The Perioperative Management of Patients With Severe Emphysema

Katherine P. Grichnik, MD, and Steven E. Hill, MD

Severe emphysema is a frequent coexistent condition in surgical patients. It is a chronic obstructive pulmonary disease (COPD), part of a heterogeneous group of diseases that also includes chronic bronchitis and asthma. COPD is characterized by airflow obstruction and hyperinflation. Specifically, emphysema is anatomically defined by "abnormal, permanent enlargement of airspaces distal to the terminal bronchiole, accompanied by the destruction of their walls, and without obvious fibrosis." More than 2.9 million people in the United States are affected by emphysema, and 13,000 people die each year. Patients are more likely to be older, male, and at the time of diagnosis have commonly lost 50% to 70% of their lung function. Optimal perioperative anesthetic care requires review of the anatomy and pathophysiology of emphysema, knowledge of the therapeutic options, understanding the reactions of emphysema patients to surgical and anesthetic procedures, and an awareness of common perioperative problems.

ANATOMY AND PHYSIOLOGY OF PULMONARY EMPHYSEMA

Definitions/Anatomy

Anatomically, the bronchiole is divided into the lobular bronchioles, the terminal bronchioles, and the respiratory bronchioles (Fig 1). Emphysema is limited to the gas exchanging acinus consisting of the respiratory bronchioles, the alveolar duct, and the alveolus itself. Pathologically, there are 5 recognized types of emphysema (Table 1).18-10

Primary etiologies for emphysema include tobacco use and α-1 antitrypsin deficiency. However, industrial exposure to toxins, air pollution, and recurrent prior respiratory illnesses may also lead to emphysema. Pathologically, lung tissue may be injured by proteinases12 (elastases) released from neutrophils and alveolar macrophages, which are normally neutralized by antielastase inhibitors such as α-1 antitrypsin. An imbalance of elastase release (stimulated by smoking, infection, and industrial exposure) to antielastase inhibitor production (α-1 antitrypsin deficiency or oxidative damage to α-1 antitrypsin from smoke inhalation) can lead to lung tissue injury and subsequent emphysema. Animal studies support this theory as the experimental inhalation of exogenous elastase and collagenase result in acinar destruction, remarkably similar to human emphysema.13

Other evidence suggests that a more intricate process of pulmonary remodeling also occurs. Pathologic loss of tissue tensile strength because of bioengineering or structural fatigue in repetitively stressed tissues is postulated.15 Chronic inflammation may also play a role, mediated by different pathways compared with asthma.16,17 Macrophages, cytotoxic T cells, and neutrophils are found in bronchial biopsies and bronchoalveolar lavage; they can release proteases to break down connective tissue in lung parenchyma.18,20 Additionally, COPD patients have increased hydrogen peroxide concentrations in exhaled breath condensates and increased breath and urinary concentrations of 8-isoprostane, a marker for oxidative stress, which can promote COPD through enhancement of inflammation and proteolytic injury.21,22

Physiology

The pathophysiology of emphysema is based on airflow obstruction because of decreased elastic recoil from loss of elastin, collagen, and surfactant at the level of the alveolus. Loss of structural protein from small airways produces dynamic airway collapse on expiration. Airway inflammation, bronchospasm, and increased secretions additionally increase airway resistance. The end result is delayed lung emptying leading to increased lung volumes, mechanical compromise of the diaphragm, and markedly increased work of breathing. The clinical consequence is incomplete exhalation with resulting intrinsic positive end-expiratory pressure (auto-PEEP) or dynamic pulmonary hyperinflation (DPH) caused by retained gas volume in the lungs. These phenomena can happen in patients with normal lungs when mechanically ventilated at high rates, but are especially characteristic of patients with emphysema during mechanical ventilation.27

Patients with emphysema have chest radiographs characterized by hyperinflated lungs, a flattened diaphragm, an increased anterior-to-posterior diameter, an elevated rib cage, and a small

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Emphysema is often heterogeneously distributed with asymmetric bullae formation or lobar predominance of emphysematous tissue (Fig 3). Clinically, pulmonary function tests are characterized by a ratio of forced expiratory volume in 1 second (FEV₁) to forced vital capacity (FVC) of <70%, a decreased diffusion capacity for carbon monoxide (DLCO), an increased residual volume (RV), an increased functional residual capacity (FRC), and an increased total lung capacity (TLC).29,30 Gas exchange is typically impaired with decreased arterial oxygen tension and increased arterial carbon dioxide tension. Etiologies for abnormal gas exchange include ventilation-to-perfusion mismatch, increased physiologic dead-

<table>
<thead>
<tr>
<th>Type of Emphysema</th>
<th>Airway Location</th>
<th>Upper Versus Lower Lung</th>
<th>Heterogeneity</th>
<th>Miscellaneous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centrilobular</td>
<td>Proximal</td>
<td>Upper</td>
<td>Heterogenous</td>
<td>Associated with tobacco</td>
</tr>
<tr>
<td>Panacinar</td>
<td>Throughout</td>
<td>Lower</td>
<td>Uniform</td>
<td>Associated with alpha-1 antitrypsin deficiency</td>
</tr>
<tr>
<td>Paraseptal</td>
<td>Periphery</td>
<td>Both</td>
<td>Heterogenous</td>
<td>Increased spontaneous pneumothorax</td>
</tr>
<tr>
<td>Irregular</td>
<td>Periphery primarily arises in scar tissue</td>
<td>Both</td>
<td>Heterogenous</td>
<td>Arises in scar tissue</td>
</tr>
<tr>
<td>Bullous</td>
<td>Peripheral</td>
<td>Both</td>
<td>Heterogenous</td>
<td>Abnormally large airspace enlargement (&gt;1 cm) in focal areas</td>
</tr>
</tbody>
</table>
space, increased work of breathing, decreased diaphragmatic function, and diminished diffusion capacity between the alveolus and the microvasculature. Physiologically, patients may have pulmonary hypertension, elevated right ventricular (RV) dimensions, elevated RV diastolic pressures, and depressed RV ejection fractions.31

Expected declines in pulmonary function occur over time including decreases in FEV1 (average of 15-30 mL/yr), DLCO, and arterial oxygen and carbon dioxide tensions.32-34 Determinants of survival include age, arterial oxygen tension, and postbronchodilator FEV1 at the time of diagnosis.33-38 Longitudinal studies report a 60% 10-year mortality after the diagnosis of emphysema (Fig 4).33,35,39

MEDICAL AND SURGICAL THERAPIES

Medical Treatment

The goals of medical therapy for emphysema are to retard chronic disease progression, treat acute exacerbations40 and control symptoms to improve quality of life (QOL).20,41 Medical management includes patient education and risk factor identification,42 avoidance of environmental toxins or causative agents (tobacco),43 prevention of infection, graded exercise and pulmonary toilet instruction,44 and pharmacologic treatment.45 Effective medications include bronchodilators (β-adrenergic agonists and anticholinergics),46 but the role of methylxanthines is unclear with conflicting evidence for efficacy.47-51 Corticosteroid therapy is commonly used to treat acute disease exacerbations52 there is no role for chronic inhaled administration to reduce disease progression as initially postulated.53-56

