Update on anesthetic management for pneumonectomy
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Purpose of review
Pneumonectomy has the highest perioperative risk among common pulmonary resections. The purpose of this review is to update clinicians on the importance of anesthetic management for these patients.

Recent findings
Two complications associated with increased perioperative mortality are relevant to anesthetic management: postoperative arrhythmias and acute lung injury. The geriatric population is particularly at risk for arrhythmias. Adequate preoperative cardiac assessment and drug prophylaxis may decrease this risk. Patients with decreased respiratory function are at increased risk for acute lung injury. The use of large tidal-volume ventilation during anesthesia may increase this risk. There is a trend to better outcomes in centers with larger surgical volumes.

Summary
Patients should have a preoperative assessment of their respiratory function in three areas: lung mechanical function, pulmonary parenchymal function and cardiopulmonary reserve. Interventions that have been shown to decrease the incidence of respiratory complications include cessation of smoking, physiotherapy and thoracic epidural analgesia. Extrapleural pneumonectomy and sleeve pneumonectomy are surgical variations that place specific increased demands on the anesthesiologist. The rare but treatable complication of cardiac herniation must always be remembered as a potential cause of life-threatening hemodynamic instability in the early postoperative period.

Keywords
pneumonectomy, pulmonary resection, thoracic anesthesia

Introduction
Complete removal of the lung is required when a lobectomy or its modifications is not adequate to remove the local disease or ipsilateral lymph node metastases or both. Atelectasis and pneumonia occur following pneumonectomy as they do following lobectomy but may in fact be less of a problem due to the absence of residual parenchymal dysfunction on the operative side. However, the mortality rate following pneumonectomy exceeds that for lobectomy because of postoperative cardiac complications and acute lung injury. The overall operative mortality for the first 30 days after pneumonectomy ranges from 5 to 13%, and correlates inversely with the surgical case volume [1*].

Preoperative assessment
The best assessment of respiratory function comes from a history of the patient’s quality of life [2]. It is useful to have objective measures of pulmonary function that can be used to guide anesthetic management and to have this information in a format that can be easily transmitted between members of the healthcare team. There are many factors that determine overall respiratory performance. It is useful to think of respiratory function in three related but somewhat independent areas that are as follows: respiratory mechanics, gas exchange and cardiorespiratory interaction.

Respiratory mechanics
Many tests of respiratory mechanics and volumes show correlation with postthoracotomy outcome. It is useful to express these as a percentage of predicted volumes corrected for age, sex and height [e.g. forced expiratory volume in one second (FEV1%)]. Of these, the most valid single test for postthoracotomy respiratory complications is the predicted postoperative forced expiratory volume in one second (ppoFEV1%) [3**] that is calculated as:

\[
ppoFEV1\% = \text{preoperative FEV1}\% \times \left(1 - \frac{\%\text{functional lung tissue removed}}{100}\right)
\]

(Usually, the right lung can be estimated to contribute 52–55% and the left 45–48% to FEV1.)
Nakahara et al. [4] found that patients with a ppoFEV1 more than 40% had no or minor postresection respiratory complications. Major respiratory complications were only seen in the subgroup with ppoFEV1 less than 40%, and patients with ppoFEV1 less than 30% required postoperative mechanical ventilatory support. The use of epidural analgesia has decreased the incidence of complications in the high-risk group [5].

Lung parenchymal function
Arterial blood gas data such as PaO2 less than 60 mmHg or PaCO2 more than 45 mmHg have been used as cutoff values for pulmonary resection. Cancer resections have now been successfully done or even combined with volume reduction in patients who do not meet these criteria [6]. The most useful test of the gas exchange capacity of the lung is the diffusing capacity for carbon monoxide (DLCO). The DLCO correlates with the total functioning surface area of alveolar–capillary interface. The DLCO can be used to calculate a postresection (ppo) value using the same calculation as for the FEV1. A ppoDLCO less than 40% predicted correlates with both increased respiratory and cardiac complications and is relatively independent of the FEV1 [7**].

