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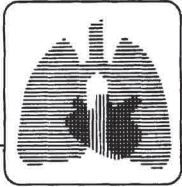
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## reviews

# Lung Volume Reduction Surgery for Emphysema\*

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There has been dramatic resurgence of interest in surgical treatment of emphysema, particularly "lung volume reduction" procedures. Recent studies have demonstrated improvements in pulmonary function, lung mechanics, exercise tolerance, and quality of life in selected patients following volume reduction procedures. However, considerable uncertainty remains regarding overall benefit, optimal patient selection, operative techniques, and duration of response. This review summarizes current approaches to lung volume reduction surgery, available clinical outcome information, selection criteria, and physiologic mechanisms of response, and discusses the potential role for surgical volume reduction in treatment of emphysema. Recent data appear to support the efficacy of bilateral staple lung volume reduction surgery in patients with severe symptomatic heterogeneously distributed emphysema. Further studies will be needed to determine relative value of different operative techniques and benefit in patients with other clinical presentations.

(CHEST 1996; 110:205-18)

**Key words:** emphysema; laser; lung; reduction; staple; surgery; volume

**Abbreviations:** CXR=chest radiograph; LVRS=lung volume reduction surgery; TLC=total lung capacity; VATS=video-assisted thoracic surgery; V/Q scan=ventilation-perfusion lung scanning

### HISTORIC BACKGROUND

#### *Resection of Giant Bullous Emphysema*

Local lung excision with plication for giant bullous lung disease was described by Nissen<sup>1</sup> more than 50 years ago. Since then, resection of giant bullous disease has been advocated for relief of dyspnea.<sup>2-8</sup> The most marked improvement in pulmonary function has been reported to occur with resection of bullae that occupy greater than one third to one half of the volume of the hemithorax.<sup>4,7,9,10</sup>

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Although many criteria for resection of giant bullae have been advanced based on clinical, physiologic, and imaging studies, these have been less than precise. Whereas the presence of "compressed" lung, especially with preserved perfusion, has been suggested as a prerequisite for surgery,<sup>8,11</sup> lack of adequate perfusion to nonbullous lung tissue has been considered a predictor of poor outcome.<sup>3</sup> Some investigators have considered generalized airflow obstruction, hypoxemia, and hypercapnia as contraindications to surgery,<sup>12-14</sup> while others have suggested that patients with hypoxemia, hypercapnia, pulmonary artery hypertension, or cor pulmonale may benefit from surgery.<sup>2,15</sup>

#### *Resection of Nongiant Bullous or Generalized Emphysema*

In 1957, Dr. Otto Brantigan,<sup>16</sup> an anatomist and surgeon, advocated a surgical approach to benefit patients with generalized emphysema by resecting peripheral emphysematous lung tissue. Although this surgery was originally designed for patients without



giant bullous disease, Brantigan and Mueller<sup>16</sup> believed that patients with more localized disease would have optimal results.

Through a standard posterolateral thoracotomy, Brantigan and Mueller<sup>16</sup> performed multiple wedge resection of the “worst” areas of emphysema (approximately 20 to 30% of the lung volume) until the hyperexpanded lung appeared to fit the chest. They also performed radical hilar nerve stripping in an attempt to reduce the production of the tenacious sputum that is commonly associated with COPD.

Brantigan’s operation was primarily directed at restoration of lung elastic recoil and thoracic volume in these patients rather than the removal of pathologic tissue. By “downsizing” the lung, he hoped to both increase circumferential or radial traction on the airways and improve chest wall and diaphragm mechanics.<sup>16,17</sup> Subjective improvement was reported in most patients, but mortality was approximately 20% and adequate objective data were not provided.<sup>17</sup> Several years later, Knudson and Gaensler<sup>2</sup> commented that it was difficult to believe that a disease characterized by extensive loss of lung parenchyma could be treated effectively by further resection of lung. Indeed, the American Thoracic Society issued a statement in 1968 in which they noted that indications for surgery in patients with bullous disease with generalized emphysema were not well defined or generally accepted.<sup>4</sup> In addition, the statement emphasized that, “Any surgical procedure which includes the removal of functioning lung tissue must be supported by sound reasoning and can be undertaken only after careful study. The rationale must be that resection of air-filled diseased portions of lung will result in improved function of the remaining lung.” As recently as 7 years ago, Connolly and Wilson<sup>18</sup> remarked that surgery has little to offer patients with generalized emphysema that diffusely involves all portions of the lung.

Despite the lack of general acceptance, others continued Brantigan’s work over four decades following his report.<sup>5,6,8,19,20</sup> Results were variable and physiologic and clinical data were frequently incomplete.

In 1991, Wakabayashi et al<sup>21</sup> rekindled interest in surgery for generalized emphysema with a report of 22 patients who underwent “laser bullectomy.” They reported a mean postoperative increase in the FEV<sub>1</sub> of 34%, although this increase was artificially inflated by the inclusion of patients with large bullae who had very large improvements. In general, success has been limited<sup>21-24</sup> and some centers have abandoned laser procedures<sup>25,26</sup> for cutting/stapling approaches developed by Cooper et al.<sup>27</sup>

In 1993, Dr. Joel Cooper began work on a “lung volume reduction surgery (LVRS) program,”<sup>27</sup> aimed

at palliative treatment of patients with severe dyspnea arising from emphysema. Cooper partially modeled the surgery on Brantigan’s approach, but he also introduced and developed innovative techniques. Cooper performed the operation via a median sternotomy in order to operate on both lungs during the same procedure. He resected peripheral wedges of lung with a linear stapler, often in a continuous fashion, and used bovine pericardial strips to buttress the staple lines.<sup>28</sup> Cooper and associates<sup>27</sup> reported initial objective and subjective success in a series of 20 consecutive patients with no operative deaths. Soon after, lung volume reduction surgery programs grew exponentially with variable, although generally positive results.<sup>25-27,29</sup>

Current selection for LVRS continues to evolve. Although variability clearly exists, selection recommendations have been advocated based on experience with lung resection, bullectomy, lung transplantation, published data, and understanding of pulmonary pathophysiology. Guidelines are being modified by the results of both physiologic investigations and imaging studies, including chest radiography (CXR), CT scanning, nuclear medicine scanning, and MRI. Selection criteria at most centers have been reasonably similar<sup>23-27,29-31</sup> and thus, the evaluation processes have often been similar as well (Table 1). The development of evaluation and selection criteria for surgery will continue to progress as more data become available and as the physiologic basis of response to surgery is better understood.

### *Rationale for LVRS*

LVRS is intended to relieve disabling dyspnea in patients with emphysema in whom it has markedly curtailed activities of daily living and proved refractory to optimal medical management. Although the mechanisms producing dyspnea are extremely complex, the structural and functional pulmonary and thoracic abnormalities occurring in emphysema are likely to be causally related to the sensation of breathlessness.