Antibiotic therapy is also indicated for acute disease exacerbation with purulent sputum production,57,58 and vaccination against pneumococcal disease and influenza is recommended.59 Psychoactive drugs such as bupropion hydrochloride may aid in smoking cessation.60 Intravenous α-1 antitrypsin supplementation is used to replace intravascular levels in the α-1 antitrypsin-deficient patient, but it is unclear if this therapy prevents disease progression.61-63 Low-flow oxygen can improve exercise tolerance and quality of life and is the only medical therapy shown to improve survival in hypoxemic patients.64

New agents include leukotriene-receptor antagonists, drugs with anti-inflammatory and bronchodilating properties.65 They are currently indicated for asthma but may become useful for emphysema as well. Potential future therapy includes the development of antagonists to postulated cellular mediators of emphysema, increased types of protease inhibitor agents, and more specific anti-inflammatory drugs.66,67

Surgical Treatment: Lung Volume Reduction Surgery

Because medical therapy has been relatively ineffective in halting the progression of emphysema, others have turned to surgical attempts to both palliate and treat this disease.68-72 Early maneuvers included costrochondrectomy and transverse sternotomy to improve thoracic mobility.73 With the understanding that thoracic distention was the result of and not the cause of emphysema, others attempted to limit lung expansion with thoracoplasty and phrenectomy or elevate the diaphragm with pneumoperitoneum and abdominal constrictive belts.74-77 Procedures such as tracheal stents to stabilize the posterior membranous trachea in expiration and denervation to relieve bronchospasm and mucus formation have also been tried.78-83 These procedures were associated with high morbidity and unpredictable results.

The concept of anatomic surgical resection of nonfunctional lung tissue was introduced in the 1940s70 but was not commonly performed until 1957, when Brantigan and Mueller...
advocated bullectomy to treat emphysema.\textsuperscript{84,85} Although 75\% of patients derived a clinical benefit from the procedure, there was also a high mortality (18\%) and a lack of objective data, preventing wide acceptance. Thirty years later, Cooper, Wakahayashi, and Eugene\textsuperscript{86-89} revitalized this procedure with an operation now known as lung volume reduction surgery (LVRS). The operation involves resection of 20\% to 30\% of hyperinflated lung that should be noncontributory to effective ventilation. Proposed benefits are improvement in elastic recoil, lung compliance, and chest wall conformation to reduce hyperinflation and allow the resumption of a more normal diaphragmatic position. Additionally, enhanced ventilation-to-perfusion matching should occur in the remaining lung tissue to result in clinical improvements in pulmonary function.\textsuperscript{87-97}

Initial studies reported significantly positive clinical results,\textsuperscript{87,98} which led to LVRS being performed by many surgeons worldwide.\textsuperscript{99} Short-term results from many nonrandomized studies and case series have been reported, most showing reduced hyperinflation and improved pulmonary function, ventilatory mechanics and exercise tolerance at 3 to 6 months after procedure.\textsuperscript{91,100-105} (Outcomes from 180 studies [1995-1999] have been well reviewed by Flaherty and Martinez.\textsuperscript{106} However, only 4 randomized trials of lung volume reduction surgery versus medical management have been reported and are presented in Table 2.\textsuperscript{107-110}

Others reported less significant clinical benefit and considerable morbidity including prolonged postoperative air leaks (greater than 7 days with some requiring reoperation), subcutaneous emphysema (Fig 5A and B), pneumonia, pneumothorax, prolonged mechanical ventilation because of respiratory failure (reintubation rate of 19\%-33\%), arrhythmias, and gastrointestinal dysfunction.\textsuperscript{111-115} Cardiac and cerebrovascular complications have also been reported.\textsuperscript{116,117}

Mortality from this procedure may also be high. Initial 30-day mortalities were reported to be 0\% to 15\% and causes

![Fig 4. Comparison of 10-year survival rates in three groups of subjects with chronic airway obstruction. Group I subjects had asthmatic bronchitis, Group II subjects had mixed features of various disease states including chronic bronchitis, asthma and emphysema, Group III subjects had the emphysematous form of COPD. Copyright © 1987 Massachusetts Medical Society. All rights reserved. Reproduced with permission.\textsuperscript{23}](image)

![Table 2. Selected Controlled Studies of LVRS Versus Medical Therapy](table)

<table>
<thead>
<tr>
<th>Study</th>
<th>Variable</th>
<th>No. Age</th>
<th>FEV\textsubscript{1}</th>
<th>Walk Test</th>
<th>Mortality</th>
<th>No. F/U</th>
<th>FEV\textsubscript{1}</th>
<th>Walk Test</th>
<th>Mortality</th>
<th>No. F/U</th>
<th>FEV\textsubscript{1}</th>
<th>Walk Test</th>
<th>Mortality</th>
<th>No. F/U</th>
<th>FEV\textsubscript{1}</th>
<th>Walk Test</th>
<th>Mortality</th>
<th>No. F/U</th>
<th>FEV\textsubscript{1}</th>
<th>Walk Test</th>
<th>Mortality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criner\textsuperscript{106}</td>
<td>Bilateral MS</td>
<td>19 59</td>
<td>0.69 260</td>
<td>6*</td>
<td>15/19</td>
<td>0.85</td>
<td>321</td>
<td>9.4*</td>
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</tr>
<tr>
<td>Medical</td>
<td>Medical</td>
<td>18 58.8</td>
<td>0.72 273</td>
<td>N/R</td>
<td>15/18</td>
<td>0.82</td>
<td>303</td>
<td>N/R</td>
<td></td>
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<tr>
<td>Bilateral MS</td>
<td>Bilateral MS</td>
<td>23 62</td>
<td>0.74 210</td>
<td>17/61</td>
<td>19/23</td>
<td>0.91</td>
<td>260</td>
<td>21</td>
<td>13/23</td>
<td>0.84</td>
<td>290</td>
<td>N/R</td>
<td></td>
<td></td>
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<tr>
<td>Medical</td>
<td>Medical</td>
<td>24 60</td>
<td>0.75 220</td>
<td>N/R</td>
<td>23/24</td>
<td>0.7</td>
<td>230</td>
<td>12</td>
<td>19/24</td>
<td>0.74</td>
<td>205</td>
<td>N/R</td>
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<tr>
<td>Meyers\textsuperscript{108}</td>
<td>Bilateral MS</td>
<td>65 66</td>
<td>0.58 249</td>
<td>N/R</td>
<td>51/65</td>
<td>0.87</td>
<td>11</td>
<td>45/65</td>
<td>0.91</td>
<td>15</td>
<td>17</td>
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<td></td>
</tr>
<tr>
<td>Medical</td>
<td>Medical</td>
<td>22 65</td>
<td>0.62 264</td>
<td>N/R</td>
<td>22/22</td>
<td>0.52</td>
<td>0</td>
<td>17/22</td>
<td>0.57</td>
<td>20</td>
<td>46</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Pompeo\textsuperscript{110}</td>
<td>Uni- or bilateral MS</td>
<td>30 61.9</td>
<td>0.86 380</td>
<td>3.3</td>
<td>30/30</td>
<td>1.32</td>
<td>473</td>
<td>6.6</td>
<td>22/22</td>
<td>0.52</td>
<td>0</td>
<td>17/22</td>
<td>0.57</td>
<td>20</td>
<td>46</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medical</td>
<td>Medical</td>
<td>30 64.1</td>
<td>0.83 376</td>
<td>0</td>
<td>30/30</td>
<td>0.84</td>
<td>407</td>
<td>3.3</td>
<td>27/30</td>
<td>0.84</td>
<td>407</td>
<td>3.3</td>
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</tbody>
</table>

Abbreviations: LVRS, lung volume reduction surgery; No., number of patients; FEV\textsubscript{1}, forced vital capacity in 1 second; Walk test, 6-minute walk test or shuttle-walk test in meters; No. F/U, number of patients followed up as a fraction of the number of patients at baseline; bilateral MS, bilateral median sternotomy lung volume reduction surgery; Uni, unilateral; medical, medical management; N/R, not reported.