Cardiopulmonary interaction
The most important test of respiratory function is an assessment of the cardiopulmonary interaction. The traditional test is stair climbing [8]. The ability to climb three flights or more is closely associated with decreased mortality and morbidity. The ability to climb less than two flights is associated with very high risk. Formal laboratory exercise testing with maximal oxygen consumption (VO2max) is the ‘gold standard’ for assessment of cardiopulmonary function. Climbing five flights of stairs approximates a VO2max value of more than 20 ml/kg/min and less than one flight a VO2max value of less than 10 ml/kg/min [9]. In a high-risk group of patients (mean preoperative FEV1 = 41% predicted), there was no perioperative mortality if the preoperative VO2max value was more than 15 ml/kg/min [10]. Alternatives to VO2max include the 6-min walk test [11] and exercise oximetry [12].

Thoracotomy is normally considered an intermediate-risk procedure for cardiac complications [13]. However, in the elderly, thoracotomy should be considered a high-risk procedure for cardiac complications, and cardiopulmonary function is the most important part of the preoperative assessment. Although the mortality after lobectomy among the elderly is acceptable, the mortality from pneumonectomy, particularly right pneumonectomy, is excessive [14**]. The in-hospital mortality following pneumonectomy is double in patients aged 65–75 years vs. a younger population and triple in patients aged more than 75 years [15]. The limiting factor in lung resection in the elderly seems to be the ability of the geriatric right ventricle to deal with the increased afterload due to lung resection [16]. Exercise tolerance seems to the primary determinant of outcome in the elderly [17]. The American College of Cardiology/American Heart Association (ACC/AHA) [18*] guidelines suggest that with ‘adequate functional capacity’ [i.e. 4 metabolic equivalents (METs) or one flight stair climbing] patients with ‘intermediate’ predictors of coronary artery disease do not need further cardiac assessment. However, this recommendation should not be extrapolated to elderly patients. The elderly should also have, as a minimum cardiac investigation, a transthoracic echocardiogram, to rule out pulmonary hypertension [19] and myocardial perfusion imaging with intermediate indicators of coronary artery disease. Diltiazem is the most useful prophylactic drug to prevent postthoracotomy supraventricular arrhythmias [20*].

Ventilation-perfusion (V/Q) scintigraphy
Prediction of postresection pulmonary function can be further refined by assessment of the preoperative contribution of the lung to be resected using V/Q lung scanning [21*]. If the lung to be resected is minimally functioning, the prediction of postoperative function can be modified accordingly. This is particularly useful in pneumonectomy patients and should be considered for any patient who has a ppoFEV1 less than 40%. Other tests of pulmonary function such as split-lung function studies and flow-volume loops have not shown sufficient predictive validity for universal adoption in potential lung resection patients.

Combination of tests
No single test of respiratory function has shown adequate validity as a sole preoperative assessment tool. Prior to surgery, an estimate of respiratory function in all three areas—lung mechanics, parenchymal function and cardiopulmonary interaction—should be made for each patient. These form the ‘three-legged stool’ of preoperative respiratory assessment for pulmonary resection (see Fig. 1) [22]. If a patient has a ppoFEV1 more than 40%, it should be possible for that patient to be extubated in the operating room at the conclusion of surgery assuming the patient is alert, warm and comfortable (AWaC). If the ppoFEV1 is more than 30% and exercise tolerance and lung parenchymal function exceed the increased risk thresholds, then extubation in the operating room may be possible depending on the status of associated diseases (see Fig. 2) [22]. Those patients in this subgroup who do not meet the minimal criteria for cardiopulmonary and parenchymal function should be considered for staged weaning from mechanical ventilation postoperatively so that the effect of the increased oxygen consumption of spontaneous ventilation can be assessed. Patients with a ppoFEV1 of 20–30% and favorable predicted
Figure 1 The ‘three-legged’ stool of prethoracotomy respiratory assessment

![Image of the three-legged stool diagram](image)

DLCO, diffusing capacity for carbon monoxide; FVC, forced vital capacity; MVV, maximum voluntary ventilation; ppo, predicted postoperative; RV/TLC, residual volume/total lung capacity. Reproduced from [22].