The fundamental structural defect in emphysema is permanent, abnormal, and nonuniform respiratory airspace enlargement with loss of the orderly appearance of the acinus and its components, without associated fibrosis.<sup>32</sup> Consequently, lung elastic recoil pressure diminishes markedly. This produces the hallmark decline in maximal expiratory airflow subsequent to both decrease of driving pressure for expiratory flow and airway instability, which increases airway resistance.<sup>33,34</sup>

Emphysema is frequently unevenly or heterogeneously distributed throughout the lung. This process produces a lung that no longer functions synchronously and homogeneously.<sup>33,35</sup> Consequently, ventilation becomes both regionally and temporally disparate,<sup>36,37</sup> resulting in increases in both ventilatory dead space



and alveolar-arterial oxygen differences. The preponderant abnormality and its severity will depend on the relative perfusion and ventilation to the diseased areas of the lung. The uneven distribution of ventilation also results in a lung that becomes more difficult to inflate with increasing respiratory rates.<sup>38</sup> Furthermore, the unique structure of the lung results in neighboring alveoli and regions sharing common structural foundations. As a result, those areas of lung more severely affected by the emphysematous process may adversely affect the mechanics of more normal surrounding lung tissue.<sup>39</sup>

In addition to airflow obstruction and dyssynchrony, emphysema is also accompanied by thoracic hyperinflation and air-trapping which adversely affects chest wall and diaphragmatic mechanics.<sup>40</sup> As the diaphragm flattens with progressive hyperinflation, at least 4 adverse consequences result: (1) muscle fibers shorten and operate at a less optimal length-tension relationship; (2) the radius of curvature increases and the diaphragm becomes less efficient at generating transdiaphragmatic pressure for a given diaphragmatic tension; (3) the zone of apposition is lost between the diaphragm and the thoracic-abdominal wall, which may adversely affect optimal lung inflation; and (4) the flattened diaphragm's attachment to the ribs cannot produce the "pump" and "bucket handle" costal motion required for inspiration. When these effects are linked with a hyperinflated chest wall that requires more work for tidal breathing, the muscles operate at marked mechanical disadvantage.

As suggested by Brantigan, surgical resection of emphysematous lung could potentially improve airflow obstruction by increasing lung elastic recoil pressure and decreasing airway resistance.<sup>41,42</sup> Removal of heterogeneously degenerated regions of lung would be expected to improve lung function by reversing the adverse effects of both hyperinflation and maldistribution of ventilation, further decreasing work of breathing and improving alveolar gas exchange.

### Evaluation of Patients for LVRS

The goal of the preoperative assessment process is to select patients with severely symptomatic disease who may benefit from surgery with an acceptable surgical risk. Routine evaluation for LVRS includes a complete medical history, physical examination, and other anatomic and physiologic evaluations. These are listed in Table 1. The eligibility criteria shown in Table 2 are currently used at Washington University. An algorithm describing this selection process used at Washington University Medical Center in St. Louis is shown in Figure 1.<sup>30</sup> Some of the most important points in the decision tree are as follows: (1) predom-

**Table 1—Methods of Assessing Patients for LVRS**

Methods
Office visit
Complete history
Physical examination
Laboratory data
Routine studies
Alpha <sub>1</sub> -antitrypsin level and phenotyping if indicated
Imaging studies
CXR*
Chest CT (plain or high resolution)
V/Q scan, quantitative
Physiologic testing
Pulmonary function tests <sup>†</sup>
Spirometry
Lung volumes by dilution technique and plethysmography
Diffusing capacity
Arterial blood gas
Exercise testing <sup>‡</sup> with a 6-min walk distance (with oxygen requirement determination by pulse oximetry)
Cardiac testing to evaluate (1) right and left heart function, and (2) for the presence of coronary artery disease (as indicated)
Subjective testing
Quality of life studies <sup>§</sup>
Dyspnea indexes <sup>  </sup>

\*Inspiratory and expiratory views may be useful to evaluate chest wall and diaphragmatic excursion, as well as mediastinal and lung parenchymal changes.

<sup>†</sup>Lung mechanics testing may be useful.

<sup>‡</sup>Cardiopulmonary exercise testing may be useful.

<sup>§</sup>Nottingham health profile,<sup>44</sup> medical outcomes survey short-form,<sup>36,45,46</sup> etc.

<sup>||</sup>Mahler dyspnea indices with transition scores,<sup>47</sup> Medical Research Council scores,<sup>48</sup> etc.

inant emphysema rather than airway disease; (2) heterogeneity of the emphysematous process with target areas for surgical resection; and (3) hyperinflation of the thorax. In addition to identifying patients for LVRS, this schema serves as a guide as to which patients we believe may best be served by medical management or lung transplantation as indicated.

For the evaluation process, the most commonly used imaging techniques are CXR, chest CT, thin cut CT, ventilation-perfusion lung scanning ( $\dot{V}/\dot{Q}$  scanning), and single photon emission CT scanning. In addition to the anatomic information gained by CXR and CT,  $\dot{V}/\dot{Q}$  scanning provides a functional analysis on a regional and quantitative basis. Examples of imaging studies from a theoretically "good" candidate for LVRS are shown in Figures 2 through 4. Newer imaging techniques are gradually being incorporated into the various evaluation algorithms. These techniques include quantitative CT and dynamic MRI.<sup>43</sup>

### Results of the Evaluation Process

At most centers, only a small percentage of patients are found to be candidates for volume reduction pro-



**Table 2—Evaluation Guidelines for LVRS\***

Qualifying	Disqualifying
Medical guidelines	
Maximized medical regimen	Continued cigarette smoking (cessation <6 months)
Marked dyspnea	Significant purulent secretions or predominant airways disease
Marked limitation in activities of daily living	Previous thoracic ipsilateral thoracic surgery or pleurodesis
Ability to undergo exercise pulmonary rehabilitation	Other systemic illness that will increase operative risk such as
Age <75 yr	Significant coronary artery disease; inadequate nutritional status; inability to taper from high-dose corticosteroid therapy
Able to consent; understands potential risks vs benefits	Ventilator dependence
Anatomic/structural guidelines as determined by imaging studies (CXR and chest CT)	
Emphysema	Chest wall/thoracic cage marked abnormalities
Hyperinflation	Bronchiectasis, pleural scarring, or adhesions (previous surgery, pleurodesis)
Heterogenous disease with target areas	
Physiologic/functional <sup>†</sup>	
Spirometry	
FEV <sub>1</sub> <35% predicted	FEV <sub>1</sub> >50% predicted
Lung volumes by plethysmography	
RV >250% predicted	RV <150% predicted
TLC >125% predicted	TLC <100% predicted
RV/TLC >60%	
Trapped gas elevated <sup>‡</sup>	
Alveolar gas exchange	
Dco <50% predicted <sup>§</sup>	Significant carbon dioxide elevation (PaCO <sub>2</sub> >55-60 mm Hg)
Cardiovascular function	
Normal right and left heart function	Significant pulmonary hypertension (mean PAP >35 mm Hg)
Heterogeneous pulmonary perfusion that is diminished in "target areas" (V/Q scan)	Significant coronary artery disease

\*RV=residual volume; Dco=diffusion of carbon monoxide; PAP=pulmonary artery pressure.

