, Toronto General Hospital, University of Toronto, Toronto, ON, Canada

11.2 Non-small Cell Lung Cancer (NSCLC)

Non-small cell lung cancer (NSCLC) is the predominant type (approximately 80%) and the rest 20% are under the small cell lung cancer (SCLC) category. NSCLC includes adenocarcinoma (most common), squamous cell, and large-cell carcinoma. Overall 5-year survival approaches 40% with surgery compared to 10% without surgery [2].

Adenocarcinoma spreads locally and tends to invade the chest wall, diaphragm, and pericardium while metastasizing early to the brain, bones, liver, and adrenals. Most Pancoast tumors are adenocarcinomas. Associated paraneoplastic syndromes include growth hormone, corticotropin, and hypertrophic pulmonary osteoarthropathy (HPOE). Bronchioloalveolar carcinoma (BAC) is a subtype of adenocarcinoma. The etiology of BAC is unrelated to smoking, with limited metastatic spread, therefore can be treated by lung transplantation [4].

Squamous cell carcinomas are large tumors strongly linked to cigarette smoking with delayed metastases. The presenting features of squamous cell lung cancer are primarily related to mass effects. They manifest as hemoptysis, obstructive pneumonia, superior vena cava (SVC) syndrome, cavitation, and large airway or vessel involvement. Hypercalcemia results from parathyroid-like factor.

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The rare large cell undifferentiated carcinoma commonly involves a rapidly growing and metastasizing peripheral lung mass.

11.3 Small Cell Lung Cancer (SCLC)

This neuroendocrine tumor is considered metastatic on presentation and generally warrants medical not surgical management. Unlike NSCLC, it is simply staged as limited or extensive. Up to 80% of patients with localized disease may respond to chemotherapy such as etoposide/cisplatin or cyclophosphamide/doxorubicin/vincristine. Additional treatment includes radiation to the lung mass and radiation prophylaxis to the brain. Nonetheless, recurrence is common and overall survival is generally below 10%. Patients with the advanced disease typically receive chemotherapy and palliative radiation [2].

SCLC has been found to have characteristics of paraneoplastic syndromes. The features include hyponatremia due to a syndrome of inappropriate anti-diuretic hormone (SIADH) and Cushing syndrome through ectopic production of adrenocorticotropic hormone (ACTH). Lambert-Eaton or myasthenic syndrome is a rare associated paraneoplastic syndrome caused by an impaired release of acetylcholine from nerve terminals in these patients of SCLC [2]. The usual manifestation is typically proximal limb weakness, and this weakness improves with physical activity. Electromyography (EMG) confirms the presence of this syndrome [5]. Like myasthenia gravis, the use of non-depolarizing neuromuscular blocking agents should be used cautiously as these patients are very sensitive to its effects. And also they have a poor response to anticholinesterase reversal agents [6]. These factors need to be considered during anesthetic planning for surgical interventions.

11.4 Carcinoid Tumors

Carcinoid tumors form a spectrum of neuroendocrine tumors from malignant SCLC to the more benign typical carcinoid. Bronchial carcinoid tumors are usually asymptomatic and discovered on screening chest radiographs [7]. Five-year survival following typical carcinoid resection is over 90%. Metastases are rare with these tumors. These tumors may be associated with the ectopic synthesis of vasoactive mediators and such a phenomenon is labeled as carcinoid syndrome. The occurrence of carcinoid syndrome is less common in SCLC as compared to tumors of gut origin with liver metastases. Resection of bronchial carcinoid tumors rarely leads to intraoperative hemodynamic instability or coronary vasospasm [8]. However, the anesthesiologist should consider specific antagonists such as octreotide to manage refractory intraoperative hypotension [9].

11.5 Pleural Tumors

The primary pleural tumors are not common and include fibrous tumors of pleura (benign mesotheliomas) and malignant pleural mesothelioma (MPM). The fibrous tumors may be benign or malignant. The localized large fibrous tumors encroach on the visceral or parietal pleura.

Asbestos exposure is implicated in up to 80% of MPM cases. The window period from exposure to asbestos and tumor manifestation is usually long and thus eliciting history for its causative factor may be missed. The incidence of MPM has been reported to double in the last two decades [2]. MPM invades the visceral and parietal pleura, usually leading to a bloody effusion and exertional dyspnea. The diagnosis requires pleural biopsy and video-assisted thoracoscopy guided biopsy remains the acceptable modality. Diagnosis cannot be confirmed by thoracentesis. The symptom management includes the tapping of pleural fluid and simultaneous talc pleurodesis is performed to minimize the recurrence of the effusion.

MPM is typically refractory to therapy with expected survival under 1 year. Extrapleural pneumonectomy for the early disease may decrease mortality. The management strategies include a multidisciplinary approach including radiation therapy, chemotherapy, and surgery. The surgical intervention includes extrapleural pneumonectomy, which is a major surgery with perioperative complications. In addition to the standard risks of a pneumonectomy, patients are at risk of extensive hemorrhage from dissection of the chest wall and major vessels, as well as the risks of pericardial and diaphragm dissection [10]

11.6 Preoperative Assessment

Preoperative assessment for surgical intervention for lung cancer surgery requires an understanding of cancer and its effects on body physiology and tools for its assessment. With evolving concepts and tools, thorough updated knowledge is paramount [2]. With the improvement in surgical techniques, a greater number of patients are scheduled for surgical excision of the tumor. The various surgical procedures for lung cancer include "lung-sparing" resections such as sleeve-lobectomies or segmentectomies, with minimally invasive techniques such as video or robotic-assisted thoracoscopic surgery (VATS/RATS). Anesthesiologists need to identify patients at elevated perioperative risk by thorough multimodal assessment and to prepare not only a holistic plan for preoperative optimization but also a strategy for perioperative care. The anesthesiologist must consider the patient's medical comorbidities and perioperative complications for lung resection [3].

11.6.1 Assessment of Lung Cancer

The basic assessment tool using "4-Ms" in cancer patients is applicable for lung cancer as well. It needs to be elicited using a thoroughly targeted history, physical examination, and investigations (Box 11.1).

In terms of medications, bleomycin is a commonly used chemotherapeutic agent for germ cell tumors and these patients may be scheduled for lung surgery for metastasectomy. The exposure to bleomycin is associated with pulmonary toxicity which can be exaggerated with a high fraction of inspired oxygen concentrations (FiO_2). Risk factors include increased age, renal insufficiency, high inspired fraction of oxygen, fluid overload, and pulmonary fibrosis [11]. The safest strategy in the patient who received bleomycin is to administer the lowest fraction of inspired oxygen in perioperative management with appropriate monitoring. Non-steroidal anti-inflammatory drugs (NSAIDs) need to be avoided in the patient who received cisplatin to avoid renal toxicity.

Box 11.1: Anesthetic Considerations in Lung Cancer Patients (the 4 "Ms") [2]

1. ***Mass effects***: obstructive pneumonia, lung abscess, superior vena cava (SVC) syndrome, tracheobronchial distortion, Pancoast syndrome, recurrent laryngeal or phrenic nerve paresis, chest wall or mediastinal extension
2. ***Metabolic effects***: Lambert-Eaton syndrome, hypercalcemia, hyponatremia, Cushing syndrome
3. ***Metastases***: brain, bone, liver, adrenal glands
4. ***Medications***: chemotherapy—pulmonary toxicity (bleomycin, mitomycin), cardiac toxicity (doxorubicin), renal toxicity (cisplatin)

11.6.2 Assessment of Respiratory Function Before Lung Resection

The thorough assessment, optimization, and appropriate planning are important as major respiratory complications like atelectasis, pneumonia, and respiratory failure have been seen in almost 15–20% undergoing lung cancer surgeries. These complications account for 3–4% mortality post lung cancer resection [12]. The assessment should include a detailed history of the patient's quality of life and objective measures of pulmonary function guide anesthetic management. A single test to predict the perioperative outcome after lung cancer surgery is not known. So, a combination of assessment strategies needs to be used for risk assessment. The "three-legged stool" approach including respiratory mechanics, pulmonary parenchymal function, and cardiorespiratory interaction is one of the useful strategies for assessment before lung cancer surgeries [3].

11.6.2.1 Lung Mechanical Function

The various respiratory mechanics' parameters like forced expiratory volume in one second (FEV1), forced vital capacity (FVC), maximal voluntary ventilation (MVV), and residual volume/total lung capacity ratio (RV/TLC) are useful in predicting postoperative outcomes after lung surgeries. Predicted postoperative FEV1 (ppoFEV1 %) remains an independent predictor of postoperative morbidity and mortality [13, 14], which is calculated as:

- *For lobectomy*: ppoFEV1 % = preoperative FEV1 % × (1– # of functional lung segments being removed/total # of functioning lung segments). (Typically, the number of lung segments is divided as follows: right upper lobe 6, right middle lobe 4, right lower lobe 12, left upper lobe 10, left lower lobe 10).
- *For pneumonectomy*: ppo FEV1% = preoperative FEV1 × (1 – a fraction of total perfusion of the resected lung)

The American College of Chest Physicians (ACCP) guidelines argue that patients with a ppo FEV1 <30% require formal cardiopulmonary exercise testing (CPET) to further stratify risk (Fig. 11.1) [14]. Patients with a PPO FEV1 of 30–60% should undergo a low technology exercise test (stair climb, shuttle walk). Those who can walk greater than 400 m or climb greater than 22 m are deemed low risk. However, patients not attaining these thresholds should undergo formal CPET [14]. Patients with a ppo FEV1 >60% do not require further testing [14]. Patients previ-