Figure 2 Anesthetic management as guided by preoperative assessment and the amount of functioning lung tissue removed during surgery

![Image of the post-thoracotomy anesthetic management diagram](image)

DLCO, diffusing capacity for carbon monoxide. Reproduced from [22].
Surgical procedure
Thoracotomy for pneumonectomy is usually performed through a standard posterolateral chest incision. The mediastinal pleura are incised and the pulmonary artery, the superior and inferior pulmonary veins, and the mainstem bronchus are evaluated for resectability. After all vessels are stapled, stapling of the bronchus occurs, and the entire lung is removed from the chest. A test for air leaks is generally performed at this point, and reconstruction of the bronchial stump is completed. The bronchial stump should be as short as possible to prevent a pocket for the collection of secretions.

There is no consensus among thoracic surgeons on the best method of management of the postpneumonectomy space. If suction is applied to an empty hemithorax or a chest drain is connected to a standard underwater-seal system, it may cause a mediastinal shift with hemodynamic collapse. Some thoracic surgeons do not place a chest drain after a pneumonectomy. Some thoracic surgeons prefer to use a temporary drainage catheter to add or remove air. The removal of air, ranging from 0.75 up to 1.5 l, is necessary to empty the chest and to keep the mediastinum (balanced) and the trachea in the midline. Some surgeons place a specifically designed postpneumonectomy chest drainage system with both high-pressure and low-pressure underwater relief valves to balance the mediastinum [24]. A chest radiographic examination is mandatory after the patient arrives in the postanesthesia care unit or in the surgical intensive care unit to assess the mediastinal shift.

Anesthetic management
The patient scheduled to undergo a pneumonectomy is considered at increased risk for perioperative morbidity and mortality. Patients undergoing a pneumonectomy commonly receive a thoracic epidural catheter for postoperative analgesia, unless there is a contradiction. The placement of a large bore intravenous (i.v.) line is necessary in case blood products need to be administered. An invasive arterial line is placed for measurement of beat-to-beat blood pressure and to monitor arterial blood gases. A central venous pressure catheter is recommended to help guide intravascular fluid management, specifically in the postoperative period.

A major lung resection, such as pneumonectomy, decreases ventilatory function and has significant effects on the right ventricular function [25]. Immediately after pneumonectomy, the right ventricle may dilate and the right ventricular function decreases. Increased right ventricular after-load is due to an increase in pulmonary artery pressure and pulmonary vascular resistance. This is considered to be one of the main causes of right ventricular dysfunction after a major lung resection.

Management of lung isolation in a pneumonectomy patient can be achieved with a double-lumen endobronchial tube (DLT), bronchial blocker or single-lumen endobronchial tube. When using a DLT for a pneumonectomy patient, it is optimal to use a device that does not interfere with the ipsilateral airway (i.e. for a left pneumonectomy, a right-sided DLT). If a left-sided DLT or bronchial blocker is used for a left pneumonectomy, it must be withdrawn prior to stapling the bronchus in order to avoid accidental inclusion into the suture line.

Specific areas of concern in the management of the patient undergoing pneumonectomy include fluid management, intraoperative tidal volume and acute lung injury postsurgery. Fluid administration after major lung resection continues to be an issue. In an early retrospective report [26], the risk factors that were identified for the development of acute lung injury (‘postpneumonectomy pulmonary edema’) were a right-sided pneumonectomy, increased perioperative i.v. fluid administration and increased urine output in the postoperative period. A more recent study has shown that the excessive administration of i.v. fluids in thoracic surgical patients (more than 3 l in the first 24 h) is an independent risk related to an acute lung injury [27]. There is reasonable clinical evidence that excessive fluid administration is associated with the development of an acute lung injury, which has a high mortality rate following pneumonectomy [28]. Consequently, pneumonectomy patients should have restricted intraoperative fluid administration while preserving renal function. Some cases might require the use of inotropes/vasopressors to maintain hemodynamic stability while restricting fluids. The list given below gives fluid management for pneumonectomy.