<sup>†</sup>Tests of lung mechanics and respiratory muscle strength may be useful.

<sup>‡</sup>Plethysmographic TLC>TLC determined by gas.<sup>49</sup>

<sup>§</sup>Could confirm the physiologic correlate of emphysema (decreased maximal transpulmonary pressure and increased static compliance) with pulmonary mechanics testing.

cedures. Comparison of patient characteristics before surgery with surgical outcome has revealed that hypercapnia and advanced age may be predictors of adverse outcome.<sup>30,31</sup> Keenan and colleagues<sup>26</sup> found that the combination of hypercapnia and decreased diffusing capacity of the lung for carbon monoxide was associated with poor outcome, though this requires confirmation for patients undergoing a bilateral procedure. Analysis of subjective and objective outcome data with preoperative CXR and CT images by Slone and Gierada<sup>43</sup> suggested that the presence of (1) heterogeneous disease with target areas for resection in the upper lobes, (2) marked hyperinflation, and (3) "compressed lung" are predictors of a positive outcome. These findings are strikingly similar to those seen by Brenner and colleagues<sup>23</sup> for bullectomy.

### Summary

Selection of patients for LVRS is a process in evolution. Previous criteria for resection of giant bullae

provided the foundation for initial criteria for LVRS. Knowledge regarding the pathophysiology of chronic airflow obstruction and previous surgical experience led to the development of newer selection criteria without the benefit of prospective analysis. Newer imaging techniques now allow better evaluation of the emphysematous lung and its surrounding structures. Further analysis of outcomes will provide improved guidelines for patient selection as well.

Based on our current knowledge, patients selected for LVRS should have severe airflow obstruction predominantly as a result of emphysema. The emphysematous process should be regionally heterogeneous to provide "target areas" for surgical resection and allow less diseased lung to remain. These patients should also have marked thoracic hyperinflation with associated air trapping. Predominant airways disease, advanced age, hypercapnia, and pulmonary hypertension are considered relative contraindications for surgery by most centers at the present time.

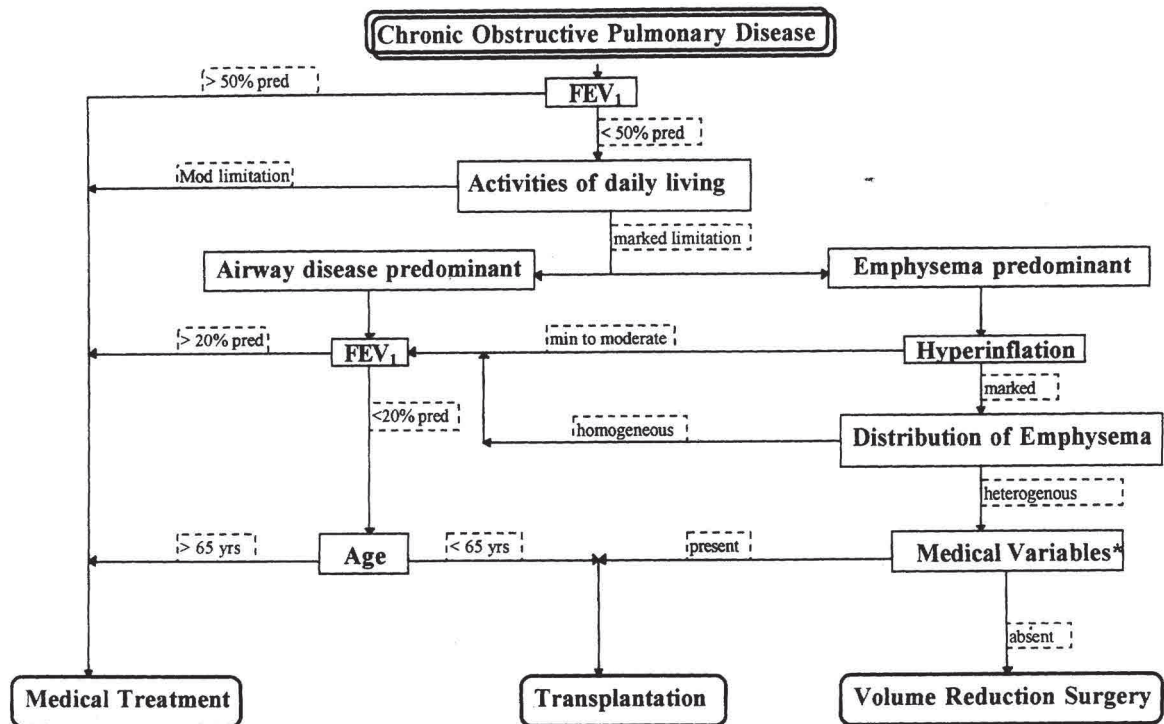


FIGURE 1. Algorithm for patient evaluation. Asterisk=medical variables consist of the following: (1) PaCO<sub>2</sub> >55 mm Hg; (2) mean pulmonary artery pressure >35 mm Hg; (3) obliteration of the pleural space; and (4) coexisting medical problems that would substantially increase surgical morbidity or mortality. Reprinted from Yusen and Lefrak.<sup>30</sup>

#### SURGICAL APPROACHES AND TECHNIQUES FOR LVRS

Numerous techniques for lung volume reduction for the surgical treatment of emphysema exist. The approaches are as varied as the surgeons performing the operations. This section will attempt to summarize various reported techniques and evaluate the strengths and weaknesses of each approach. Obviously, there may be more than one acceptable approach to the surgical treatment of emphysema.

##### *Bilateral Stapled Lung Volume Reduction via Median Sternotomy and Open Techniques*

Bilateral stapled lung volume reduction via median sternotomy was popularized by Cooper and colleagues<sup>27</sup> following the publication of his initial experience with 20 patients. This is probably the most commonly utilized approach because most surgeons are comfortable and experienced with median sternotomy. Dr. Cooper also initiated the use of bovine pericardium reinforced linear staples to reduce staple line air leaks.<sup>28</sup>

The patient is intubated with a left-sided double-lumen entotracheal tube and position is confirmed bronchoscopically. The procedure itself utilizes a standard median sternotomy. The pleurae are opened and one-lung ventilation is initiated. The nonventilated operative lung is reported to demonstrate absorption

atelectasis of the healthy areas with continued hyperinflation of the diseased portion. A linear stapler buttressed with bovine pericardium is then utilized to resect the diseased portion of the lung. From 20 to 30% of the overall lung volume on each side is removed. The lungs are inspected for air leaks and the pleura is subsequently closed bilaterally. Postoperative analgesia is via epidural catheter that was placed preoperatively and patients are extubated as soon as possible following surgery. Currently, chest tubes are placed to water seal and are removed after cessation of air leak. Approximately 50% of patients have an air leak for greater than 7 days with this technique. Cooper's group stresses importance of early extubation and avoidance of chest tube suction to reduce air leak complications.