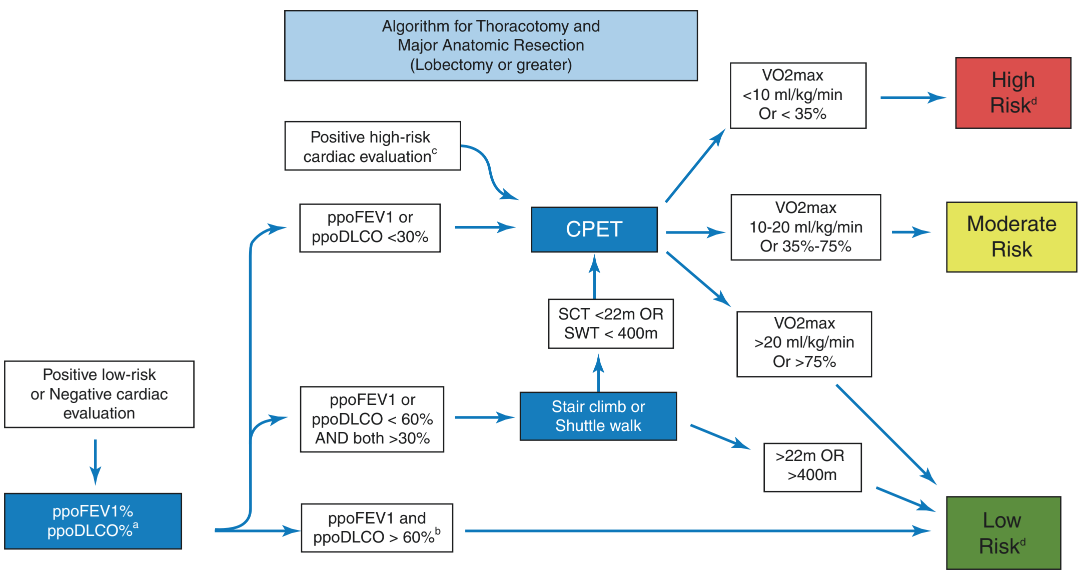

Fig. 11.1 Physiologic evaluation resection algorithm. Definition of risk: Low risk: The expected risk of mortality is below 1%. Major anatomic resections can be safely performed in this group. Moderate risk: morbidity and mortality rates may vary according to the values of split lung function tests, exercise tolerance, and extent of resection. Risks and benefits of the operation should be thoroughly discussed with the patient. High risk: The risk of mortality after standard major anatomic resections may be higher than 10%. Considerable risk of severe cardiopulmonary morbidity and residual functional loss is expected. Patients should be counseled about less invasive surgical or non-surgical options. ppoDLCO%, percent predicted postoperative diffusing capacity for carbon monoxide; ppoFEV1%, percent predicted postoperative forced expiratory volume in 1 s; SCT, stair climb test; SWT, shuttle walk test; VO_2 max, maximal oxygen consumption. Reproduced with permission from Brunelli et al. Physiologic evaluation of the patient with lung cancer being considered for resectional surgery. *CHEST 2013;143(5)(Suppl):e166S–e190S*

ously deemed too high risk can be operated on with acceptable morbidity and mortality, ideally using epidural analgesia and VATS approach in a high volume thoracic center [15–17]. Emphysematous patients have a lung-volume reduction effect on the residual lobe(s) and may exceed their ppoFEV1 if a hyper-inflated lobe is resected [18].

11.6.2.2 Parenchymal Lung Function

The assessment for gas exchange capacity of the lung is usually done by measuring the diffusing capacity for carbon monoxide (DLCO). The DLCO reflects the total functioning surface area of the alveolar-capillary interface. Predicted postoperative (ppo) values are calculated using the same formulae as for the FEV1. Numerous studies have shown that ppo DLCO is an equal or stronger predictor of perioperative morbidity and mortality than ppo FEV1, including in patients with a normal FEV1 [14, 19]. The 2013 ACCP guidelines use the same thresholds for DLCO as for FEV1 to stratify a patient's perioperative risk and pursue additional investigations (Fig. 11.1) [14]. When there is a discrepancy between the ppo FEV1 and ppo DLCO, the lower of the two values should determine risk [13].

11.6.2.3 Cardiopulmonary Interaction

The assessment of the cardiopulmonary interaction remains one of the crucial assessments before lung cancer surgeries. The "gold standard" assessment tool for this function is by laboratory exercise [20]. The estimated maximum oxygen consumption (VO_2max) as per the patient's age, sex, and height is no more useful than the absolute value [21].

VO_2 max is an excellent tool to predict a patient's risk of morbidity and mortality post lung resection, independent of FEV1 and DLCO [14, 22, 23]. The ACCP guidelines state that patients with a VO_2 max below 10 mL/kg/min have an unacceptably high risk, 10–20 mL/kg/min moderate risk, and >20 mL/kg/min low risk requiring no additional testing [14]. European guidelines recommend performing CPET on all patients with an FEV1 or DLCO <80%, then performing ppo FEV1 and DLCO on patients with values below 20 mL/kg/min [24].

Formal CPET is too time-consuming and expensive for routine use before pulmonary resection. The six-minute walk test (6MWT) is a low-tech assessment of exercise capacity with excellent correlation to VO_2 max and similar prognostic value [25, 26]. The 6MWT distance assessment is a valuable tool to estimate the VO_2max by dividing by a figure of 30 (i.e., 600 m distance is equivalent to a VO_2max of 600/30 = 20 mL/kg/min) [27]. Climbing five flights of stairs correlates with a VO_2max >20 mL/kg/min while climbing two flights corresponds to a VO_2 max of 12 mL/kg/min. The patient's inability to climb 2 flights of stairs indicates restricted cardiorespiratory function and surgical management remains extremely high-risk [28, 29].

11.6.2.4 Ventilation Perfusion Scintigraphy

The ventilation-perfusion (V/Q) lung scanning is an important assessment modality in lung cancer patients scheduled for lung resection surgeries. This aids in the prediction of the post-resection pulmonary function. At times, the lobe or region of the lung involved with cancer may be already non-functional, therefore calculating PPO values based on perfusion rather than lung segments may be more accurate [13, 14]. V/Q scanning is likely more beneficial in pneumonectomy than lobectomy patients [30].

11.7 Intraoperative Monitoring

Generally, lung cancer resections are major procedures of moderate duration (2–4 h). The patient is positioned in a lateral position with the opening of the hemithorax. Anesthesia induction and airway management are initially done in the supine position, so on turning the patient laterally, the rechecking of monitors and airway is required. Also, the vitals and respiratory parameters should be checked soon after the change of position. The choice of invasive monitoring is usually based on patient assessment but the placement of these invasive monitoring after the positioning of the patient for surgery is difficult. So, in patients with cardiorespiratory compromise, placement of the invasive monitoring like arterial catheter is advisable.

11.7.1 Oxygenation

Significant desaturation (SpO_2 <90%) is seen in almost 1–10% of patients undergoing lung surgeries during one-lung ventilation even with FiO_2 of 1 [2]. The arterial P_aO_2 via arterial blood gases (ABG) provides better oxygenation status as compared to the use of pulse oximeter (SpO_2) in these situations. Considering the sigmoidal shape of the oxyhemoglobin dissociation curve, the P_aO_2 may better indicate how much buffer exists before the patient rapidly desaturates to dangerous levels

11.7.2 Capnometry

The gradient of arterial (P_aCO_2) to end-tidal ($P_{ET}CO_2$) increases during OLV. The $P_{ET}CO_2$ signifies lung perfusion during OLV, though it does not correlate well with the alveolar minute ventilation [31]. The $P_{ET}CO_2$ briefly decreases at the initiation of OLV due to a higher ventilation/perfusion ratio to the dependent lung. Subsequently, it tends to increase as hypoxic pulmonary vasoconstriction (HPV) shunts blood from the non-dependent to the dependent lung. Severe (>5 mmHg) or prolonged falls in $P_{ET}CO_2$ is a good indicator of perfusion maldistribution among the two lungs and thus can predict desaturation [2].

11.7.3 Arterial Line

Surgical compression of major vascular structures may cause sudden decreases in cardiac output manifested as hypotension. This emphasizes the need for arterial line placement for ABG sampling in patients undergoing major lung surgeries. Maintaining a catheter position intraoperatively may be easier in the dependent arm, but using either side is feasible.

11.7.4 Central Venous Line

The utility of central venous access for purpose of pressure monitoring to guide fluid status remains grossly restricted due to lateral positioning an open chest. It is indeed not an acceptable tool to guide fluid management. However, it provides access for administering vasopressors and inotropes in cases where limited intravenous fluids are administered (e.g., pneumonectomies) or excessive blood loss is anticipated (re-do thoracotomies, decortications).

11.7.5 Pulmonary Artery Catheters

Intraoperative pulmonary artery (PA) pressure may also not accurately reflect left-heart preload. Given the variable distribution of lung perfusion, the use of thermodilution cardiac output measurements during OLV is controversial [32].

11.7.6 Fiberoptic Bronchoscopy

The lung surgeries require OLV and thus need airway devices for lung separation like double-lumen tubes or bronchial blockers. The placement of these devices requires flexible bronchoscopic guidance and should be re-confirmed after in the lateral position due to frequent migration of these devices, which can be missed by auscultation alone [33, 34].

11.7.7 Continuous Spirometry

Side-stream spirometry provides valuable data during OLV including inspiratory and expiratory volumes, pressures, and flow interactions. Sudden discrepancies between inspired and expired tidal volumes may provide an early signal of migration of the lung isolation device, as well as air leaks post lung resection. Auto-PEEP manifests as persistent end-expiratory flow during OLV, with potential hypoxia due to increased shunt to the non-dependent lung and hypotension due to decreased venous return.