*In this crossover study, 1 patient died before surgery, and 13 patients crossed over to surgery after completion of the medical arm

\textsuperscript{1}Initial high mortality noted (5/15) with patients with very low DL\textsubscript{co} and walk distance. Inclusion criteria were subsequently modified to exclude these patients. 17\% includes these patients and 6\% does not.

Adapted with permission.\textsuperscript{104}
included respiratory failure, cardiac failure, sepsis, multiorgan failure, pneumonia, acute respiratory distress syndrome, and aspiration. There are limited long-term mortality data, with the few studies reporting 18% to 68% mortality at 3 to 5 years (Table 3); causes additionally include cancer, suicide, gastrointestinal bleeding, and pulmonary embolus.

A review of 711 Medicare claims in 1995 revealed LVRS patients suffered from prolonged hospital length of stay, a high readmission rate, and high use of rehabilitation services. Review of the published data and data requested from centers performing the surgery determined that the reported results were compromised by small patient numbers, inadequate controls with variability in patient selection, baseline assessments, perioperative care, the type of surgery performed, definitions of adverse outcomes, and duration of follow-up. In 1 study, 60% of LVRS patients did not return for follow-up after surgery; it was discovered that 27% of the nonreturn patients had died as compared with 3% of the patients who returned. The cost of LVRS was also considered. At a reimbursement rate of $31,398 per procedure, it was estimated that if LVRS were performed on every eligible Medicare beneficiary that almost 1 billion dollars would be spent. Thus, the role and expenses of LVRS were questioned, and, in January 1996, Medicare stopped funding for this procedure, citing inadequate evidence for efficacy and long-term benefit.

Subsequently, a multicenter randomized prospective clinical trial has been designed and supported by the National Heart, Lung and Blood Institute, the Health Care and Finance Organization (now known as the Centers for Medicare and Medicaid Services), and the Agency for Health Care Policy and Research. The purpose of the National Emphysema Treatment Trial (NETT) is to determine (1) whether surgical or medical therapy is more efficacious for patients with emphysema with respect to short- and long-term improvement of pulmonary function and quality of life, (2) whether different surgical approaches (median sternotomy or thoracoscopy) are associated with different outcomes, (3) the costs associated with this procedure over time. This trial was designed to define who would and who would not benefit from LVRS. Similar studies are underway in Massachusetts (Overholt-Blue Cross Emphysema Surgery Trial), Canada, and Great Britain.

Important concepts are emerging from the study of emphysema and the widely variable responses of patients to LVRS. The first NETT results examined 1033 patients and identified a group of 69 patients at high risk of death compared with medical management (relative risk [RR] = 3.9, 95% confidence interval [95%CI] = 1.9-9.0). They were patients with a low preoperative FEV1 and a uniform pattern of emphysema or a low D L CO. Others have also identified poor outcomes with a homogenous distribution of emphysema, lower-lobe LVRS, a low D L CO, higher age, limited initial walk test, and pleural adhesions. In contrast, improved outcomes have been associated with emphysema heterogeneity, upper- versus lower-lobe LVRS, bilateral versus unilateral LVRS, and the use of buttressed staples for resection versus laser resection.

Of concern is the finding that pulmonary function appears to improve to maximal levels at 3 to 6 months and then regresses (Fig 6); in some, there was a correlation between the magnitude of short-term incremental improvement and the rate of deterioration in FEV1. When long-term data were averaged, the rate of decline in FEV1 was 163 mL/y; it could then be predicted that an average patient would return to baseline FEV1 approximately 2 to 5 years postoperatively. These data suggest that surgery produced a one-time benefit but did not modify the natural history of the disease. However, it has been argued that the improved QOL with reduced dyspnea is a long-lasting benefit of LVRS.
may be independent of FEV₁ changes and more dependent on improvements in other domains of the respiratory system.²⁶,¹⁴⁹

Other findings have included the development of pulmonary hypertension in some patients,¹⁵⁰ the observation that the contralateral lung function can improve after unilateral lung reduction,¹⁵¹ the finding of variable arterial blood gas effects,¹⁵² and a lack of difference between a sternotomy versus video-assisted thoracoscopic approach.¹⁵³,¹⁵⁴ Still controversial is the amount of lung to resect.¹⁵⁵ Severe hypercapnea may not be a contraindication as initially determined.⁹³,¹⁵⁶

Independent of the NETT trial, others have sought reliable predictors of who will benefit from LVRS. Preoperative imaging techniques have been used for risk assessment but are variable among surgical centers.¹³³,¹⁵⁷,¹⁵⁸ Highly quantitative assessment of computed tomography scans can measure volume and severity of emphysema versus normal lung;¹³⁶,¹⁵⁹-¹⁶² scoring systems to assess the heterogeneity of emphysema distribution are proposed to correlate with LVRS outcome variables.¹⁶³ The radiologic pattern of emphysema may also be prognostic as patients with centrilobular

### Table 3. Selected Studies of Long-Term Survival After LVRS

<table>
<thead>
<tr>
<th>Study</th>
<th>Population</th>
<th>Technique</th>
<th>Perioperative Survival %</th>
<th>2 Year %</th>
<th>3 Year %</th>
<th>4 Year %</th>
<th>5 Year %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flaherty¹³⁶</td>
<td>89 from 1994-1998</td>
<td>Bilateral MS</td>
<td>30 day = 94.4</td>
<td>89</td>
<td>82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gelb¹¹¹</td>
<td>26 patients in 1995</td>
<td>Bilateral VATS</td>
<td>180 day = 96</td>
<td>81</td>
<td>69</td>
<td>54</td>
<td>42</td>
</tr>
<tr>
<td>Naunheim¹¹³</td>
<td>330, from 1993-1998</td>
<td>Unilateral VATS</td>
<td>30 day = 94.8</td>
<td>75</td>
<td>69</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>343, from 1993-1998</td>
<td>Bilateral VATS</td>
<td>30 day = 93</td>
<td>81</td>
<td>74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yusen¹¹⁸</td>
<td>200 patients, from 1993-1998</td>
<td>Bilateral MS</td>
<td>90 day = 95.5</td>
<td>87</td>
<td>82</td>
<td>74</td>
<td>71</td>
</tr>
</tbody>
</table>

Abbreviations: MS, median sternotomy; VATS, video-assisted thoracic surgery.