1. Total positive fluid balance in the first 24 h perioperative period should not exceed 20 ml/kg.
2. For an average adult patient, crystalloid administration should be limited to less than 3 l in the first 24 h.
3. No fluid administration for third space fluid losses during pulmonary resection.
4. Urine output more than 0.5 ml/kg/h is unnecessary.
5. If increased tissue perfusion is needed postoperatively, it is preferable to use invasive monitoring and inotropes rather than to cause fluid overload.
Table 1  Suggested ventilation parameters for one-lung ventilation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Suggested</th>
<th>Guidelines/exceptions</th>
</tr>
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<tbody>
<tr>
<td>Tidal volume</td>
<td>5–6 ml/kg</td>
<td>Maintain</td>
</tr>
<tr>
<td>PEEP</td>
<td>5 cm H₂O</td>
<td>Peak airway pressure &lt; 35 cm H₂O</td>
</tr>
<tr>
<td>Respiratory rate</td>
<td>12 per minute</td>
<td>Plateau airway pressure &lt; 25 cm H₂O</td>
</tr>
<tr>
<td>Mode</td>
<td>Volume or pressure controlled</td>
<td>Patients with COPD, no added PEEP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maintain normal PaCO₂, Pa-et CO₂ will usually increase 1–3 mmHg during OLV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pressure control for patients at risk of lung injury (bullae, pneumonectomy, postlung transplantation, etc.)</td>
</tr>
</tbody>
</table>

COPD, chronic obstructive pulmonary disease; OLV, one-lung ventilation; PEEP, positive end-expiratory pressure.

Respiratory failure is a leading cause of postoperative morbidity and mortality in patients undergoing pneumonectomy. Patients with decreased respiratory function (FEV₁ or DLCO) are particularly at risk [29]. A retrospective report [30] involving 170 pneumonectomy patients showed that patients that received median tidal volumes greater than 8 ml/kg had a greater risk of respiratory failure in the postoperative period after pneumonectomy. In contrast, patients that received tidal volumes less than 6 ml/kg were at lower risk of respiratory failure. Schilling et al. [31] have shown that a tidal volume of 5 ml/kg during one-lung ventilation (OLV) significantly reduces the inflammatory response of alveolar cytokines. Considering these factors, it is prudent to use lower tidal volumes (i.e., 5–6 ml/kg, ideal body weight) in the pneumonectomy patient and limit peak and plateau inspiratory pressures (i.e., <35 and 25 cm H₂O, respectively) during OLV (see Table 1).

The incidence of acute lung injury (postpneumonectomy pulmonary edema) after pneumonectomy is only 4%. However, the mortality rate is 30–50%. The cause seems multifactorial. One study [27] has identified four independent risk factors for acute lung injury after pulmonary resection; these include pneumonectomy, excessive administration of fluids in the intraoperative period, high intraoperative ventilatory pressure index (combined airway pressure and time), and preoperative alcohol abuse. The incidence of an acute lung injury is greater for a right-sided vs. left-sided pneumonectomy. The presentation is biphasic. The primary form has a clinical onset during the first 72 h. The secondary, or late, form appears after 72 h and is usually related to other complications such as aspiration, bronchopleural fistula, or surgical complications. At the present time, only symptomatic management is appropriate. This includes fluid restrictions, diuretic administration, low ventilatory pressures and tidal volumes (if mechanical ventilation is used) and measures to decrease the pulmonary artery pressure. Although pneumonectomy is associated with mild postoperative pulmonary hypertension during exercise, right ventricular systolic function is usually minimally affected [32].

**Extrapleural pneumonectomy**

Extrapleural pneumonectomy is a therapeutic option for selected patients with malignant pleural mesothelioma [33]. Significant improvement in survival has been achieved in patients who have an advanced malignant pleural mesothelioma with extrapleural pneumonectomy and high-dose radiotherapy in the postoperative period. Extrapleural pneumonectomy involves an extensive resection that may include lymph nodes, pericardium, diaphragm, parietal pleura and the chest wall. The anesthetic management of the extrapleural pneumonectomy patient is characterized by significant loss of blood due to chest-wall vessel involvement. In these patients, it is recommended that a central venous pressure catheter be used to guide intravascular fluid administration and insure large-bore i.v. access. During tumor dissection, venous return to the heart maybe compromised due to multiple factors including blood loss, compression effect by the tumor in superior vena cava or surgical causes. If excessive bleeding ensues, it must be replaced to maintain an acceptable hematocrit and the coagulation profile kept within normal limits. Because of extensive tumor resection and the potential for a pericardial resection in right-sided surgery, cardiac herniation or hemodynamic instability can appear postoperatively after the patient is turned from lateral decubitus to supine position. It is common to ventilate these patients for a short period postoperatively due to the extended duration of the surgery and the large fluid shifts. If a DLT is used intraoperatively, the DLT is usually replaced at the end of the case with a single-lumen endotracheal tube.