11.7.8 Transesophageal Echocardiography (TEE)

TEE provides a dynamic monitor of myocardial function and cardiac preload, which may be more reliable than other hemodynamic monitors [35]. Potential indications for TEE during lung cancer surgery include hemodynamic instability, pericardial effusions, cardiac involvement by a tumor, air emboli, and detecting a patent foramen ovale during refractory hypoxemia.

11.8 Lung Isolation

The OLV is required for lung surgeries for various reasons including better surgical exposure, prevention of contralateral lung soiling from blood, infected material, whole lung lavage, and isolate ventilation in cases of bronchopleural fistula, tracheobronchial trauma, and severe bullous disease [36]. At times, in conditions like lung transplantation or pulmonary thromboendarterectomy, lung isolation aids in the provision of differential ventilation to lungs to avoid unilateral reperfusion injury. The methods for lung isolation include double-lumen tubes (DLTs), bronchial blockers, or single-lumen endobronchial tubes (SLTs) (Table 11.1).

11.8.1 Double-Lumen Tubes

The most common technique for lung isolation is with a DLT, which contains both endotracheal

Table 11.1 Options for lung isolation [2]

Options	Advantages	Disadvantages
Double-lumen tube 1. Direct laryngoscopy 2. Via tube exchanger 3. Fiberoptically	Easy to place successfully Repositioning rarely required Bronchoscopy to isolated lung Suction to isolated lung CPAP easily added Can alternate one-lung ventilation to either lung easily Placement still possible if bronchoscopy not available Best device for absolute lung isolation	Size selection more difficult Difficult to place in patients with difficult airways or abnormal tracheas Not optimal for postoperative ventilation Potential laryngeal trauma Potential bronchial trauma
Bronchial blockers (BB) 1. Arndt 2. Cohen 3. Fuji 4. EZ blocker	Size selection rarely an issue Easily added to regular ETT Allows ventilation during placement Easier placement in patients with difficult airways and children Postoperative two-lung ventilation by withdrawing blocker Selective lobar lung isolation possible CPAP to isolated lung possible	More time needed for positioning Repositioning needed more often Bronchoscope essential for positioning Limited right lung isolation due to RUL anatomy Bronchoscopy to isolated lung impossible Minimal suction to isolated lung Difficult to alternate one-lung ventilation to either lung
Univent tube	Same as BBs Less repositioning compared with BBs Rarely used	Same as BBs ETT portion has higher airflow resistance than regular ETT ETT portion has a larger diameter than regular ETT
Endobronchial tube	Like regular ETTs, easier placement in difficult airways Longer than regular ETT Short cuff designed for lung isolation	Bronchoscopy necessary for placement Does not allow for bronchoscopy, suctioning, or CPAP to isolated lung Difficult one-lung ventilation to right lung
Endotracheal tube advanced into the bronchus	Easier placement in patients with difficult airways	Does not allow for bronchoscopy, suctioning, or CPAP to isolated lung Cuff not designed for lung isolation Extremely difficult right one-lung ventilation

CPAP, continuous positive airway pressure; ETT, endotracheal tube; RUL, right upper lobe

Table 11.2 Comparative diameters of single- and double-lumen tubes [2]

Single-lumen tubes		Double-lumen tubes			
ID (mm)	ED (mm)	French size (Fr)	Double-lumen ED (mm)	Bronchial lumen ID (mm)	FOB size (mm)
6.5	8.9	26	8.7	3.2	2.4
7	9.5	28	9.3	3.4	2.4
8	10.8	32	10.7	3.5	2.4
8.5	11.4	35	11.7	4.3	≥3.5
9	12.1	37	12.3	4.5	≥3.5
9.5	12.8	39	13.0	4.9	≥3.5
10	13.5	41	13.7	5.4	

ED, external diameter; FOB, fiberoptic bronchoscope; ID, internal diameter

Double-lumen ED is equal to the approximate external diameter of the double-lumen portion of the tube. FOB size is equal to the maximum diameter of the fiberoptic bronchoscope that will pass through both lumina of a given size of a double-lumen tube

Table 11.3 Selection of double-lumen tube size based on adult patient sex and height [2]

Sex	Height (cm)	Size of double-lumen tube (Fr)
Female	<160 (63 in.)[a]	35
Female	>160	37
Male	<170 (67 in.)[b]	39
Male	>170	41

[a]For females of short stature (<152 cm or 60 in.), examine the bronchial diameter on CT; consider a 32-Fr double-lumen tube

[b]For males of short stature (<160 cm), consider a 37 Fr double-lumen tube

and endobronchial lumens with corresponding cuffs capable of isolating the right or left lung. Table 11.2 lists the different sizes of DLTs, corresponding fiberoptic bronchoscope size, and comparable SLT diameter.

11.8.1.1 Size Selection

Ideally, the bronchial lumen of the left-sided DLT should be 1–2 mm smaller in diameter than the patient's left mainstem bronchus (LMSB) to accommodate the bronchial cuff. In addition to reviewing chest imaging to detect abnormal airway anatomy, a simplified guide can assist appropriate DLT sizing (Table 11.3) [37].

11.8.1.2 DLT Placement Method

The various methods have been described in the literature for DLT placement. The traditional blind technique of DLT placement includes placing it using the direct laryngoscopy method and when once the endobronchial cuff crosses the vocal cords, the DLT is turned 90–180° counterclockwise (for a left-sided DLT placement) and advancing it further to place it in the bronchial lumen in the left mainstem bronchus (LMSB). Since the diameter at the level of the cricoid ring is not smaller than that of LMSB, so the DLT should negotiate the site without obstruction if an appropriate size DLT is selected [38]. In the direct vision technique, the placement of DLT in the respective bronchial lumen is guided by a flexible fiberoptic bronchoscope once the initial placement is across the glottis. Bronchoscopy must ultimately confirm placement with either technique.

11.8.1.3 Right-Sided Double-Lumen Tubes

The left-sided DLT is mostly used for lung surgeries. However, in some specific situations, a right-sided DLT is required [39] (Box 11.2). The right-sided DLT cuff is different from the left-sided DLT cuff due to the anatomy of the right bronchus. The right mainstem bronchus is shorter and the right upper lobe originates only 1.5–2 cm from the carina. Given this anatomical variation, to keep the right upper lobe patent for ventilation, the cuff of right-sided DLT has a slot [40] (Fig. 11.2).

11.8.2 Bronchial Blockers

Bronchial blockers occlude the mainstem bronchus of the operative lung to allow distal lung collapse. More distal placement can achieve selective lobar collapse. Currently, available devices are either within a modified SLT (Torque Control Blocker Univent®; Vitaid, Lewiston, NY) or are used independently within (intraluminal/coaxial) a conventional SLT: the Arndt® wire-guided endobronchial blocker (Cook Critical

Box 11.2: Indications for a Right-Sided Double-Lumen Tube [2]

- Distorted anatomy of the entrance of left mainstem bronchus
  - External or intraluminal tumor compression
  - Descending thoracic aortic aneurysm
- Site of surgery involving the left mainstem bronchus
  - Left lung transplantation
  - Left-sided tracheobronchial disruption
  - Left-sided pneumonectomy[a]

[a]It is possible to manage a left pneumonectomy with a left-sided DLT or bronchial blocker; however, the DLT or bronchial blocker has to be withdrawn before stapling the mainstem bronchus

Care, Bloomington, IN), the Cohen® tip-deflecting endobronchial blocker (Cook Critical Care, Bloomington, IN), the Fuji Uniblocker® (Vitaid, Lewiston, NY), and the EZ Blocker® with right and left mainstem balloons sitting at the carina (Teleflex, Dresden, Germany) (Fig. 11.3).

Bronchial blockers are a good alternative to DLT in situations of the difficult airway, contralateral pulmonary resection, or anticipated need for postoperative mechanical ventilation. The Cohen and Fuji Uniblocker can also be placed extra-luminal in patients with small airway dimensions (pediatrics or tracheostomy sites).

Table 11.4 describes the characteristics of current bronchial blockers. For standard 9-Fr blockers, an ETT greater than or equal to 7.0 mm ID can be used with a bronchoscope less than 4.0 mm in diameter. Larger bronchoscopes