![Fig 6. Change in forced expiratory volume in one second (mL) over time. The median changes in FEV₁ were obtained by comparing the responses of each subject with his or her baseline values. Twenty-four patients underwent LVRS (surgical group) and 24 patients underwent medical rehabilitation (medical group). P values are for comparison of the surgical group to the medical group at each point. The bars show 95% confidence intervals. Note the initial improvement in FEV₁ at 3 months for the surgical group, which subsequently declines at approximately the same rate as the medical group. Reprinted with permission.¹⁸⁸](image-url)
Emphysema may benefit more than patients with panacinar emphysema. 164

Mechanical lung function may be prognostic. Dueck et al 166 examined the improvement of preoperative flow limitation after LVRS as an indicator of reduced dynamic pulmonary hyperinflation (DPH) and correlated it to postoperative reductions in FRC and FRC/TLC. 165 Similarly, preoperative auto-PEEP was found to correlate with postoperative FEV1. 166 Improved postoperative workload was associated with reductions in pulmonary resistance, auto-PEEP, and WOB. 167 However, Ingenito et al 168 found that only preoperative inspiratory resistance correlated inversely with improved FEV1 after surgery.

The use of LVRS in patients with undiagnosed pulmonary nodules and/or isolated lung cancer is controversial. 169 In pathologic analysis of tissue from LVRS patients, a wide range of abnormal tissue including adenocarcinoma, bronchoalveolar metaplasia, and carcinoid tumorlets has been found in tissue from LVRS patients. 170,171 DeRose et al advocated LVRS combined with nodule resection and reported recurrent cancer in only 1 of 14 patients at 1 year. 172

Although the role of LVRS is not firmly established, it is also being used in combination with other procedures to allow surgery for patients deemed inoperable because of the severity of emphysema. LVRS has been performed in conjunction with coronary artery bypass surgery, cardiac valvular surgery, and aortic aneurysm surgery. 173-175

Future results from the NETT trial and similar trials in other countries will clarify the questions of safety, efficacy, and cost of LVRS surgery with emphasis on prognostic markers to identify patients most able to benefit from the procedure.

**Surgical Treatment: Lung Transplantation**

The only other surgical alternative for treatment of severe emphysema is lung transplantation (LT), usually reserved for patients not expected to live more than 2 years. 13,176-178 In general, patients considered for LT have similar expiratory flow volumes (FEV1 less than 30% predicted) to LVRS candidates; patients with relative contraindications to LVRS (such as homogenous lung disease) may be considered for LT. 178 Optimal candidate selection criteria are presented in Table 4.

<table>
<thead>
<tr>
<th>Table 4. Selection Criteria for Lung Transplantation in Patients With Emphysema</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Indications</strong></td>
</tr>
<tr>
<td>Severe emphysema, distribution less important</td>
</tr>
<tr>
<td>FEV1 &lt;30% predicted</td>
</tr>
<tr>
<td>Rapid decline in oxygenation, ventilation</td>
</tr>
<tr>
<td>Development of secondary pulmonary hypertension</td>
</tr>
<tr>
<td>SLT &lt;65 years</td>
</tr>
<tr>
<td>SLT &lt;60 years</td>
</tr>
<tr>
<td>Ambulatory</td>
</tr>
<tr>
<td>Body weight 70-130% of ideal</td>
</tr>
<tr>
<td>Six minute walk test &gt;300 meters</td>
</tr>
<tr>
<td>Global psychosocial risk assessment adequate</td>
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</tbody>
</table>

Abbreviations: FEV1, forced expiratory volume in 1 second; SLT, single-lung transplant; BLT, bilateral lung transplant; HIV, human immunodeficiency virus; Hep B, hepatitis B virus; Hep C, hepatitis C virus; BiPAP, biphasic positive airway pressure. Data in table from Schulman. 177

*Ambulatory patients with tracheotomy for nocturnal ventilation and patients using noninvasive ventilation such as BiPAP masks are acceptable candidates.

Thirty-nine percent of the total lung transplants performed from 1995 to 2001 were to treat COPD/emphysema using both single and bilateral lung transplants (SLT, BLT). 179-181 SLT is performed most frequently to allocate the precious resource of donor lungs. 176 However, LT for emphysema may have an advantage of preventing the remaining native emphysematous lung from “crowding out” the newly transplanted normal lung and may have better long-term outcomes. 181

The major benefit of LT is that a patient can achieve near-normal lung function posttransplant, especially for BLT. 181,182 Maximal gains in FVC and FEV1 occur 6-12 months after LT 181 in contrast to LVRS, at which time decline in lung function may be occurring. If lung function does decline, it is usually related to infection or rejection, not native disease progression. 183 BLT is characterized by normal spirometry, oxygenation, and ventilation with resolution of thoracic hyperinflation; a mild restrictive defect may remain. 184,185 SLT pulmonary function differs because of the physiologic interaction with the native diseased lung: acutely, mediastinal shift may occur with hemodynamic compromise. Chronically, a biphasic expiratory flow pattern is observed with high initial flow from the transplanted lung followed by slower terminal flow from the native diseased lung; 178,186 hyperinflation of the thorax may remain. 187,188 Interestingly, the curvature of the diaphragm on the transplanted side may return to normal with abnormalities remaining on the contralateral side. 189 Despite these limitations, marked clinical and spirometric improvements (FEV1 improved from 0.49 L, 16% predicted to 1.6 L, 54% predicted) in 1 study 190 are seen; SLT recipients perform as well as BLT recipients in some exercise testing. 191

Potential complications of LT are multiple including acute and chronic rejection, infection, primary organ dysfunction, development of bronchial strictures, gastroparesis, and the gradual development of obliterative bronchiolitis. 192-195 Unique to SLT are (1) unchanged hyperinflation of the native lung, 196,197 (2) large ventilation-to-perfusion defect if severe reperfusion injury of the transplanted lung occurs, 198 and (3) lesions from the native lung (carcinoma, tuberculosis reactivation, and infectious contamination) affecting the transplanted lung. 178,179
Perioperative mortality is 7% to 10%, and overall survival for lung transplantation in COPD/emphysema patients is greater than 25% at 7 years with patients receiving bilateral lungs having a survival advantage (Fig 7). Early mortality is usually from infection or primary graft failure, and late mortality is usually from bronchiolitis obliterans or infection. As with LVRS, the relative survival risk of LT for emphysema versus medical therapy has been questioned. Hosenpad et al compared survival after LT (65% at 3 years) versus survival of patients on the waiting list for LT (70% at 3 years) and found that the relative risk of LT for emphysema never dropped below the risk of waiting. However, the analysis may be confounded by the common practice of placing patients on a lung transplant waiting list in anticipation of needing a transplant after a long waiting period. The health-related QOL was also not examined; similar to LVRS, patients after transplant report significant improvements in wellbeing.

Because organ supply is limited and waiting time for LT candidates continues to increase, LVRS versus LT has been examined. In a comparison of SLT, BLT, and LVRS, superior pulmonary function was found with LT: 79% improvement in FEV1 after LVRS versus 231% after SLT and 498% after BLT; similar results in exercise tests and oxygenation were reported. LVRS was performed on 20 patients awaiting LT; 95% survived at 32 months and 75% improved enough not to need LT. Similarly, Meyers et al performed LVRS on 99 patients potentially eligible for LT; 59% of survivors did not need to be listed for LT. Cost must also be considered: LVRS costs approximately $31,000 with few postprocedural expenses, whereas lung transplantation costs $108,000 with an estimated $1000/month medication cost. Other considerations for LVRS versus LT include the age of the patient, the risks of immunosuppression and comorbid conditions that could exclude a patient from transplantation but not from LVRS (eg, pulmonary nodule); LVRS has been performed before LT as a bridge to transplant or at the time of SLT to prevent/treat hyperinflation of the remaining native lung. Salvage of respiratory function by LVRS has been attempted in patients with SLT who are incapacitated by bronchiolitis obliterans.