*Clamshell Incision:* The procedure can be performed in a similar fashion utilizing a clamshell or bilateral anterior thoracotomy incision.<sup>50</sup> The chest is opened in the sixth intercostal space bilaterally and the sternum is divided transversely with sacrifice of the internal mammary arteries. Proponents of this approach claim improved visualization of the lateral and posterior portions of the lung with postoperative healing and pain comparable to that of a median sternotomy. This is also the incision of choice for bilateral lung transplantation and may be considered in a young patient who may require transplantation in the future. The details of stapling via this open incision approach



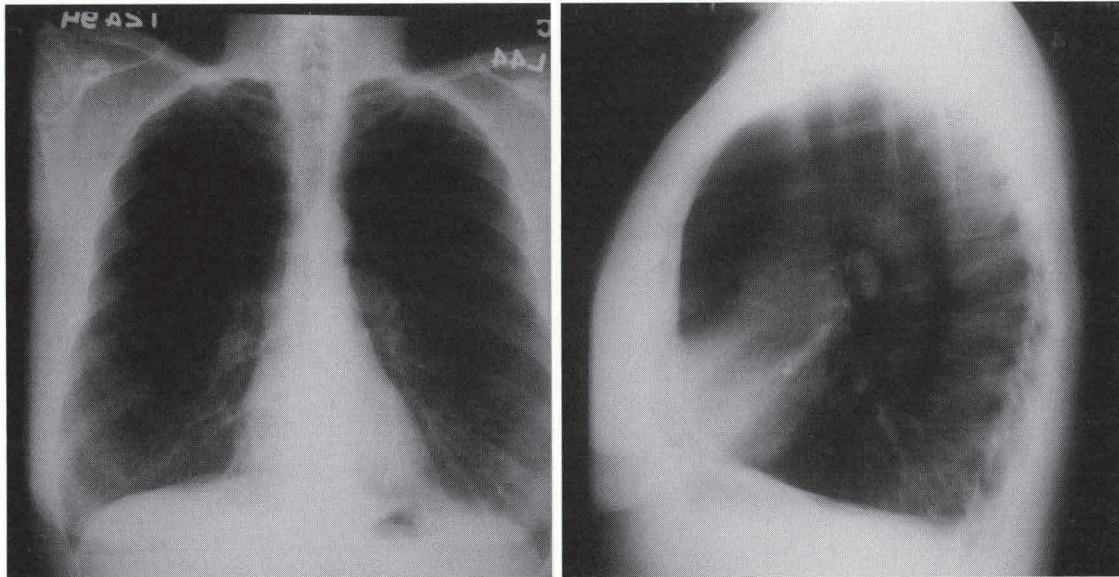


FIGURE 2. Posterior-anterior (*left*) and lateral projection (*right*) CXR taken before LVRS showing hyperinflation of the chest with increased anteroposterior diameter, retrosternal airspace, and retrocardiac airspace. Posterior ribs are angled upward and the shoulder girdles are elevated compared with normal. The diaphragm is depressed and relatively flattened. There is a paucity of lung vascular markings and cystic changes are seen in the upper lobes, suggesting the presence of marked upper lobe-predominant emphysema.

are the same as with sternotomy. In both cases, the patient is positioned supine and simultaneous access to both pleural spaces is obtained.

The prone position may also be utilized for simultaneous bilateral access when utilizing video-assisted thoracic approaches to be discussed in the next section.

*Standard Lateral Decubitus:* The standard lateral decubitus position can be utilized for either open or video-assisted approaches. Multiple variations of thoracotomy or minithoracotomy are utilized to provide access to the thoracic space for stapling, laser, or combination techniques.<sup>24,29,51</sup> Of course, this approach provides access to only one pleural space necessitating repositioning of the patient if bilateral procedures are to be performed during the same anesthetic period. The advantages again are improved visualization of the posterior, apical, and hilar areas of the lung.

#### *Video-Assisted Thoracoscopic Stapled LVRS for Emphysema*

The potential advantages of a video-assisted thoracic surgery (VATS) approach to lung reduction surgery are both real and perceived. At least half of the pleural space has been obliterated by adhesions in 24% of patients in one series.<sup>52</sup> The VATS approach offers better visualization for posterior and inferior adhesions than that afforded by median sternotomy. VATS does eliminate the standard postoperative constraints associated with median sternotomy (*ie*, driving restrictions) and the risk of sternal infection or dehiscence. Many

patients perceived a VATS procedure to be “less invasive,” although the postoperative course is comparable to that of a median sternotomy.

*Operative Techniques:* Surgery is performed with a double-lumen endotracheal tube. The patient is placed in the full lateral decubitus position. The ipsilateral endotracheal lumen is clamped during the skin preparation to maximize time for resorptive atelectasis to occur. Suction with the fiberoptic bronchoscope in the mainstem bronchus and occasionally CO<sub>2</sub> insufflation into the thoracic cavity may be required to facilitate lung collapse.

The trocar and 30° thoracoscope affords maximal visualization of the chest with an ability to see over the top of the lung as well as the anterior and posterior hilum. All pleural adhesions are lysed. Extrapleural dissection is performed in areas of dense, fibrous adhesions.

Additional incisions are made in the eighth intercostal space, midclavicular line, in the fourth intercostal space in the midaxillary line just anterior to the latissimus dorsi muscle, and in the auscultatory triangle under thoracoscopic visualization. These incisions optimize insertion of instruments for lung manipulation and stapling.

The preoperative CT and V/Q scan identify target tissue for resection. Ring forceps manipulate this tissue into an endoscopic stapler. It is important for the stapler to approach the lung tissue precisely to avoid tearing. For bilateral procedures, the average number of firings of the 60-mm endoscopic stapler is 15. In our