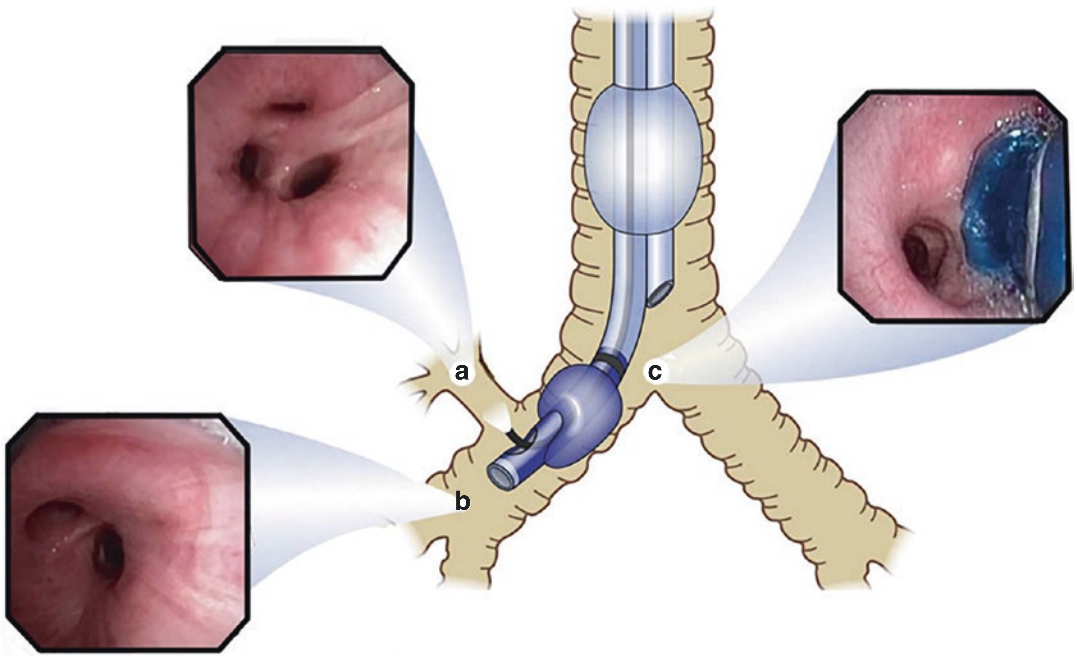

Fig. 11.2 The optimal position of a right-sided DLT is seen from the endobronchial or endotracheal view with a fiberoptic bronchoscope. (**a**) Shows the take-off of the right upper lobe bronchus with three segments (apical, anterior, and posterior) when the fiberoptic bronchoscope emerges from the opening slot located in the endobronchial lumen. (**b**) Shows an unobstructed view of the entrance of the right middle and right lower lobe bronchus when the fiberscope is passed through the endobronchial lumen. (**c**) Shows a view of tracheal carina to the right edge of the blue balloon fully inflated, to the left unobstructed view of the entrance of the left mainstem bronchus when the fiberscope is advanced through the tracheal lumen. Reproduced with permission from Slinger P: *Principles and practice of anesthesia for thoracic surgery*, New York, Springer, 2011

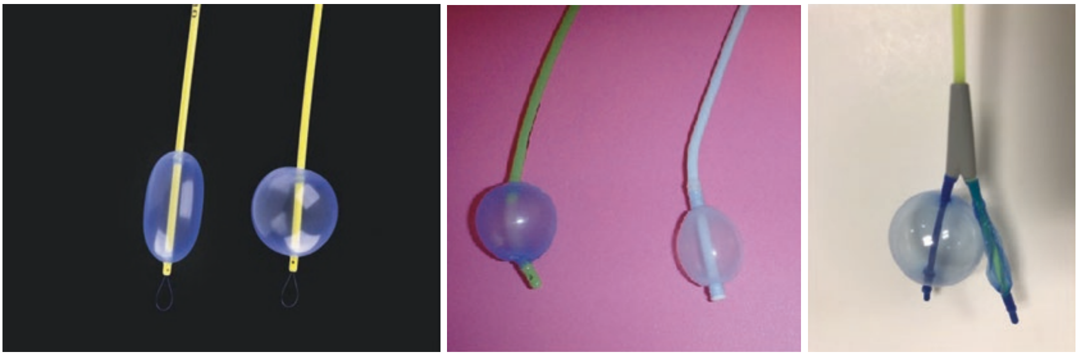

Fig. 11.3 Currently available bronchial blockers. Far left: The original elliptical and the newer spherical Arndt designs (Cook Critical Care, Bloomington, Ind). Middle: The Cohen (left, Cook Critical Care) and Fuji Uniblocker (right, Vitaid, Lewiston, NY). Right: The Rusch EZ Blocker (Teleflex, Dresden, Germany). Reproduced with permission from: Slinger P and Campos J. *Anesthesia for Thoracic Surgery. In: Miller's anesthesia*. Eighth ed. Philadelphia, PA, 2015

Table 11.4 Characteristics of the Cohen, Arndt, Fuji, and EZ bronchial blockers [2]

	Cohen blocker	Arndt blocker	Fuji uniblocker	EZ blocker
Size	9 Fr	5 Fr, 7 Fr, 9 Fr	5 Fr, 9 Fr	7 Fr
Balloon shape	Spherical	Spherical or elliptical	Spherical	Spherical × 2
Guidance mechanism	Wheel device to deflect the tip	Nylon wire loop coupled with the fiberoptic bronchoscope	None, pre-shaped tip	None
Smallest recommended ETT for coaxial use	9 Fr (8.0 ETT)	5 Fr (4.5 ETT) 7 Fr (7.0 ETT) 9 Fr (8.0 ETT)	9 Fr (8.0 ETT)	7.5
Murphy's eye	Present	Present in 9 Fr	Not present	Not present
Center channel	1.6 mm ID	1.4 mm ID	2.0 mm ID	1.4 mm ID

ETT, endotracheal tube; ID, internal diameter

require greater than 7.5 mm ID. Prior lubrication of the blocker is essential.

Current evidence shows that compared to double-lumen tubes, bronchial blockers require slightly more time for insertion, provide comparable timing and quality of lung isolation, decrease the risk of sore throat and airway trauma, but require more frequent repositioning which may affect surgical exposure [41–43]. The inflated balloon may lodge in the trachea, causing complete airway obstruction and potential cardiorespiratory arrest unless the blocker is immediately deflated [44]. The presence of abnormal airway anatomy or inadequate seal within the bronchus has been reported for the failure of this device [45]. Clear communication about the placement of blockers should be ensured with surgeons to prevent surgical stapling during lung resection [46].

11.8.3 Endobronchial Tubes

The use of single-lumen tubes (SLT) for OLV requires advancing tube in the respective bronchus under flexible bronchoscope guidance. This technique is usually reserved for difficult airways, carinal resection, post-pneumonectomy, or uncuffed SLTs in small children.

11.8.4 Difficult Airways and Lung Isolation

Patients requiring OLV may present with an anticipated or unanticipated difficult airway. Carcinoma of the head and neck with previous radiation or surgical resection may greatly complicate lung isolation. Anatomy may be distorted in the distal airways due to compression by a thoracic aortic aneurysm or an obstructing tumor near the tracheobronchial bifurcation.

Difficult airways should be secured with an SLT by awake fiberoptic intubation or asleep intubation with airway adjuncts immediately available. Under general anesthesia, lung isolation can subsequently be achieved by passing a bronchial blocker, advancing the SLT into the mainstem bronchus, or changing the SLT to a DLT over an airway exchange catheter (through the bronchial lumen) with visualization by video laryngoscopy. A 14 Fr exchange catheter should be used for 41 Fr and 39 Fr DLTs; for 37 Fr or 35 Fr DLTs, an 11 Fr exchange catheter is required. Soft tipped exchange catheters may be less traumatic (e.g., Cook Exchange Catheter, Cook Critical Care, Bloomington, IN).

11.8.5 Summary

The "ABCs" of lung isolation are:

- Anatomy—The understanding of the tracheobronchial airway anatomy is essential for ensuring the appropriate placement of airway devices for achieving OLV [47].
- Bronchoscopy—The fundamental knowledge and skill of the use of fiberoptic bronchoscopy for positioning and correctly identifying the correct placement of lung isolation devices is mandatory. The virtual online bronchoscopy simulator is available to familiarize themselves with the lung isolation devices (www.thoracicanesthesia.com).
- Chest imaging—The airway imaging basics should also be clear to anesthesiologists involved in providing OLV. Known airway abnormalities can guide optimal methods for lung isolation.

11.9 One-Lung Ventilation

11.9.1 Hypoxic Pulmonary Vasoconstriction (HPV)

In response to low alveolar oxygen tension (PAO_2), hypoxic pulmonary vasoconstriction (HPV) diverts pulmonary blood to well-ventilated lung regions to optimize ventilation/perfusion matching [48]. HPV decreases perfusion to the non-ventilated lung by approximately 50% [49]. HPV has a biphasic temporal response to alveolar hypoxia, plateauing at 20–30 min then again at approximately two hours [50]. The biphasic offset of HPV implies surgeries where bilateral thoracic surgeries are being performed and the collapse of the contralateral lung is required. Preconditioning leads to a greater response to a second hypoxic challenge [51].

All volatile anesthetics, especially older agents, inhibit HPV in a dose-dependent manner (halothane > enflurane > isoflurane) [52]. In doses under 1 MAC, current volatiles (isoflurane, sevoflurane, and desflurane) are weak and equipotent inhibitors of HPV [53–55]. Theoretically, the volatile agent can only access the hypoxic lung pulmonary capillaries during its return through mixed venous blood. Total intravenous anesthesia does not provide superior oxygenation than modern volatile anesthetics provided less than 1 MAC is used [56, 57]. Nitrous oxide is generally avoided in thoracic anesthesia because it can increase postoperative atelectasis and increase pulmonary pressures (inhibit HPV) [2].

11.9.2 Acute Lung Injury

Acute respiratory distress syndrome (ARDS), also known as acute lung injury (ALI), is the leading cause of morbidity and mortality after thoracic surgery [2, 58]. Its incidence of post-thoracotomy is 4–15% and associated mortality is up to 40% [58, 59]. The consensus "Berlin Definition" for ARDS defines mild, moderate, and severe ARDS, which apply post lung resection [60]. Risk factors for ALI post lung resection include peak airway pressures >40 mmHg, plateau airway pressures >29 mmHg, pneumonectomy, excessive intravenous fluids, and preoperative alcohol abuse [61].

The pathophysiology of ALI post OLV mirrors that of ARDS [62]. Modifiable triggers, including barotrauma, volutrauma, atelectrauma, hyperoxia, surgical manipulation, and ischemia-reperfusion, contribute to the inflammatory response capable of causing multiorgan failure

[58]. Therefore, an expanding body of literature guides anesthetic interventions that mitigate the risk of postoperative ALI, most notably "lung-protective ventilation."