**Preoperative Evaluation**

Initial preoperative inspection should assess the adequacy of prior medical management as determined by optimization of medications, pulmonary toilet, and pulmonary rehabilitation. Absence of concurrent infection will augment a limited ability to clear secretions postoperatively. Review of prior steroid use may determine the need for use of steroids intraoperatively.
Preoperative arterial blood gas analysis and pulmonic function testing with and without bronchodilators can both determine the sufficiency of medical therapy and assist in risk assessment.

Patients with severe COPD are at higher risk of serious postoperative pulmonary complications compared to patients with mild COPD or no COPD (relative risk from 2.7 to 4.7).212-216 Additionally, upper abdominal and thoracic surgery are independently associated with decline in pulmonary function with a 10% to 40% risk of postoperative pulmonary complications.212,217 The value of spirometry, split lung function tests and mimicy of postoperative conditions have also been used to assess perioperative respiratory risk, as promulgated in many anesthesia textbooks (Table 5).218,219 It has been suggested that increased risk is associated with an FEV1 or FVC less than 50% to 70% of predicted value or a ratio of FEV1 to FVC of less than 65%.220,221 However, such risk tables were constructed from methodologically flawed studies,222 use data acquired about thoracic surgical outcomes before improvements in anesthetic care and surgical technique,223 and do not address the role of exercise tolerance in risk assessment.

Spirometry has been found to have a variable predictive value (RR of an abnormal finding from 0.9 to 4.0)212 and is not better than clinical findings in the prediction of respiratory complications.213,224-226 The use of a “risk score” such as the cardiorespiratory risk index is also not reliable.227 However, the calculation of a predicted postoperative (ppo) FEV1 based on the amount of lung to be resected may correlate with pulmonary complications.228 Some also found preoperative partial pressure of arterial carbon dioxide (PACO2) >45 mmHg to be a predictor of risk.229,230 Exercise tolerance has been advocated as one of the best predictors of pulmonary outcomes after surgical procedures.231-235

Slinger and Johnston236 have addressed the above concerns in a novel approach to risk stratification. They propose evaluation in three domains: respiratory mechanical function, cardiopulmonary reserve, and lung parenchymal function, and describe the most valid test(s) for prediction of respiratory risk in each.

Respiratory mechanical function is most accurately evaluated by the predicted postoperative FEV1 (ppo FEV1) (ppo FEV1 in L = preop FEV1 in L [% lung resected × preop FEV1 in L]). Nakahara et al228 found that a ppo FEV1 40% of the predicted normal for a particular patient resulted in no postoperative respiratory complications, whereas a ppo FEV1 <30% of normal resulted in all patients needing postoperative mechanical ventilatory support.228

Cardiopulmonary function can be assessed simply by a 6-minute walk test with oximetry and more completely with an assessment of maximal oxygen consumption and ppo maximal oxygen consumption (calculated as for FEV1).237 In 1 study of 25 thoracic patients, patients with complications had a ppo maximal oxygen consumption of 10.6 mL/kg/min compared with patients without complications who had 14.8 mL/kg/min (p < 0.1); all patients with a ppo maximal oxygen consumption of less than 10 mL/kg/min died.238 A 6-minute walk test of less than 2,000 feet correlated with an oxygen consumption of less than 15 mL/kg/min239 and thus may be associated with increased perioperative morbidity.

Lung parenchymal function is best assessed by a ppo DLCO (calculated as for ppo FEV1). In a multivariate analysis of 376 thoracic surgical patients, a ppo DLCO of <40% was associated with increased respiratory complications (p < 0.004); DLCO and FEV1 were largely unrelated indicators of risk and should be assessed independently.236,240

Should a patient fall into a high-risk category based on ppo FEV1, surgery does not need to be cancelled but additional testing, precautions and perioperative care may be indicated as in Table 6.236

### Table 5. Assessment of Operative Risk Using Pulmonary Function Tests

<table>
<thead>
<tr>
<th>Testing Phase</th>
<th>Pulmonary Function Test</th>
<th>Increased Operative Risk Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole-lung tests</td>
<td>Arterial blood gas (room air)</td>
<td>PaCO2 &gt;45 mmHg, PaO2 &lt;60 mmHg, FVC &lt;1.5 mL/kg, FEV1 &lt;50% of FVC</td>
</tr>
<tr>
<td></td>
<td>Spirometry</td>
<td>FEV1 &lt;50% of FVC, VC &lt;2L, MVV &lt;50% predicted</td>
</tr>
<tr>
<td></td>
<td>Lung volume</td>
<td>RV/TLC &gt;50%, residual volume to total lung capacity; PAP, pulmonary artery pressure.</td>
</tr>
<tr>
<td>Single-lung tests</td>
<td>Right and left individual lung function tests of perfusion and ventilation using radioisotopes</td>
<td>Predicted postoperative FEV1 &lt;0.85 L or &gt;70% blood flow to diseased lung</td>
</tr>
<tr>
<td>Mimic postoperative conditions</td>
<td>Unilateral balloon occlusion of a right or left pulmonary artery</td>
<td>Mean PAP &gt;40 mmHg, PaCO2 &gt;60 mmHg, or PaO2 &lt;45 mmHg</td>
</tr>
</tbody>
</table>

Abbreviations: PaCO2, partial pressure of arterial carbon dioxide; PaO2, partial pressure of arterial oxygen; FVC, forced vital capacity; FEV1, forced expiratory volume in 1 second; VC, vital capacity; MVV, maximum voluntary ventilation; RV/TLC, residual volume to total lung capacity; PAP, pulmonary artery pressure. Data from217,218,220

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### Table 6. A Suggested Approach to Anesthetic Management Based on Preoperative Assessment of Risk

<table>
<thead>
<tr>
<th>Predicted Postoperative FEV1</th>
<th>&gt;40%</th>
<th>30%-40%</th>
<th>&lt;30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhale in the OR if clinically indicated</td>
<td>Consider extubation based on:</td>
<td>Staged weaning from mechanical ventilation</td>
<td></td>
</tr>
<tr>
<td>1. Exercise tolerance</td>
<td>Establish effective thoracic epidural analgesia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Assess ppo DLCO</td>
<td>3. V/Q scan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Associated diseases</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: FEV1, forced expiratory volume in 1 second; OR, operating room; DLCO, diffusion capacity for carbon monoxide; ppo, predicted postoperative; V/Q, ventilation to perfusion. Reprinted with permission.235
Monitoring and Sedation

Monitoring selected for the patient with severe emphysema should be tailored to the type and extent of the procedure while accounting for the severity of the pulmonary disease. In addition to the usual American Society of Anesthesiologists monitors, an arterial cannula should be considered for most patients. Frequent arterial blood gases and the ability to rapidly identify hemodynamic compromise are crucial. Central venous access should be considered for procedures with significant potential for third-space volume shifting or blood loss. However, care must be taken to avoid unintentional pneumothorax as a complication of line insertion (ipsilateral internal jugular vein cannulation for thoracotomy is preferred). Foley catheterization should be used for any operation that may require significant fluid administration.