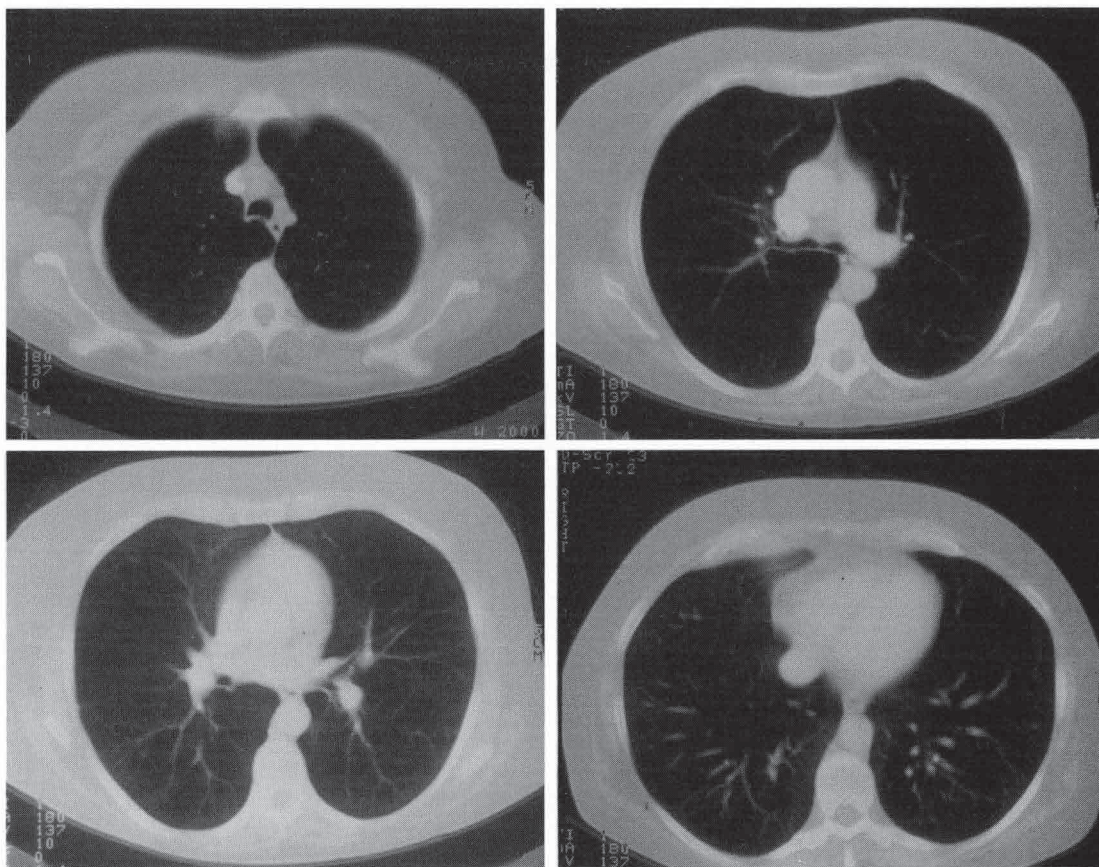


FIGURE 3. Chest CT scan windows taken before LVRS; axial slices are taken at the level of (1) the midtrachea (*top left*), (2) just below the carina (*top right*), (3) the lower third of the lungs (*bottom left*), and (4) the base of the lungs (*bottom right*). There is marked lucency in the upper lobes (levels 1 and 2) with vascular markings predominantly in the lower lobes (levels 3 and 4). Nongiant bullous emphysema with marked heterogeneity is depicted, with emphysematous disease most prominent in the upper lung fields compared with the lower lung fields. Areas of the upper lobes can serve as target areas for surgical resection.

experience, the weight of lung tissue removed generally ranges from between 30 and 110 g per side with an average of 75 g per side (including the weight of the staples and excised pericardial stripping material).<sup>52</sup> For upper lobe emphysematous disease, at least half of the upper lobe is resected. For lower lobe emphysema, the equivalent of four segments is usually resected. For upper lobe emphysema, the inferior pulmonary ligament is divided only if it extends to the diaphragm. For lower lobe emphysema, the inferior pulmonary ligament is routinely divided to facilitate the resection.

Either bovine pericardium (Peristrips; Biovascular; St. Paul, Minn) or bovine collagen (Instat; Johnson & Johnson; New Brunswick, NJ) is used to buttress the staples. Studies are currently underway comparing the efficacy of these two materials in the control of air leak. Additional studies have been initiated using nonbuttressed staples (such as the Ethicon EZ45). Intercostal nerves are blocked with 0.5% bupivacaine hydrochloride (Marcaine) and epinephrine under direct thoracoscopic visualization. Thoracoscopy confirms

apical placement of two straight 28F chest tubes. In our protocol,<sup>52</sup> the anesthesiologist measures inspiratory volume and expiratory volume to quantitate air leaks. If a leak is present, it is most often found lateral to staple lines, in areas where adhesions were lysed or at the trocar insertion sites. When possible, air leaks are closed with sutures or additional staples. After turning the patient 180°, the opposite side is prepared for contralateral lung volume reduction during the same anesthesia.

Postoperatively, an epidural catheter is placed for postoperative pain control, and the patient is extubated in the operating room or as soon as possible in the ICU. The chest drainage system is placed on water seal. Suction is not used as long as the patient is in clinically stable condition.

*Postoperative Care:* After patients are transferred out of the ICU, on postoperative day 1, physical therapy and rehabilitation are begun. Chest tubes are removed as early as 48 h if no air leak is present. Epidural and Foley catheters are discontinued at 48 h. If an