11.9.3 Tidal Volumes

Low tidal volume ventilation (4–6 mL/kg of ideal body weight—IBW) compared to conventional high tidal volume ventilation (10–12 mL/kg IBW) during OLV decreases the incidence of ALI post lung cancer resection, especially pneumonectomy [59, 61–66]. To decrease the risk of barotrauma and volutrauma, ventilation should be with a tidal volume of 4–6 mL/kg of IBW during OLV and 6–8 mL/kg of IBW during TLV [62].

11.9.4 Positive End Expiratory Pressure (PEEP)

There is no consensus for optimal PEEP during OLV because patients sit at various points on the alveolar compliance curve. However, in most patients, PEEP is a crucial component of lung-protective ventilation. Inadequate PEEP can derecruit the dependent lung and cause intraoperative hypoxia and atelectrauma. Excessive PEEP can divert blood to the operative lung and increase shunt fraction. Auto-PEEP averages 4–6 cm H_2O in lung cancer patients and is likely higher in emphysema [2]. Its measurement involves an end-expiratory hold, typically with an ICU ventilator. It is recommended to begin OLV with a PEEP of 3–10 cm H_2O, titrating to oxygenation and monitoring for inadequate expiration. Patients with COPD often require lower or zero PEEP [62].

11.9.5 Airway Pressures

While there are no clear thresholds for safety, minimizing peak and plateau airway pressures during OLV are key strategies to reduce the risk of lung stress. A recent review recommends maintaining peak airway pressure below 30 cm H_2O and plateau pressures below 20 cm H_2O [62].

11.9.6 Alveolar Recruitment Maneuvers (ARM)

To decrease atelectasis and shunt fraction, it is recommended to perform an ARM at a pressure of 30 cm H_2O for at least 10 s at the onset of OLV [67]. Additional ARMs should be performed as needed to improve oxygenation and optimize PEEP.

11.9.7 Fraction of Inspired Oxygen (FIO_2)

Reactive oxygen species are a known contributor to the inflammatory cascade preceding acute lung injury [58]. While an FIO_2 of 1.0 is recommended before lung isolation to decrease atelectasis, thereafter the minimal FIO_2 required to maintain a saturation of 92–96% should be used. Hyperoxia is particularly toxic as a component of ischemia-reperfusion injury. Therefore initial re-expansion of the operative lung should be performed with the lowest FIO_2 possible [62].

11.9.8 Ventilation Mode

Despite being associated with a lower peak airway pressure, pressure-controlled ventilation (PCV) does not improve oxygenation compared to volume-controlled ventilation (VCV) [2]. It is reasonable to use either mode, recognizing that with PCV tidal volumes can vary drastically.

11.9.9 Maintenance of Anesthesia

Studies demonstrate that volatile anesthetics (desflurane and sevoflurane) enhance ischemic preconditioning and attenuate lung injury in OLV compared to propofol infusion [58]. Therefore, anesthesia should be maintained with volatile anesthetics during OLV unless contraindications exist.

11.9.10 Postoperative Care

Chest physiotherapy, incentive spirometry, and early mobility are crucial in minimizing postoperative pulmonary complications. Early extubation minimizes the risk of ventilator acquired pneumonia (VAP). Acute respiratory failure is managed supportively (oxygenation, ventilation, antibiotics if indicated) to support vital organs while minimizing further lung damage [2].

11.9.11 Hypoxemia During One-Lung Ventilation

Hypoxemia during OLV is rapid and predictable in most cases (Box 11.3) [68]. Patients with longstanding unilateral disease tolerate OLV relatively well with the decreased shunt. Right-sided procedures usually have a larger shunt and hypoxemia during OLV because the right lung normally receives 10% more perfusion than the left [69]. Patients with obstructive airway disease may tolerate OLV better than restrictive lung disease due to auto-PEEP [2]. For bilateral pulmonary surgery such as metastectomies, it is recommended to operate on the lung with better ventilation (usually the right) first because surgical trauma temporarily impairs gas exchange [70].

Box 11.3: Risk Factors for Oxygen Desaturation During One-Lung Ventilation [2]

1. Relatively high ventilation or perfusion (VQ) to the operative lung on the preoperative VQ scan
2. Low PaO_2 during two-lung ventilation, including while in the lateral position
3. Right-sided procedure
4. Normal preoperative FEV1 or FVC
5. Supine position during one-lung ventilation

Management of hypoxemia during OLV should follow a sequence of steps tailored to the individual patient, procedure, and acuity (Box 11.4). These measures can be used prophylactically in high-risk patients.

Box 11.4: Treatments for Oxygen Desaturation During One-Lung Ventilation [2]

- **Severe desaturation:**
  - Resume two-lung ventilation on FIO_2 of 1.0 (if possible)
- **Gradual desaturation**
  - Increase FIO_2 to 1.0
  - Verify the position of lung isolation device with fiberoptic bronchoscopy
  - Optimize cardiac output—inotropes/vasopressors, ensure volatile <1 MAC, minimize IVC compression by the surgeon
  - Recruitment maneuver to the ventilated lung (may briefly increase shunt to non-dependent lung)
  - Apply PEEP at ≥5 cm H_2O to the ventilated lung (after a recruitment maneuver; except in patients with emphysema)
  - Apply CPAP 1–2 cm H_2O and FIO_2 1.0 to the non-ventilated lung (after recruitment)
  - Intermittent re-inflation of the non-ventilated lung
  - Partial ventilation techniques of the non-ventilated lung
    - Passive oxygenation
    - Lobar insufflation (see Fig. 11.4)
  - Lobar collapse (with a bronchial blocker)
  - Surgical obstruction of blood flow to operative lung

IVC, inferior vena cava; PEEP, positive end-expiratory pressure; CPAP, continuous positive airway pressure

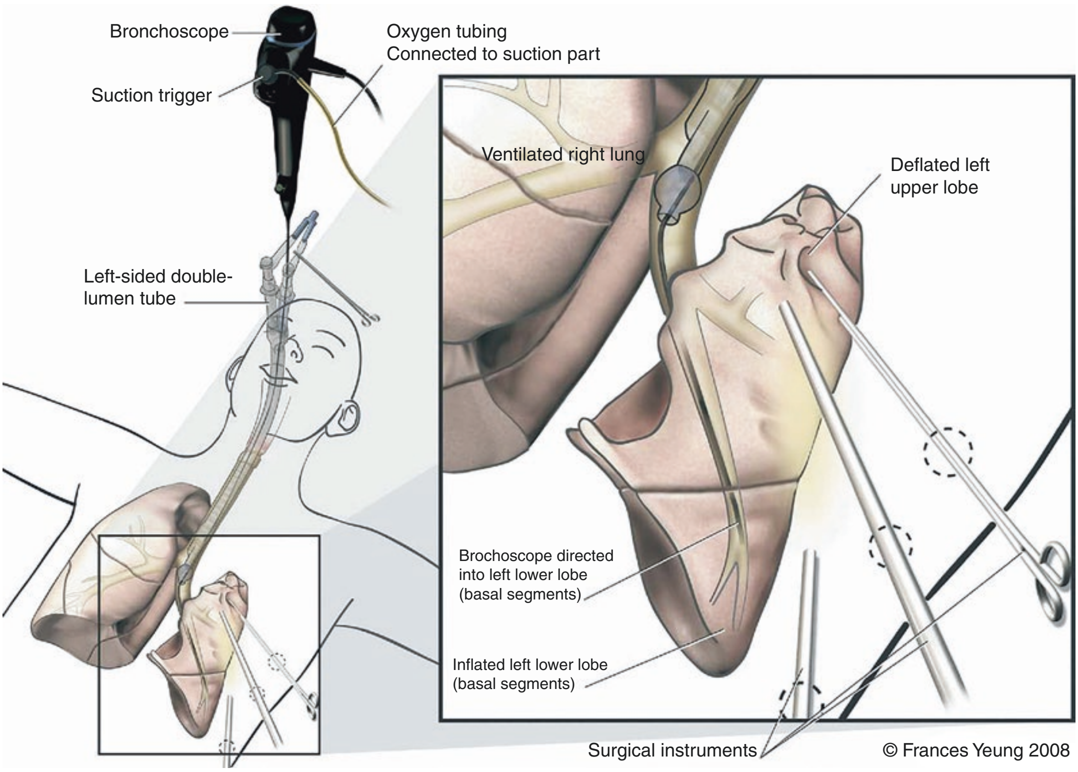

Fig. 11.4 Intermittent oxygen insufflation during thoracoscopic surgery to segments of the non-ventilated lung on the side of surgery using a fiberoptic bronchoscope. Reproduced with permission from: Slinger P. *Principles and practice of anesthesia for thoracic surgery*, New York, Springer, 2011

PEEP to the dependent lung is as effective as CPAP to the non-dependent lung for increasing PaO_2 levels during OLV [71]. CPAP can be applied through a DLT or bronchial blocker and interferes less in open than thoracoscopic surgery [72].

In refractory hypoxemia, intermittent partial ventilation of the operative lung can be administered through the DLT or blocker lumen. Selective insufflation of non-operative segments of the surgical lung is possible by directing the bronchoscope tip into such segments and intermittently compressing the suction port attached to oxygen tubing flowing at 5 L/min (Fig. 11.4) [73]. This technique is particularly useful in thoracoscopic surgery where surgical exposure is more affected by lung recruitment. A third technique is to selectively collapse the surgical lobe by the placement of a bronchial blocker into that lobar bronchus through an SLT or a DLT [74]. To limit shunt, the surgeon can obstruct blood flow to the non-ventilated lung, temporarily in emergencies or definitively in pneumonectomy or lung transplantation [75].