While placing catheters, sedation should be given cautiously as patients may be very susceptible to respiratory depression from sedatives and residual effects may create difficulty with emergence from anesthesia. The relationship between CO₂ retention and lung mechanics in 311 patients with COPD and varying degrees of hypercapnea was examined. At rest, patients with more hypercapnea (PaCO₂ >55) had greater hyperinflation, airflow obstruction, and respiratory pump dysfunction that resulted in a significantly lower minute ventilation than normocapnic patients, mostly because of a reduction in tidal volume. Gross et al examined the effect of midazolam on changes in minute ventilation in response to hyperkapnea in patients with and without COPD (Fig 8). Although both groups had a diminished minute ventilation response to hyperkapnea with midazolam, the patients with COPD had a more profound decrease, which lasted for a longer period of time. A low-dose infusion of the short-acting agent propofol may be advantageous over bolus administration of benzodiazepines in this setting.

Choices of Anesthesia and Analgesia

Although the type of anesthetic administered is probably not as important as the expertise with which it is administered, every plan must take into account the difficulties of ventilation in this patient population. Regional anesthesia can and should be considered when appropriate. Avoidance of high spinal or epidural block levels is desirable for patients who rely on intercostal muscles for ventilation to prevent dyspnea and carbon dioxide retention. A combined regional and light general anesthetic approach can be effective. Regional techniques (eg, epidural, intercostal, paravertebral blocks) can facilitate reduced intraoperative opioid use and minimization of inhalation agents to decrease prolonged anesthetic effects.

In developing a strategy for postoperative analgesia, consideration should be given to the expected duration of chest tube drainage and/or the intensity of the postsurgical pain. The epidural route is especially effective for procedures expected to require more than 1 day of analgesia and procedures in which delayed return of gastrointestinal function may prevent oral analgesic administration. In general, placement of the epidural close to the dermatomal level of the surgical incision can increase the efficacy of the analgesics administered. Local anesthetic use in the epidural can minimize the need for opioids and their respiratory depressant effects; it has been suggested that the combination of local anesthetic and opioids for synergism is most effective. Adequate inspiratory and expiratory muscle function must be assured with local anesthetic use in a regional analgesic technique.

Paravertebral blocks, intercostal blocks, and intrathecal opioids are alternative techniques, especially useful for short-stay procedures. Paravertebral blocks can provide unilateral analgesia with local anesthetic, to allow avoidance of opioids, less hypotension, and less urinary retention than epidural analgesia. Single administration paravertebral blocks provide effective analgesia for only 9 to 12 hours, but catheter techniques can be used to extend the duration of the block. Similarly, single administration intercostal blocks may last 6 to 12 hours, although intercostal catheters can be used for a longer duration of analgesia. Intrathecal opioids may provide analgesia for up to 24 hours and intrathecal catheters for prolonged analgesia have been used. The optimal technique for postoperative analgesia in the patient with severe emphysema is not known.

Should parenteral and/or epidural opioids be administered, care must be taken to meticulously monitor respiratory function, as patients may be uniquely susceptible to carbon dioxide retention from the ventilatory depressant effects of the opioids. Supplemental analgesics devoid of respiratory depression such as nonsteroidal antiinflammatory agents should be considered if not contraindicated to limit the respiratory effects of opioid administration.

A theoretical concern about thoracic epidural analgesia is the potential to cause increases in bronchial tone and reactivity through pulmonary sympathetic blockade and respiratory muscle weakness, with adverse effects on ventilation.
tigate these concerns, Gruber et al.270 examined 12 patients with severe emphysema presenting for LVRS. Preoperative thoracic epidural anesthesia with bupivacaine was found to improve tidal volume, peak inspiratory flow rates and decrease pulmonary resistance as compared with baseline values. Similarly, Groeben et al.269 found no increase in airway obstruction in 20 patients with severe COPD undergoing breast surgery with high thoracic epidural blockade as the sole anesthetic.

Two large analyses support the use of regional analgesia for patients to preserve pulmonary function in the perioperative period. Richardson et al.271 examined 55 studies using epidural analgesia, paravertebral, or extrapleural analgesia (grouped together); intercostal block, cryoablation; intrapleural analgesia; and transcutaneous nerve stimulation. Spirometric function was reported as the percentage of preoperative pulmonary function that was preserved. Paravertebral blockade preserved spirometric function to 75% of preoperative values, whereas intercostal blockade and epidural analgesia preserved spirometric function to 52% and 47%, respectively, of preoperative values. Statistical analysis was not attempted because of variable study methods, and no comparison to intravenous analgesia was made.

In a more rigorous analysis, Ballantyne et al.272 examined 65 studies using epidural analgesia, intercostal blockade, local wound infiltration, and interpleural and intravenous analgesia as compared with systemic opioid analgesia. They examined relevant clinical outcomes of atelectasis incidence, pulmonary infections, pulmonary complications, and postoperative arterial partial pressure of oxygen (PaO₂). Secondarily, spirometric function was assessed. Epidural opioid analgesia compared with systemic opioids reduced the incidence of atelectasis (relative risk [RR] = 0.53, 95% confidence interval [CI] = 0.33-0.85, p = 0.01). Epidural local anesthetic analgesia compared with systemic opioids decreased the incidence of pulmonary infections (RR = 0.36, 95% CI = 0.21-0.65, p < 0.001), pulmonary complications (RR = 0.58, 95% CI = 0.42-0.80, p < 0.001) and resulted in a greater postoperative PaO₂ (difference at 25% correlation = 4.56, 95% CI = -9.0757 to 0.0585, p = 0.047). In contrast to the findings of Richardson et al, no differences in spirometric function were evident with any of the therapies. It can be concluded that regional anesthetic techniques can improve pulmonary outcomes perioperatively, as compared with conventional intravenous analgesia. It has been suggested that the recent trend of improved outcome in high-risk thoracic patients after pulmonary resection seems to be related to the use of epidural analgesia.273 Thoracic epidural administration of bupivacaine has also been shown to attenuate supraventricular tachyarrhythmias after pulmonary resection as compared with epidural morphine alone.274

Anesthetic Induction

Induction must be carefully undertaken when general anesthesia with endotracheal intubation is necessary. Initially, an extended period of denitrogenation is required. COPD patients may need 9 to 10 minutes to achieve an end-tidal fractional oxygen concentration of 90% after breathing 100% oxygen, whereas patients with normal lung function take only 2 to 3 minutes (Fig 9).275 This is likely because of ventilation-to-perfusion and diffusion abnormalities in patients with severe emphysema.

Hemodynamic instability is commonly observed in these patients during induction. Severe hypotension has been reported (and perhaps underreported) on induction of anesthesia.13,276-281 This may be because of the occurrence of DPH; institution of positive-pressure ventilation (PPV); the inadvertent application of positive end-expiratory pressure (PEEP); pneumothorax; vasodilatation from anesthetic agents; and/or sympathetic blockade from regional anesthesia, hypovolemia, and myocardial ischemia. It is important to avoid excessive ventilation immediately after induction as can occur with mask ventilation or when confirming endotracheal tube placement by auscultation as overventilation can lead to pulmonary gas trapping (Fig 10). Hypoventilation with ventilator timing set for a prolonged expiratory phase after induction may be advantageous until the degree of pulmonary dysfunction under anesthesia is determined.