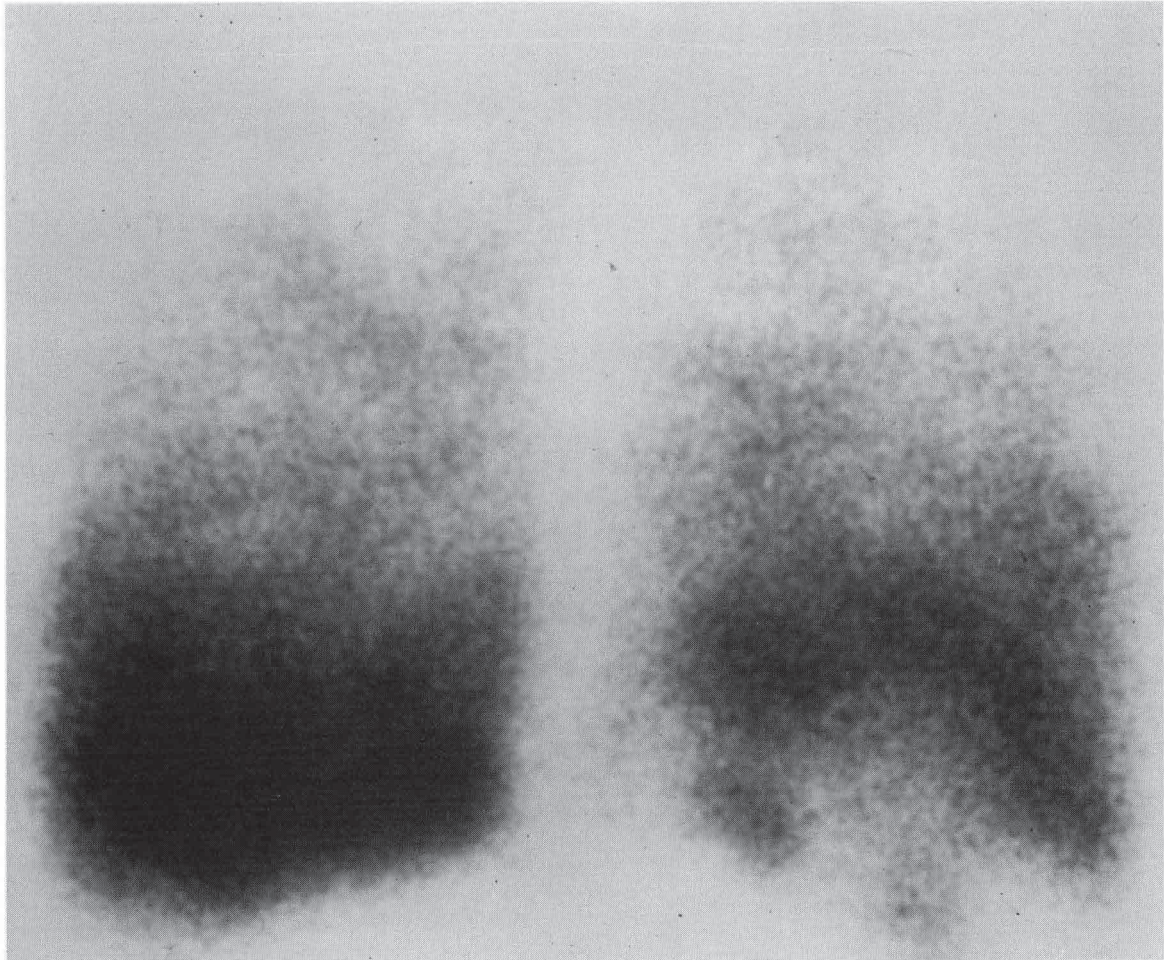


FIGURE 4. Posterior view lung perfusion scan (radionuclide scintigraphy) using  $^{99m}\text{Tc}$ , performed prior to LVRS, reveals decreased relative perfusion to the upper lung zones and best perfusion to the right lung base. This is also consistent with the CXR (Fig 2) and chest CT scan (Fig 3) findings which suggest heterogeneity and the presence of upper lobe target areas for surgical resection.

air leak persists for greater than 5 days, Heimlich valves are placed on the chest tubes to allow earlier hospital discharge as soon as the patient is in clinically stable condition.

#### *Laser Therapy for Bullous Emphysema*

The information available on laser therapy for emphysema covers a multitude of techniques and laser energy sources.

The laser is applied to the lung surface via either an open or thoracoscopic approach and bullae are seen to contract or shrink. Proponents of laser treatment contend that no functional lung tissue is removed or damaged. However, the laser is capable of treating only bullae or areas of severe emphysematous degeneration near the surface of the lung. The laser can be applied either in direct contact with the lung surface or as a free beam directed at the lung from a distance. Wakabayashi<sup>51</sup> performs unilateral procedures utilizing the contact tip Nd:YAG laser at 8 to 12 W. The CO<sub>2</sub> laser

and argon beam coagulator have also been used with a high incidence of reported air leaks resulting from areas of perforation.<sup>21,22</sup> In addition, the current requirement for articulated delivery arms and increased difficulty in using the CO<sub>2</sub> laser has led to discontinuance of its application.

Proponents of free-beam YAG laser treatments argue that the laser energy is more effectively applied with less heat damage to surrounding normal lung tissue. Little et al<sup>24</sup> applied the YAG laser as a free beam at a setting of 40 W with a 0.5-s pulse interval while another surgeon in the same group preferred a lower energy setting of 10 to 15 W with the YAG in the continuous wave mode. In some cases, the entire surface of the lung is treated while others selectively apply the laser to visible bullae. Current reports would suggest that this method is associated with a decreased rate of late pneumothorax when compared with the contact tip YAG.<sup>25</sup> In most cases, inflammatory responses from laser treatment have precluded simultaneous bilateral



procedures, although investigations evaluating this concept are underway (Alex Little, MD, 1996, personal communication).

### Combined Laser and Staple Approaches:

Several investigators have proposed that the ideal procedure would combine the positive properties of both the stapled and laser reduction approaches. Eugene et al<sup>29</sup> utilized either KTP or YAG free beam laser to treat diffusely diseased areas of the lung while discretely bullous or hyperinflated areas were resected using buttressed linear stapling devices. KTP laser radiation was delivered using 8 to 18 W continuous wave power and Nd:YAG laser radiation was delivered using 15 to 30 W continuous-wave power, depending on tissue response. A mini-thoracotomy in combination with thoracoscopic port technology was utilized.

### Summary

In conclusion, there are a number of techniques currently in practice for the surgical treatment of emphysema. The greatest improvements in FEV<sub>1</sub> and overall patient function appear to occur with bilateral stapling procedures independent of the surgical approach utilized (VATS vs sternotomy). The role of laser, although quite successful in some cases, will require further investigation.

### SURGICAL RESULTS

There are only limited data to compare the efficacy of the various approaches for LVRS available at the present time. In a prospective study, McKenna et al<sup>25</sup> randomized patients to undergo a unilateral VATS procedure for either staple lung volume reduction (39 patients) or contact tip Nd:YAG treatment (33 patients). The morbidity and mortality (1.5%) were essentially the same for both procedures except for an 18% incidence of delayed pneumothorax following laser procedures. However, patients who underwent staple procedures had greater improvement in oxygen independence in 6-month follow-up FEV<sub>1</sub> (33% vs 13%) and in overall lifestyle and dyspnea scale when

compared with patients treated with Nd:YAG contact laser.

A comparison of effects of various procedures on postoperative pulmonary function is seen in Table 3. Little et al<sup>24</sup> reported a series of 55 patients with diffuse emphysema who underwent unilateral free beam Nd:YAG laser treatment. The mean FEV<sub>1</sub> improved from 0.74 to 0.85 L (18%). Little et al<sup>24</sup> noted a 20% incidence of delayed pneumothorax, similar to that seen with contact tip lasers in the McKenna et al<sup>25</sup> study. Although free beam laser treatment resulted in greater improvement in FEV<sub>1</sub> than contact tip laser (18% vs 13%), it was still not as effective as unilateral staple procedures.

In unilateral VATS procedures, Eugene et al<sup>29</sup> combined staples and free beam laser treatment (either KTP or Nd:YAG) for 28 patients with diffuse emphysema. The FEV<sub>1</sub> increased from 0.68 to 0.91 L (34%). There were no hospital deaths, but 3 patients died within 3 months (11%, 3-month mortality). Subjective improvement occurred in 22 of 28 (78.6%) patients and oxygen dependence was eliminated in 5 of 23 (21%) patients. Thus, these results do not clearly demonstrate additional improvement from combination of laser with staples compared to staple reduction alone.

The studies discussed so far involve unilateral procedures. With a bilateral stapling technique, Cooper et al<sup>27</sup> reported marked clinical improvement and an 82% mean increase in the FEV<sub>1</sub>. In their initial 20 patients, Cooper et al<sup>27</sup> reported no mortality, a mean hospital stay of 15 days, air leak greater than 7 days in 11 patients, and surgical reexploration in 4 patients. Oxygen independence with exercise was achieved in 10 of 14 (71%) patients. Further analysis of the larger cohort of patients in the series of Cooper et al<sup>27</sup> has revealed similar improvements in oxygen dependence, more modest improvements in FEV<sub>1</sub>, and hospital mortality of less than 5% (R. Yusem, MD, 1996, unpublished data).