Avoiding potent vasodilators such as nitroglycerin, halothane, and large doses of volatiles will improve oxygenation during OLV [2]. Intravenous almitrine enhances HPV, prevents, and treats hypoxemia during OLV when anesthesia is maintained with propofol [76–78]. Inhaled nitric oxide (iNO) combined with intravenous phenylephrine improves oxygenation in ventilated intensive care unit patients with ARDS, which may translate to OLV [79].

11.10 Intravenous Fluid Management

Due to hydrostatic effects, endothelial and lymphatic dysfunction, intravenous fluids during lung cancer resection may lead to increased shunt

Box 11.5: Fluid Management Recommendations in Pulmonary Resection [2]

- Postoperative fluid balance in the first 24 h less than +20 mL/kg
- Administer under 3L of crystalloid to the typical adult patient in the first 24 postoperative hours
- Do not replace theoretical third-space losses
- Do not strive for urine output over 0.5 mL/kg/h
- Postoperatively, consider treating hypotension or hypoperfusion with inotropes rather than intravenous fluids

and pulmonary edema of the dependent lung. Excessive intravenous fluids are a well-established risk factor for postoperative acute lung injury, especially in pneumonectomy (Box 11.5) [59, 61, 80–82].

11.11 Surgical Procedures

11.11.1 Flexible Fiberoptic Bronchoscopy

Flexible fiberoptic bronchoscopy is performed perioperatively to confirm the cancer diagnosis, determine airway invasion by the tumor, and intraoperatively to verify airway anatomy during a test clamp of the surgical bronchus. Options include awake vs. general anesthesia and oral vs. nasal approaches. Effective topical anesthesia is crucial for the awake approach, with or without sedation or antisialogogues. Under general anesthesia, advantages of a supraglottic airway (SGA) technique include visualization of the vocal cords and subglottic structures, lower airway resistance versus an endotracheal tube, and the potential to maintain spontaneous ventilation in a patient with a difficult airway [83].

11.11.2 Rigid Bronchoscopy

Interventional rigid bronchoscopy with laser, tracheobronchial dilation, or stent placement is a common treatment of airway malignancies [84]. There are five basic methods of ventilation for rigid bronchoscopy:

1. **Spontaneous ventilation**—adults are much less likely than children to breathe effectively under this deep anesthetic
2. **Apneic oxygenation (high flow nasal prongs)**—requires thorough pre-oxygenation; still requires frequent surgical pauses for ventilation to clear CO_2 and maintain oxygen saturation
3. **Positive pressure ventilation via a ventilating bronchoscope**—attach the anesthesia circuit to a side port on the rigid bronchoscope; surgeon usually must interrupt the procedure and occlude the eyepiece; consider throat packs to limit air leaks.
4. **Jet ventilation**—via a handheld injector or with a high-frequency ventilator; risk of barotrauma and pneumothorax
5. **Intermittent rigid bronch removal**—ventilate by bag-mask ventilation, SGA, or ETT

These techniques are most useful with total intravenous anesthesia (often propofol and remifentanil) because volatile anesthetics involve unpredictable dosing and environmental contamination. It is crucial to maintain a deep plane of anesthesia, often with muscle relaxation, to mitigate risks of awareness, laryngospasm, bronchospasm, hemorrhage, and perforation in a tenuous, unprotected airway. In cases where a neodymium-doped yttrium aluminum garnet (Nd: YAG) laser is used, the inspired fraction of oxygen should be limited to mitigate the risk of airway fire. At induction, the surgeon must be present and prepared to establish airway control with the rigid bronchoscope. Effective team communication is paramount. Consider serial arterial blood gases to monitor oxygenation and ventilation. Highly edematous airways may require systemic steroids, helium, racemic epinephrine, or intubation at the end of the case [2].

11.11.3 Mediastinoscopy

Cervical mediastinoscopy is the traditional method for staging mediastinal lymph nodes in NSCLC. Chest imaging should be carefully reviewed preoperatively to assess airway compromise. Given the risks of coughing during this stimulating procedure, patients are typically managed with a deep general anesthetic, including paralysis, with an SLT. To monitor innominate artery compression and cerebral hypoperfusion, the pulse oximeter is typically placed on the right hand with the blood pressure cuff on the left arm.

The most feared complication of mediastinoscopy is hemorrhage. When mild this usually responds to tamponade by the surgeon, head-up position, and avoiding hypertension. Severe hemorrhage requires emergency management including invasive hemodynamic monitoring, volume and possibly blood transfusion (consider lower body venous access), and thoracotomy or sternotomy. Lung isolation can be achieved with a bronchial blocker or double-lumen tube [2]. Other potential complications include airway obstruction, pneumothorax, recurrent laryngeal or phrenic nerve injuries, esophageal injury, chylothorax, and air embolism [85].

11.11.4 Endobronchial Ultrasound-Guided Biopsy

Endobronchial ultrasound-guided biopsy (EBUS) has replaced mediastinoscopy for preoperative lung cancer staging [2, 86]. EBUS employs a radial probe through a channel of the fiberoptic bronchoscope to allow fine needle aspiration under direct vision [87]. In general, these patients are managed in a bronchoscopy suite with topical anesthesia, intravenous sedation, and possibly an anesthesiologist, depending on the complexity of the case.

11.11.5 Minimally Invasive Thoracoscopic Surgery

Advantages of pulmonary resection by video-assisted thoracoscopic surgery (VATS), compared to open thoracotomy, include: (1) decreased pulmonary complications and mortality in high-risk patients, (2) reduced hospital length of stay, (3) less blood loss and transfusion, (4) less pain (less rib spreading), (5) improvement in pulmonary function, (6) less atrial fibrillation, and (7) less inflammatory response [17, 88–91]. VATS lobectomy is performed with a limited number of incisions, the largest approximately 5 cm in length [92]. Bilateral VATS metastectomies may be performed in the supine position. The anesthesiologist must discuss with the surgeon the potential for conversion to open thoracotomy. While most VATS procedures are done under general anesthesia with lung isolation, minor procedures can be done under intercostal blocks or thoracic epidural with TLV [93, 94].

11.11.6 Robotic-Assisted Thoracic Surgery

Robotic thoracic surgery has been a logical advancement of VATS due to the perceived improve 3D vision and instrument mobility in the chest [95]. Anesthetic considerations are outlined in Box 11.6.

Box 11.6: Anesthetic Considerations for Robotic Thoracic Surgery [2]

- Establish a protocol for immediate undocking (<60 s) of the robot in case of intraoperative emergency
- Given limited patient access, confirm the position of the lung isolation device before docking the robot
- Extensions to intravascular lines and anesthesia circuit
- Increased intrathoracic CO_2 insufflation with hypercarbia and hemodynamic compromise

- Take measures to prevent movement of the OR table during the robotic procedure
- Risk of neuropathies if lateral position prolonged
- Judicious intravenous fluids

11.11.7 Lobectomy

Lobectomy is the standard approach to lung cancer resection to reduce local recurrence. Lobectomy is being increasingly performed via a VATS approach vs. an open thoracotomy. The local invasion may be required that an elective lobectomy be converted intraoperatively to a bi-lobectomy (right lung) or pneumonectomy (left lung). Surgeons may request that a variable degree of positive airway pressure be used to assess the integrity of the bronchial stump. Uncomplicated patients can usually be extubated in the operating room [2].

Sleeve lobectomy is a parenchyma-sparing mainstem bronchial resection, typically for bronchogenic carcinoma. This technique has lower morbidity and mortality as compared to pneumonectomy in patients with lung cancer [96, 97]. The airway management requires the placement of a contralateral DLT or an endobronchial tube. For carinal resections, options include cross-field ventilation with a sterile circuit and endobronchial tube or high-frequency jet ventilation. For resection of major vessels, heparinization may be necessary. Hence, epidural catheter manipulation needs to be avoided for around 24 h. During pulmonary arterioplasty, massive hemorrhage may occur.

11.11.8 Pneumonectomy

Pneumonectomy for lung cancers requires posterolateral thoracotomy. After removing the lung, it is crucial to test for air leaks from the lung before reconstructing the bronchial stump which should be kept shorter to minimize the accumulation of secretions. The empty thoracic cavity after pneumonectomy remains a potential source of complications like a mediastinal shift with hemodynamic collapse. Surgical drain and application of suction may lead to exacerbation of mediastinal shift. The management of post-pneumonectomy thoracic space is not well elucidated. The management options for preventing complications related to the empty thoracic space include either not placing a chest tube or placing a dedicated post-pneumonectomy chest drainage system. This is a specially designed drain which has both high- and low-pressure under-water relief valves and thus prevents mediastinum shift [2]. A postoperative chest X-ray should be done after pneumonectomy.

Pneumonectomy carries significantly greater risk than a lobectomy. The perioperative mortality rate after pneumonectomy for NSCLC is approximately 5–8% [98, 99]. The risk of complications increases with lesser surgical case volume and patients more than 65 years of age [100]. The risk of complications increases fivefold in patients over age 65. The greatest morbidity post pneumonectomy is ALI, with an incidence of 4–18% and mortality greater than 50% [58, 66]. The risk is greater after right-sided pneumonectomy due to increased pulmonary vascular resistance and right ventricular failure after right pulmonary artery ligation [101].

Airway management strategy includes the use of a DLT on the contralateral side. In case same sided DLT is required, then it should be withdrawn during bronchial stapling. Extubation should be done after surgery and postoperative mechanical ventilation should be avoided to prevent the dehiscence of the bronchial stump. Anesthetic strategies to mitigate the risk of perioperative acute lung injury (ALI) are especially critical to pneumonectomy patients (see Sects. 11.9 and 11.10). The preventive strategies include lower tidal volumes, airway pressures along with an optimal PEEP and FiO_2. The fluid management should be done judiciously using restrictive fluid administration (prevention of fluid overload) and judicious vasopressors/inotropes to maintain hemodynamics if required.