**Sleeve pneumonectomy**

Tumors involving the most proximal portions of the mainstem bronchus and the carina may require a sleeve pneumonectomy. These are most commonly performed for right-sided tumors and can usually be performed without cardiopulmonary bypass through a right thoracotomy. A long single-lumen endobronchial tube can be advanced across into the left main stem bronchus during the period of tracheo-bronchial anastomosis. High-frequency positive pressure ventilation (HFPPV) has also been used for this procedure, and the combined use of
HFPPV and a double-lumen tube has been described [34]. As the carina is surgically more accessible from the right side, left sleeve pneumonectomies are commonly performed as a two-stage operation. First a left thoracotomy and pneumonectomy, then a right thoracotomy for the carinal excision. The complication rate and mortality are higher and the 5-year survival (20%) significantly lower than for other pulmonary resections. Postpneumonectomy pulmonary edema is particularly a problem following right sleeve pneumonectomy.

Cardiac herniation

Acute cardiac herniation is an infrequent, but well described complication of pneumonectomy when the pericardium is incompletely closed or the closure breaks down [35]. It usually occurs immediately or within 24 h after chest surgery and is associated with more than 50% mortality. Cardiac herniation may also occur after a lobectomy with pericardial opening or in other chest tumor resections involving the pericardium or in trauma. When cardiac herniation occurs after a right pneumonectomy, the clinical presentation is due to impairment of the venous return to the heart with a concomitant increase in central venous pressure, tachycardia, profound hypotension, and shock. An acute superior vena cava syndrome ensues due to the torsion of the heart [36]. In contrast, when cardiac herniation occurs after a left-sided pneumonectomy, there is less cardiac rotation, but the edge of the pericardium compresses the myocardium. This may lead to myocardial ischemia, the development of arrhythmias and ventricular outflow tract obstruction. Cardiac herniation occurs after chest closure due to the pressure differences between the two hemithoraces. This pressure difference may result in the heart being extruded through a pericardial defect.

Management for a patient with a cardiac herniation should be considered as dire emergent surgery. The differential diagnosis should include massive intrathoracic hemorrhage, pulmonary embolism or mediastinal shift from improper chest drain management. Early diagnosis and immediate surgical treatment by relocation of the heart, can be considered during pericardial patch repair to prevent excessive compression of the heart by the repair [37]. In general, patients undergoing an emergency thoracic reexploration remain intubated and are transferred to the intensive care unit postoperatively.

Conclusion

Patients having pneumonectomy should have a preoperative assessment of their respiratory function in three areas that are lung mechanical function, pulmonary parenchymal function and cardiopulmonary reserve (the ‘three-legged stool’ of respiratory assessment). Following pneumonectomy, it is usually possible to wean and extubate patients with adequate predicted postoperative respiratory function in the operating room provided they are ‘AWaC’. Interventions that have been shown to decrease the incidence of respiratory complications in high-risk patients include cessation of smoking, physiotherapy and thoracic epidural analgesia. Geriatric patients are at an increased risk for cardiac complications, particularly arrhythmias, following pneumonectomy. Preoperative exercise capacity is the best predictor of postthoracotomy outcome in the elderly. DLTs are the standard method of providing lung isolation in adults. Bronchial blockers are a reasonable alternative for lung isolation in patients with abnormal upper or lower airways. The use of large tidal volumes during OLV (e.g. 10 ml/kg) can contribute to acute lung injury, particularly in patients at increased respiratory risk.

References and recommended reading

Papers of particular interest, published within the annual period of review, have been highlighted as:

• of special interest
** of outstanding interest

Additional references related to this topic can also be found in the Current World Literature section in this issue (p. 131).


The ppoFEV1 continues to be a useful factor in risk assessment for pulmonary resection surgery.


The above study demonstrates the importance of the postoperative lung parenchymal function, as demonstrated by the predicted DLCO, on outcome.
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The above study demonstrated an increased risk of complications with transfusion of more than four units of blood and with right-sided pneumonectomy.