Because both unilateral and bilateral lung volume reduction can achieve many of the goals of surgical treatment of emphysema, McKenna et al<sup>52</sup> analyzed

**Table 3—Results of Various Techniques for Lung Reduction Surgery for Diffuse Emphysema\***

Author	Procedure	Method	No. of Patients	FEV <sub>1</sub> , %	No O <sub>2</sub> , %
McKenna <sup>25</sup>	YAG contact	Unilateral	33	13.4	36
Little <sup>24</sup>	YAG	Unilateral	55	18	NA
Eugene <sup>29</sup>	YAG/KTP+ Staples	Unilateral	28	34	21
McKenna <sup>25</sup>	Staples	Unilateral	87	33	36
McKenna <sup>52</sup>	Staples	Bilateral (VATS)	4 <sup>†</sup>	72	68
Cooper <sup>27,61</sup>	Staples	Bilateral (MS)	20 (46) <sup>†</sup>	82 (57) <sup>†</sup>	71

\*Laser procedure was performed in the free beam mode unless otherwise stipulated. Method indicates whether the procedure was performed unilaterally or bilaterally. Bilateral (VATS) indicates bilateral staple procedure via thoracoscopy, and bilateral (MS) indicates bilateral staple procedure via median sternotomy. No O<sub>2</sub> means that the patients no longer required oxygen following the operation.

<sup>†</sup>Data from reference 61.



**Table 4—A Comparison of the Results of Unilateral and Bilateral Staple LVRS\***

Results	Unilateral	Bilateral
Operative mortality, %	3.5	1.1
Hospital stay, d	11.4	10.9
O <sub>2</sub> independence, %	36	68
Steroid independence, %	54	85
FEV <sub>1</sub> (upper lobe), %	35	68

\*From McKenna et al.<sup>52</sup>

the results of 166 consecutive patients who underwent either unilateral (87) or bilateral (79) stapled lung reduction procedures (Table 4). There was no statistically significant difference in acute operative mortality (3.5% vs 2.5%), mean length of stay (11.4+1 days vs 10.9+1 days), or morbidity for the unilateral and bilateral groups, respectively (p=NS for all variables). Neither procedure improved all patients. In the unilateral group, grade 3 or 4 dyspnea remained present in 44% of the patients, postoperatively, but in only 12% in the bilateral group (p<0.001). Oxygen dependence was eliminated in 18 of 50 (36%) patients in the unilateral group and 30 of 44 (68%) patients in the bilateral group (p<0.01). Prednisone dependence was eliminated in 38 of 51 (54%) patients in the unilateral group compared with 30 of 35 patients in the bilateral group (85%) (p=0.02).

No late deaths (posthospitalization to 1-year follow-up) occurred in the bilateral group, in contrast to a 17% 1-year mortality (primarily due to respiratory failure) after unilateral operations (p<0.001). This mortality occurred in patients older than 75 years with room air Po<sub>2</sub> less than 50 and/or with FEV<sub>1</sub> less than 500 mL who died primarily of respiratory failure because their conditions failed to improve enough after a unilateral operation.

#### OVERVIEW: THE PRESENT AND FUTURE OF LVRS

The goals for lung volume reduction operations for emphysematous pulmonary disease are to significantly improve subjective dyspnea, exercise tolerance, and quality of life. Secondary benefits include the reduction or elimination of supplemental oxygen or steroid dependence. Physiologic benefits include improved objective measurements of pulmonary function. Currently, surgery for emphysema is performed with lasers, staples, and a combination of both in open procedures (via median sternotomy, clamshell incision, and thoracotomy incisions) or closed procedures (VATS). There is only a limited amount of data to compare the efficacy of these various approaches, so many questions remain.

The operative results in Table 4 suggest that the bilateral staple operation is the procedure of choice in most cases. The unilateral free beam Nd:YAG laser

without staples (Little et al<sup>24</sup>) appears to be slightly better than the contact tip (McKenna et al<sup>25</sup>), but neither is as good as the unilateral staple procedure alone. The combination of the staples and laser procedure (Eugene et al<sup>29</sup>) provided the same improvement in pulmonary function achieved with staples alone (McKenna et al<sup>25</sup>). The risk of additional morbidity (delayed pneumothorax) and the lack of additional benefit from the use of the laser has led some centers to discontinue its use for this indication at the current time. Although there may be clinical settings where the laser is indicated for LVRS, such indications remain to be defined.

Both unilateral and bilateral procedures can substantially improve the conditions of patients with generalized emphysema. Overall, however, the results show greater improvement in dyspnea, oxygen independence, prednisone independence, and pulmonary function for the bilateral procedure compared with the unilateral procedure.

So what is the role for a unilateral procedure? One potential rationale for a unilateral procedure is that some patients may be too debilitated to tolerate a bilateral procedure, so a unilateral procedure might be safer and could be done to improve the patient's condition enough for an operation on the contralateral side. The operative morbidity and mortality for unilateral and bilateral operations in debilitated patients were comparable in our series, but the improvement was much greater for the bilateral procedure. Therefore, severe debility is not an indication for performing a unilateral operation rather than a bilateral operation. In fact, severely debilitated patients fare better with a bilateral operation than with a unilateral procedure. One-year follow-up reveals dramatically higher mortality following the unilateral procedure compared with the bilateral LVRS. This delayed mortality occurred in severely debilitated patients (with preoperative room air Po<sub>2</sub> <50 mm Hg, age older than 75 years, or FEV<sub>1</sub> <500 mL) whose conditions did not improve enough with the unilateral procedure to sustain survival longer term. There was no delayed mortality in these subgroups of patients after a bilateral operation. These data also show that an extremely low FEV<sub>1</sub> is not a contraindication to LVRS. The operative mortality was not increased in patients with an FEV<sub>1</sub> less than 500 mL. Therefore, it appears at this time that a bilateral procedure is the procedure of choice in severely compromised patients.

Lung reduction surgery for emphysema is a procedure that provides palliation for uncertain periods of time. It is currently unknown if longer periods of palliation might be achieved if a patient initially undergoes a bilateral operation or a unilateral operation with plans



to reserve the contralateral side for a time when the patient becomes more symptomatic.

If the surgical plan is sequential operations, then it is necessary to be able to predict which patients will get enough improvement from a unilateral operation. We have been unable to clearly identify such patients, so our current operative approach is generally a bilateral operation.

Bilateral staple LVRS can be performed by either a VATS procedure<sup>52</sup> or via median sternotomy.<sup>4</sup> The average improvement in the FEV<sub>1</sub> is related to the degree of hyperinflation. Cooper's patients have an average total lung capacity (TLC) of 144%. With a bilateral VATS procedure,<sup>52</sup> a subgroup of hyperinflated patients comparable to Cooper's patients<sup>27</sup> experienced an average improvement in FEV<sub>1</sub> of 410 mL (72%) from baseline, compared to the 390 mL (82%) improvement for Cooper's patients. The results of these studies suggest that bilateral procedures can be performed by median sternotomy or bilateral thoracoscopy with approximately equivalent results. It is likely that both approaches will continue to be used based on the experience of the surgical team.

The optimal amount of lung to be resected is also unknown. In one series,<sup>52</sup> up to 114 g of tissue was resected from 1 lung and at least half of the upper lobe from each lung was resected with an average weight of 60 to 75 g per side. A close correlation was seen between the total weight of tissue resected (including staples and bovine pericardium) and response to LVRS (Fig 4). Perhaps the resections should be even more extensive. This issue will require further investigation.