Extrapleural pneumonectomy is typically performed for malignant pleural mesothelioma but may have a role in the pleural spread of other cancers [102]. This is an extensive procedure requiring clearance of lymph nodes, pericardium, diaphragm, parietal pleura, and chest wall. The key points for anesthetic management include the potential for significant bleeding, coagulopathy, and appropriate blood product use. Postoperative cardiac herniation can cause severe hemodynamic instability. In cases of postoperative mechanical ventilation due to extensive surgery, a single endotracheal tube should replace the DLT at the end of the surgery.

11.11.9 Limited Pulmonary Resections: Segmentectomy and Wedge Resection

Segmentectomy in lung cancer patients refers to resection of a segment of the lung lobe along with its artery, vein, and bronchus. It is an indicated technique in primary lung cancer patients with limited cardiorespiratory reserves. The other pulmonary resection includes wedge resection which is a non-anatomical resection of the part of lung parenchyma having the tumor lesion. These types of resections are usually reserved for the patient with associated comorbidities and peripherally located tumor masses [2]. Limited resections are best performed for peripheral cancers, especially in patients with previous contralateral pulmonary resections [2]. The principles of perioperative care including anesthetic management remain the same as for other major lung resections with the additional strategy for management of associated comorbidities. A selective lobar collapse with a bronchial blocker may be considered in patients with poor cardiorespiratory reserves [103].

11.12 Postoperative Analgesia

Various sensory afferents transmit nociception following thoracotomy. The pain generators during thoracotomy for lung cancers are intercostal nerves T4-6 due to surgical incision; vagus nerve due to surgical handling of pleura; phrenic nerve due to the handling of diaphragmatic pleura; and brachial plexus [104]. Therefore, analgesia should be multimodal. Compared to thoracotomy, there is very little consensus on analgesic techniques for VATS procedures [105, 106]. Effective perioperative analgesia is crucial for the prevention of pulmonary complications and chronic post-thoracotomy pain and a multimodal approach of analgesics is preferred [107].

11.12.1 Systemic Medications

11.12.1.1 Opioids

The patients of cancer may have basal pain and may be managed using pharmacological agents as per pain assessment and its severity. The surgical interventions require additional analgesics. Cautious use of opioids is desirable to avoid respiratory sedation in lung cancer patients after lung resections. The dynamic nature of pain due to breathing movements needs to be managed using appropriate measures [108].

11.12.1.2 Non-steroidal Anti-inflammatory Drugs (NSAIDs)

NSAIDs and acetaminophen remain an important component of the perioperative analgesia in lung cancer patients. It has an opioid-sparing effect and is devoid of respiratory depressive effect. These agents are effective for ipsilateral shoulder pain frequently missed by epidural analgesia. The side effects of NSAIDs platelet dysfunction, gastric erosions, increased bronchial reactivity, and renal dysfunction need to be kept in mind when being used in patients for pain management [2]. Acetaminophen has weak COX inhibition and remains useful with a good safety profile for analgesia [109].

11.12.1.3 Ketamine

Ketamine is an NMDA antagonist with an established role in multimodal post-thoracotomy analgesia through both intravenous and epidural routes. However, the evidence is mixed on its ability to prevent chronic post-thoracotomy pain [110]. Potential psychomimetic effects can be minimized by using sub-anesthetic doses and supplementing with benzodiazepines.

11.12.2 Local Anesthetic Drugs and Regional Nerve Blocks

11.12.2.1 Intercostal Nerve Blocks

Intercostal nerve blocks remain an easy and effective analgesic technique for thoracotomies or VATS. The block can be administered either percutaneously or under direct vision during surgical exposure. Ultrasound has emerged as an important modality for these blocks. These are good for acute pain but may be limited by short duration. The use of a continuous approach using catheter placement is reported but catheter placement is difficult [111]. Also, the systemic absorption remains a concern and thus doses should be appropriately calculated.

11.12.2.2 Epidural Analgesia

Thoracic epidural analgesia (TEA) technique is one of the most studied, well-proven, and considered as the gold standard techniques for the management of pain during thoracotomy [12, 112]. While the paramedian approach may facilitate insertion, ultrasound guidance has not established its place for mid-thoracic epidurals [113]. Local anesthetics and opioids (e.g., sufentanil or fentanyl) synergistically improve perioperative analgesia [114]. More hydrophilic opioids such as morphine should be considered for procedures spanning a large number of dermatomes due to greater CSF spread. Fortunately, bupivacaine 0.25% via TEA does not impair respiratory mechanics, including patients with severe COPD [115].

There is an ongoing debate about the merits of TEA for VATS procedures. Despite smaller incisions, patients report a similar rate of chronic postoperative pain to thoracotomy. This may be related to similar intercostal nerve trauma [116]. Current evidence does not support a single regional analgesic strategy for VATS procedures [106]. Patients with low pulmonary reserve, chronic pain issues, or a high chance of converting to a thoracotomy may benefit most from TEA.

11.12.2.3 Paravertebral Block

Paravertebral blockade (PVB) involves the injection into a wedge-shaped potential space bordered anteriorly by the parietal pleura, medially by the vertebral bodies and intervertebral foramen, and posteriorly by the superior costotransverse ligament. Local anesthetics cause ipsilateral somatic and sympathetic blockade of multiple spinal levels [117]. Co-administration of paravertebral dexmedetomidine can augment analgesia [107]. The block can be performed under direct vision by the surgeon and/or a percutaneous approach from behind the patient, usually with catheter placement to prolong analgesia. Ultrasound guidance for the percutaneous approach has the potential to increase efficacy and decrease complications such as pneumothorax [118, 119].

For thoracotomy, multiple studies claim that PVB provides comparable analgesia to TEA with fewer complications including hypotension, urinary retention, nausea and vomiting, block failure, arrhythmia, ICU admission, and neuraxial hematoma [120–122]. However, a recent Cochrane Review demonstrated that compared to TEA, PVB is associated with comparable perioperative mortality and major complications [123]. The relative impact on postoperative respiratory function and chronic pain is unclear [120, 121, 123, 124]. For VATS procedures, single-shot paravertebral local anesthetics can reduce pain for up to six hours [125].

11.12.2.4 Erector Spinae Plane (ESP) Block

ESP block has emerged as an effective fascial plane block in recent times with potential application to acute pain management for both thoracotomy and VATS procedures (Fig. 11.5) [126]. It involves ultrasound-guided injection of local anesthetics into the tissue plane deep to the erector spinae muscle superficial to the transverse process to cover the dorsal and ventral rami of thoracic spinal nerves [127].

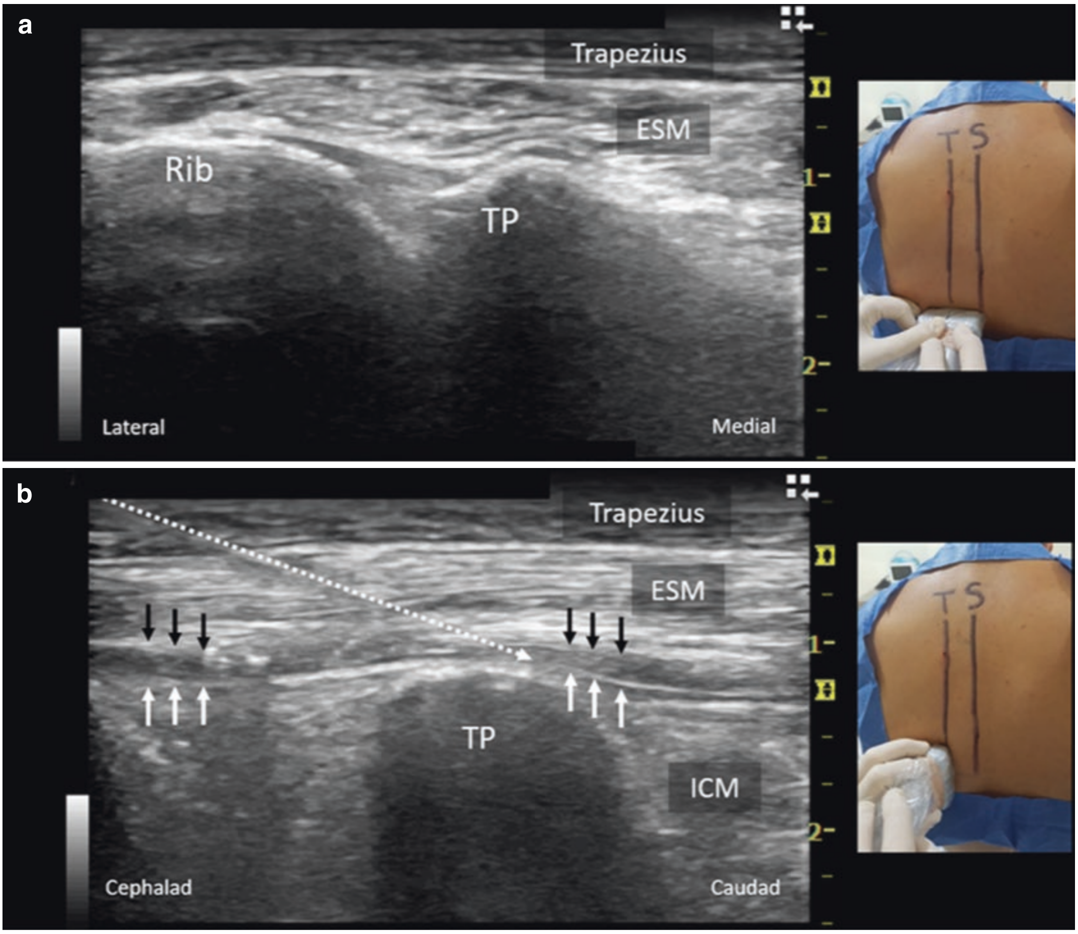

Fig. 11.5 Sonoanatomy and technique of the erector spinae plane (ESP) block. (**a**) The probe is placed lateral to the spinous processes (line S) to obtain a transverse view of the tip of the transverse process (TP) and rib with the overlying trapezius and erector spinae muscle (ESM). (**b**) The probe is rotated into a longitudinal orientation to obtain a parasagittal view of the tips of the TPs (line T), and the block needle (dotted arrow) is advanced in a cephalo-caudad direction to contact the TP. Correct needle tip position is signaled by the linear spread of local anesthetic (solid arrows) deep to the ESM and superficial to the TP and intercostal muscle (ICM). Reproduced with permission from Forero M, Rajarathinam M, Adhikary S, Chin KJ. *Erector spinae plane (ESP) block in the management of post-thoracotomy pain syndrome: A case series*. Scand J Pain. 2017