The properties of the ventilator used may influence the intraoperative course of the patient. A volume-controlled ventilator will deliver a preset volume without regard for the pressure necessary to deliver that volume. Use of a pressure-limited ventilator has been advocated in the literature.282 If auto-PEEP or breath stacking should occur, the pressure-limited ventilator will sense the accumulating pressure and respond by reducing the volume of the next breath; an alarm for low minute ventilation will alert the anesthesiologist if this phenomenon compromises minute ventilation. In the absence of a pressure-limited ventilator, use of an ICU ventilator with an intravascular anaesthetic technique may be used. Close monitoring of peak and mean airway pressures is important because these are surrogate measures for retained volume in the lungs. Flow-volume loops available on selected ventilators can directly display breath stacking by observation of continued expiratory flow at the point of starting the next inspiration (Fig 11).

The risk of bronchospasm during an anesthetic in a population with obstructive lung disease has been estimated to be 7.7/1,000 as compared with the overall rate of 1.7/1,000 patients based on a retrospective analysis of 156,064 patients.283 There was a lower incidence with regional versus general anesthesia, but bronchoscopy and mediastinoscopy were associated with more bronchospasm. Although many have recommended intravenous lidocaine to prevent intraoperative bronchospasm,284-286 its efficacy remains to be proven.286-288 Upper airway reactivity is also important to control; inhalation agents at various minimum alveolar concentration levels and nebulized bronchodilators can facilitate this goal.289

The modes of ventilation used may be critically important. Maintenance of a short I:E ratio has been shown to reduce pulmonary hyperinflation auto-PEEP.290,291 Slinger et al.292 showed the importance of I:E time management as the application of external PEEP to patients with auto-PEEP during one-lung ventilation (OLV) did not increase the total PEEP if expiratory flow time was increased. Further, use of an end-expiratory pause (as is common for many operating room ventilators) will shorten the expiratory time period; increased auto-PEEP and decreased arterial oxygenation can occur.293 A
Fig 9. End-tidal oxygraphy over time in patients with and without chronic obstructive pulmonary disease (COPD). $F_{\text{E}}O_2$ tidal fractional oxygen concentration, ▲=patients without COPD, ○=patients with COPD. Reprinted with permission. 274

Fig 10. The development of dynamic pulmonary hyperinflation during mechanical ventilation and a representation of lung deflation during apnea. FRC=functional residual capacity. Adapted with permission. 284
simple maneuver is to intermittently disconnect from the ventilator to allow expiration of trapped pulmonary gas.

Intraoperative hypoxemia may be achieved with short-dur-ration drugs and inhalation agents to facilitate rapid emergence and reduce the possibility of excessive sedation or inadequate ventilation. Nitrous oxide should be avoided because of the risk of expansion of a closed gas space within diseased lungs and to allow for changing fraction of inspiratory oxygen (FiO2) without changing anesthetic depth. The use of short- to intermediate-duration nondepolarizing neuromuscular blockade agents can avert ill-timed coughing during the surgical procedure, reducing the risk of barotrauma and yet allowing for a rapid recovery of neuromuscular function.

Treatment of intraoperative hypoxemia with OLV may need to be carefully considered. Application of continuous positive airway pressure (CPAP) to the nondependent lung may lead to lung expansion because of increased compliance in emphysema. A useful first maneuver is to do fiberoptic bronchoscopy to confirm correct dual-lumen endotracheal tube position and remove secretions. Careful application of CPAP and PEEP may then be considered with attention to lung hyperinflation; nondependent lung re-expansion is the ultimate treatment. More common is intraoperative hypercarbia with increased ventilation-to-perfusion mismatch, significant deadspace ventilation, and the need for caution with ventilatory patterns. Extrathoracic endoscopic procedures using insufflation of carbon dioxide (CO2) may also result in impaired CO2 excretion. Hypercarbia in the absence of severe acidosis and hypoxia is usually well tolerated but may require inotropic support or lidocaine treatment.

Prolonged emergence and return to adequate respiratory function may occur. Volatile agents in concentrations as low as 0.1 minimum alveolar concentration can depress the ventilatory response to hypoxia in normal patients and may have a more profound effect in patients with emphysema. It has been shown that patients with COPD have a higher volume of deadspace and that PaCO2 is higher for spontaneously breathing patients under anesthesia using volatile agents compared with patients without COPD. The importance of successfully extubating the patient with severe emphysema should be stressed. Spontaneous ventilation improves preloading, avoids increased afterload, minimizes DPH, and should decrease stress on pulmonary suture lines in the setting of lung surgery.

Parenchymal air leaks are a common perioperative problem first encountered with initial lung re-expansion; high flows may be required to adequately ventilate the patient. Excessive air leak can compromise the ability to extubate the patient and may lead to the need for prolonged chest tube drainage. Experience from care of the LVRS patient suggests that hypercarbia may be expected in the postoperative period, with elevations of PaCO2 noted to 48 hours after surgery. PaCO2 greater than 70 mmHg may be treated with a short period of CPAP.

A period of postoperative ICU care or intensive postanesthesia care unit observation should be considered for the patient with severe emphysema to assure adequate pulmonary function postoperatively, assess the chest X-ray, optimize analgesia, and assess any issues related to the operation. ICU care should always be considered after any major surgery, especially thoracic or upper abdominal procedures, because these procedures can cause significant pulmonary dysfunction (reduction in FRC, depression of respiratory drive, impaired mechanics of ventilation, impaired gas exchange) even in the absence of emphysema. A longer than usual hospital length of stay can be anticipated with an increased need for postoperative oxygen administration.

COMMON PERIOPERATIVE PROBLEMS

Dynamic Pulmonary Hyperinflation and Intrinsic PEEP

DPH and auto-PEEP, which occur as more ventilation is inspired than is expired, may occur with increased expiratory airflow resistance (Fig 10). Three factors determine DPH and auto-PEEP: (1) the patient’s intrinsic respiratory system resistance and compliance, (2) added external resistance (endotracheal tube diameter, ventilator tubing, and devices), and (3) ventilatory pattern (frequency, tidal volume, inspiration-to-expiration time ratios, inflation volume, and end-inspiratory pause). These conditions are particularly dangerous with OLV for thoracic surgery as the entire ventilatory demand is placed on a single dependent diseased lung. Hemodynamic consequences include impaired venous return, a tamponade-like effect on the RV from hyperinflated lungs, compression of the alveolar blood vessels by elevated intra-alveolar pressures, and septal shift causing left ventricle dysfunction. Excessive DPH or auto-PEEP may cause cardiac arrest characterized by electromechanical dissociation.

DPH or auto-PEEP can be particularly challenging to manage because most standard anesthesia machines or ICU ventilator monitors do not readily detect progressively increasing intrathoracic volume. Use of a flowmeter may allow detection of interrupted expiratory flow (Fig 11). Bardoczky et al have correlated interrupted expiratory flow with the develop-
Pulmonary barotrauma is defined as extra-alveolar air in locations in which it is not normally found and can occur as the result of a sustained increase in intramural pulmonary pressure, secondary to alveolar overdistension. In patients with high levels of DPH and auto-PEEP, conventional ventilatory settings (such as a tidal volume of 10-12 mL/kg) may shift ventilation to the upper, less-compliant portion of a volume-pressure curve, thus risking alveolar rupture with overdistention. The risk of barotrauma increases with high intrapleural pressure, increased expiratory resistance because of an endotracheal tube, coughing, or “bucking” against the ventilator and high levels of extrinsic PEEP. The hemodynamic effects of barotrauma are similar to hemodynamic effects of DPH and may include mediastinal shift toward the nontraumatized lung. Increased inflation pressures in the nontraumatized lung can occur because it is compressed by the volume of gas in the contralateral intrapleural space.

Avoidance of barotrauma may be aided by the use of muscle relaxants, intermittent disconnection from the ventilator, a long expiratory time, and close monitoring. Minimization of peak inspiratory and plateau airway pressures have been recommended, although others have found no correlation of these pressures to the incidence of barotrauma in acute respiratory distress syndrome (ARDS) patients. Ventilation with smaller tidal volumes than traditionally used (6 mL/kg v 10-12 mL/kg) is beneficial. The addition of a small amount of external PEEP to prevent distal airway collapse in a sheep model also resulted in less inflammation and histologic injury, factors thought to predispose to barotrauma. Improved clinical outcomes have been shown in patients with ARDS.
using such “lung-protective strategies” based on individual patient lung mechanics (Table 7).317

Intraoperative pneumothorax in the dependent ventilated lung may be difficult to detect and can quickly become a tension pneumothorax with positive-pressure ventilation.318,319 Emergent treatment includes resuscitative vasoactive medications and relief of intrapleural pressure can be accomplished rapidly by chest tube thoracostomy or a large-gauge IV catheter. It may be necessary to turn the patient supine for adequate resuscitation. Barotrauma can also manifest as pneumomediastinum, pneumoperitoneum, and subcutaneous emphysema (Fig 5A and B).320,321

**Post–Lung Resection Pulmonary Edema**

Pulmonary edema is a perioperative problem of significance to anesthesiologists.322,323 The syndrome of post–lung resection pulmonary edema (PLRPE) has been reported after 2% to 4% of pneumonectomy procedures (right > left), after 1% of lobectomies and after 0.1% to 0.2% of thoracoscopic surgeries.322-324 Radiologic signs may appear before symptoms, with symptoms most commonly occurring on postoperative days 2 to 4. The syndrome is resistant to treatment, with a 30% to 50% mortality. Histologically, PLRPE is similar to the ARDS. PLRPE can occur with normal pulmonary capillary wedge pressure (PCWP),322,325 although the measurement of PCWP may be difficult postpneumonectomy326 or in mechanically ventilated patients with COPD.327 The physiology of PLRPE is unclear. The volume of fluid given to the patient has been implicated, with most authors citing Zeldin et al.328 However, this study examined only 10 pneumonectomy patients with PLRPE, and adequate fluid data were available on only 40% of the patients. Two other studies support the concept that perioperative fluid administration greater than 6 L and associated with the syndrome.329,330

However, the pathophysiology may not entirely rest on the fluid balance because postpneumonectomy edema also occurs in patients without high perioperative fluid load.324,331,332 A comprehensive review by Slinger322 suggests that fluid therapy is only one of the contributing factors to this syndrome; other potential mechanisms are presented in Table 8.322,324,325,333-336

Risk factors that predispose the patient to PLRPE include a right pneumonectomy (because of disruption of differential lymphatic drainage with R>L),337 increased perioperative pulmonary arterial pressures (in part because of hypoxemia, hypercarbia, pain),322,338 perioperative volutrauma (large tidal volume during OLV, mediastinal shift, and lung hyperinflation postsurgery),339,340,343 prior radiation therapy,330 and resection of normally perfused lung (acutely shunting that blood flow to remaining lung tissue).330

Perioperative fluid loading could aggravate the above mechanisms and patient risk factors. Increased cardiac output, increased pulmonary artery pressures, and increased net filtration pressure across the pulmonary capillary bed can result in fluid translocation to the pulmonary interstitial space. These principles may also be important in nonthoracic surgery.344 Pulmonary edema correlated with patients who received more than 67 mL/kg/d for various surgical procedures,345 and a 10% incidence of respiratory failure was documented in a study of peripheral vascular patients, in which patients received more than 6 L of fluid in 24 hours.346

Debate also exists about the type of fluid, especially colloid versus crystalloid. Among the proposed benefits of colloids are slower and perhaps less translocation of the fluid from the intravascular (IVC) space to the extravascular space (EVC).347,348 Improved tissue microperfusion with less endothelial swelling, resulting in improved tissue oxygen tension, has been presented.349 However, conflicting data exist because some investigators have found increased long-term mortality with colloid use in sepsis patients.350-351 Ernest et al.348 found that colloid agents, once translocated to the EVC space, actually increased the volume of that space in excess of the amount of colloid given in septic patients. Others found that colloid administration can promote lung water retention in burn patients.352 A meta-analysis of randomized clinical trials of isotonic crystalloid versus colloid fluid therapy found no difference in pulmonary edema or mortality.353

The total volume of fluid seems to be a critical contributory factor for PLRPE. In the absence of a leaky capillary syndrome (as in sepsis or burns), a combination of crystalloid and colloid is one strategy to attempt to prevent PLRPE. A minimal amount of crystalloid can be initially administered with the understanding that much of this fluid will translocate to the EVC space. Further fluids can be administered as colloids to replace intravascular volume because less total fluid volume is needed. The total amount of intravenous fluid to be given can be guided by indices of adequate volume status, such as urine output and CVP. Mild hypotension may not need to be treated with fluid boluses as positional changes and vasoactive agents can be used to support hemodynamics if urine output and CVP are adequate.

**Other Potential Problems**

Perioperative supraventricular arrhythmias are common (18%-25%); increased age, increased intraoperative blood loss, and extent of resection are risk factors.354-356 Atrial fibrillation was found to be the most common arrhythmia; 80% converted to normal rhythm by 3 days.354 Postoperative SVT is associated with a higher rate of ICU admission, longer hospital LOS, and a higher 30-day mortality.356 Although infrequent, cardiac ischemia or infarction can occur as well.117

Pulmonary hypertension or right ventricular dysfunction may also occur after pulmonary resection.150,356,358 Postulated mechanisms include an increase in pulmonary vascular resistance with a decrease in lung cross-sectional area, reactive vasoconstriction, an alteration of vasodilatory to vasoconstric-
tive mediators, and kinking of the pulmonary blood vessels. Pulmonary infection remains a devastating complication and may be related to ability to mobilize secretions postoperatively.

Emphysema may be commonly encountered in many surgical populations. The pathophysiology rests on airspace enlargement and obstruction to airflow, especially expiratory airflow. Medical therapy can ameliorate symptoms and improve exercise tolerance but not cure the disease. Surgical attempts to treat emphysema with LVRS remain investigational and lung transplantation is limited by donor availability. Unique anesthetic considerations include the potential for dynamic pulmonary hyperinflation, barotrauma, and pulmonary edema.

SUMMARY

Emphysema may be commonly encountered in many surgical populations. The pathophysiology rests on airspace enlargement and obstruction to airflow, especially expiratory airflow. Medical therapy can ameliorate symptoms and improve exercise tolerance but not cure the disease. Surgical attempts to treat emphysema with LVRS remain investigational and lung transplantation is limited by donor availability. Unique anesthetic considerations include the potential for dynamic pulmonary hyperinflation, barotrauma, and pulmonary edema.

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SEVERE EMPHYSEMA


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