11.12.3 Postoperative Pain Management Problems

11.12.3.1 Shoulder Pain

Postoperative ipsilateral shoulder pain is very common after VATS and thoracotomy, even with a functioning epidural. It is thought to be caused primarily by diaphragmatic irritation referred to by phrenic nerve afferents [109]. Other causes of shoulder pain should be considered, including chest drains placed too deeply, inadequate coverage of the posterior thoracotomy incision by TEA, chronic pain, and referred pain from myocardial ischemia [2].

Pre-emptive acetaminophen decreases postoperative shoulder pain scores [109]. Increasing epidural medications is usually ineffective. Low volume interscalene block and phrenic nerve injection are effective but carry significant respiratory risks [104, 128]. Otherwise systemic opioids and/or NSAIDs should be considered.

11.12.3.2 Opioid Tolerant Patients

Opioid tolerant patients present significant challenges in lung cancer surgery. Patients may be using prescribed opioids for thoracic pathology, other chronic pain syndromes, be active narcotic abusers, or in rehabilitation receiving daily methadone. Patients should take their regular analgesics perioperatively, otherwise, substitute opioids must be provided. Perioperative opioid requirements are variably increased.

Multimodal analgesia is optimal. Typically, both epidural and systemic opioids are increased to mitigate withdrawal. Fixed dosing is likely superior to patient-controlled techniques, which can lead to the escalation of doses and challenges discharging patients. It is crucial to set realistic expectations that pain scores will be limited by baseline pain levels. Supplemental analgesia options include adding epinephrine 5 ug/mL to the epidural solution and low dose intravenous ketamine [129].

11.12.4 Postoperative Complications

11.12.4.1 Empyema

Empyema is one of the postoperative complications after lung surgeries and is observed in 2–16% of cases of lung cancer resections. It is associated with increased mortality by around 40% as well which is more commonly seen in patients who develop a bronchopleural fistula [2]. Treatment options for empyema include open or VATS decortication, open window thoracostomy, and in less severe cases, tube drainage and systemic antibiotics [130].

Anesthetic management for invasive procedures includes early lung isolation in the supine position to protect from contralateral soiling. A DLT is preferable to facilitate bilateral pulmonary toileting. The risk of massive hemorrhage mandates large-bore IV access, an arterial line, and potentially a central venous line for vasopressors. Patients frequently present with sepsis. Therefore, one must carefully weigh the risks and benefits of a thoracic epidural.

11.12.4.2 Bronchopleural Fistula

A bronchopleural fistula (BPF) may be caused by (1) rupture of a lung abscess or airway into the pleural space, (2) erosion by cancer or inflammation, or (3) dehiscence of a bronchial stump suture line. BPF occurs in 4–20% of pneumonectomy patients compared to <1% of lobectomy patients, with a mortality of up to 70% [131, 132]. BPF is a clinical diagnosis which may include acute dyspnea, subcutaneous emphysema, persistent air leak, contralateral deviation of the trachea, and purulent drainage. The diagnosis is confirmed by bronchoscopy, and less commonly bronchography, sinograms, indicator injection into the pleural space, or inhaled gases to detect transfer across the fistula [133].

Early post-pneumonectomy BPF can be life-threatening and require re-suturing of the bronchial stump. Late post-pneumonectomy BPF is managed with chest tube drainage or a Clagett procedure, which also includes a muscle flap to reinforce the stump. In non-pneumonectomy cases, if the lung fully expands, chest tube suction can usually resolve the air leak. However, in large fistulae with a persistent pneumothorax, surgical resection is usually necessary. Non-surgical treatments include OLV and differential lung ventilation, including high-frequency ventilation, PEEP to the pleural cavity equal to intrathoracic PEEP, unidirectional chest tube valves, and one-way endobronchial valves (for patients unfit for surgery) [134].

Preoperatively, a large BPF is detected through continuous air bubbling through the chest drain or discrepancies in inhaled versus exhaled tidal volumes through spirometry in an intubated patient. The larger the leak, the more crucial it is to establish early and effective lung isolation.

A pre-induction chest drain is mandatory. The main anesthetic goal is to achieve lung isolation before positive pressure ventilation to minimize the risk of tension pneumothorax and contamination of the contralateral lung. One general option is to maintain spontaneous ventilation, either through an inhalational induction, titrated intravenous induction, or awake fiberoptic intubation with airway topicalization. Another general option is to perform "rapid sequence lung isolation," which includes thorough pre-oxygenation, pre-calculated doses of induction drugs and muscle relaxants, then immediate intubation without bag-mask ventilation. Patients are likely to desaturate rapidly and subsequent bag-mask ventilation can be ineffective due to oxygen passing through the fistula instead of the contralateral lung. Therefore, the "rapid sequence" method should be reserved for experienced hands with airway adjuncts (e.g., video laryngoscope) in patients with generally reassuring airway exams.

A DLT is ideal for lung isolation, airway toileting, and visualization of the affected bronchus, but likely too traumatic for awake fiberoptic intubation. Patients with difficult airways may be better managed with a single-lumen awake intubation, with either a contralateral endobronchial tube or a bronchial blocker pushed into the affected bronchus. Airway placement should always be guided by bronchoscopy to ensure accuracy and minimize trauma. Bronchial blockers are generally not compatible with the bronchial stump post pneumonectomy. Early extubation avoids prolonged positive pressure to the stump.

The thoracic epidural anesthesia with intravenous sedation has been used for minimally invasive BPF repair post pneumonectomy [135]. Pitfalls include incomplete visceral coverage by the epidural and potential contamination of unprotected contralateral airways. An alternative method is high-frequency oscillatory ventilation with permissive hypercapnia, which can minimize barotrauma to the non-operative lung, decrease bronchopleural fistula air leak, and optimize the operative outcome [136].

11.12.4.3 Atrial Fibrillation

Atrial fibrillation (AF) is one of the common cardiac complications and is seen in almost 46% post pneumonectomy patients [137]. Theoretical mechanisms include surgical inflammation, catecholamine surge, myocardial ischemia, and autonomic imbalance [138]. Postoperative AF is associated with increased length/cost of hospital stay, morbidity, mortality, and stroke risk [139, 140].

A recent systematic review and meta-analysis determined that the most effective pharmacologic AF prophylaxis, in descending order, is through: beta-blockers > ACE inhibitors > amiodarone > magnesium > statins > calcium channel blockers > digoxin [137]. Intraoperative prophylaxis can be complicated by hemodynamic instability including epidural use and the risk of residual neuromuscular blockade, therefore should be administered on a case-by-case basis.

11.12.4.4 Cardiac Herniation

An acute cardiac herniation is one of the rare complications after lung surgeries especially pneumonectomy or with pericardial involvement [141]. It usually manifests with pericardial closure dehiscence within 24 h postoperatively. This is associated with increased mortality by almost 50% [142]. It typically results from pressure differences in the two hemi-thoraces after chest closure. The superior vena cava syndrome and profound shock may be seen in cardiac herniation after right lung removal [143]. Herniation after left pneumonectomy may manifest arrhythmias and features suggestive of ventricular outflow tract obstruction.

A cardiac herniation is a surgical emergency. Also, the differential diagnosis like massive intrathoracic hemorrhage, tension pneumothorax, and pulmonary embolism needs to be considered with patients manifesting acute symptoms in the postoperative period. While mobilizing the patient to the operating room for thoracotomy and definitive repair, management includes securing the airway with a single-lumen tube (address lung isolation once surgical control is established), positioning the patient lateral decubitus with the surgical side up, hemodynamic support with inotropes and invasive monitors, and minimizing suction to the affected hemithorax. Intraoperative TEE can help prevent excessive compression of heart chambers by surgical repair [2]. These patients should remain intubated to recover in the intensive care unit.

11.13 Summary

Resectable lung cancers are associated with various regional mass effects, paraneoplastic syndromes, and neoadjuvant therapies which greatly impact anesthetic management. Anesthesia for lung cancer surgeries involves many challenges including one-lung ventilation in patients with limited pulmonary reserve, complex airway management, and critical analgesia to facilitate postoperative recovery. Preoperative assessment of the patient's mechanical and parenchymal lung function, as well as cardiopulmonary interaction, stratifies the risk of perioperative complications. The thoracic anesthetist requires strong knowledge of bronchoscopic anatomy for effective lung isolation and surgical exposure. It is crucial to have an organized approach to managing hypoxemia during one-lung ventilation, both during thoracoscopic and open chest surgery.

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