In conclusion, available data suggest that standard operation at this time for a patient with severe heterogeneous emphysema should be bilateral staple lung volume reduction procedures performed by either median sternotomy or VATS. Unilateral operations should generally be reserved for patients with unilateral heterogeneous emphysema, prior contralateral thoracic operations, pleural scarring or pleurodesis, and cases in which complications occur while operating on the first side during a planned bilateral operation.

Surgery for emphysema is an exciting new frontier for pulmonologists and thoracic surgeons. There are numerous patients with severe emphysema who now enjoy improved quality of life after LVRS. Over the next few years, research will hopefully clarify these issues regarding patient selection, surgical technique, and long-term outcome.

#### MECHANISMS OF IMPROVEMENT FOLLOWING LUNG REDUCTION SURGERY FOR DIFFUSE EMPHYSEMA

Assessment of mechanisms responsible for physiologic improvement following lung reduction surgery

must address the impact of the procedure on lung and chest wall mechanics as well as gas exchange and pulmonary vascular function. Ultimate improvement in dyspnea and exercise tolerance may be related to the impact of any one or combination of these physiologic parameters.

Brantigan and Mueller<sup>16</sup> initially proposed that their multiple segmental resection procedure restored the elastic recoil pressure of the lung, thus reversing a basic defect that leads to hyperinflation and increased work of breathing. Following resection of the most emphysematous lung tissue in patients with generalized emphysema, expansion of the relatively less affected regions would generate greater elastic recoil. This would result in greater driving pressure and better airway traction to maintain the caliber of the airway during exhalation. Other investigators have confirmed the impact of the increased radial traction on the intraparenchymal airways by documenting improved airway conductance at a given lung volume following this procedure.<sup>53</sup> These investigators also demonstrated that lung volume reduction in the form of lobectomy does not confer these important increases in airway conductance because of the simultaneous removal of conducting airways.

We and others have previously investigated an increase in lung elastic recoil following resection of bullae in bullous lung disease and in bullous emphysema. We recently reported a significant increase in lung elastic recoil following unilateral LVRS for generalized emphysema using a combination of laser and stapling techniques.<sup>54</sup> The improvement in lung elastic recoil resulted in an increase in static transpulmonary pressure (liters) at TLC from  $10.3 \pm 0.5$  cm H<sub>2</sub>O (mean  $\pm$  SEM) to  $14.6 \pm 1.0$  cm H<sub>2</sub>O ( $p < 0.001$ ). This increase in lung elastic recoil was responsible for significant improvements in expiratory flow rate and reduction in lung volume. Furthermore, all patients had improvement in the transitional dyspnea index and the 16 patients with improved lung elastic recoil had significantly greater improvement in 6-min walking distance than 4 patients whose conditions did not improve.<sup>54</sup> Similar changes in lung elastic recoil occurred at 6 months following bilateral LVRS for generalized emphysema in 12 patients using a bilateral thoracoscopic approach with stapling (A.F. Gelb, MD, 1996, personal communication).

By relating maximal expiratory flow to static lung elastic recoil pressure at the corresponding lung volume (from flow-pressure curves), mechanisms of expiratory airflow limitation may be determined.<sup>55,56</sup> The relative contribution of loss of lung elastic recoil and intrinsic airway obstruction may be estimated and compared with predicted values.<sup>57,58</sup> Analysis of maximum expiratory flow pressure curves following sur-



gery in 4 of 12 patients indicates that the abnormal maximum expiratory airflow preoperatively resulted almost completely from loss of lung elastic recoil that improved with surgery. Similar results have been seen in patients with diffuse bullous lung disease<sup>58</sup> and mild emphysema.<sup>58,59</sup> In the remaining eight patients, abnormal airflow preoperatively was accounted for by loss of lung elastic recoil as well as intrinsic airways disease and/or bronchial compression.

The increased recoil following LVRS is responsible for the subsequent repositioning of the chest wall and diaphragm. The impact of these volume changes includes ventilation in a more optimal chest wall position, thus reducing the work of breathing. The reduced lung volume also allows for improved respiratory muscle vector forces and a more efficient length-force interrelationship of the muscle fibers. Finally we have documented reductions in end-expiratory thoracic pressure (Sciurba et al<sup>54</sup>). Such increases in end-expiratory pressure, a consequence of incomplete exhalation, result in a threshold load that must be overcome prior to initiation of inspiratory flow.

Changes in arterial oxygenation may occur in the presence or absence of improvement and appear to occur less frequently following unilateral than bilateral procedures.<sup>26-28</sup> Potential mechanisms of improved gas exchange include a reduction in low ventilation-perfusion units due to the global effects of improved elastic recoil on alveolar ventilation as well as the regional expansion of partially compressed lung adjacent to the resected tissue. The improved arterial PCO<sub>2</sub> identified in several series may be consequent to either reductions in dead-space ventilation or increases in alveolar ventilation enabled by the improved lung and chest wall mechanics.

The impact of lung reduction surgery on pulmonary vascular function may be of equal importance to the mechanical and alveolar gas exchange features discussed above. Further resection of the already limited vascular reserve has the theoretical potential to induce cor pulmonale or worsen exercise performance even in the setting of improved pulmonary mechanical function. However, the global improvement in lung elastic recoil and regional decompression following lung reduction may actually improve intraparenchymal vascular reserve. We have documented significant improvements in right ventricular ejection fraction following this procedure in a group of 20 patients, suggesting indirectly that pulmonary vascular resistance had in fact improved (Sciurba et al<sup>54</sup>).

Despite the recent documentation in short-term improvement following lung reduction surgery, it is uncertain whether long-term improvements will be realized. Return of airway conductance toward preoperative levels following the multiple segmental re-

section of emphysematous lung described by Brantigan and Mueller<sup>16</sup> was found to occur over 6 to 18 months, most likely secondary to stress relaxation of underlying bullae.<sup>60</sup> Cooper and colleagues have described sustained improvements following LVRS in some patients followed up as long as 3 years (J. Cooper, MD, 1996, unpublished data). The duration of physiologic response to LVRS remains to be determined and requires careful follow-up studies of pulmonary mechanics.

#### LVRS: WHAT ARE THE CRITICAL ISSUES?

Current data support that for appropriate patients, LVRS improves pulmonary function, relieves dyspnea, and thereby ameliorates a patient's symptoms. As a development of the past 50 years of thoracic surgery for giant bullous disease, the work of Brantigan and Mueller<sup>16</sup> with diffuse emphysema, transplantation, and contemporary understanding of the pathophysiology of pulmonary emphysema, we believe that LVRS should no longer be considered experimental surgery for appropriately selected and informed patients. What remains to be seen is the following: (1) What are the mechanisms producing improvement so that appropriate patients can be identified with precision and inappropriate patients excluded with confidence? (2) For how many years does the improvement last? (3) Is morbidity or even mortality affected? (4) What is the cost to the health-care system when factors such as utilization of health-care facilities, delay in the need for transplantation, possible return to work by disabled patients, increased need for care if life is prolonged, etc, are analyzed? (5) Which surgical approach is best suited to which patient?

While these questions need to be answered and will be over time, the eventual role of LVRS is difficult to predict as the major issues that must be faced are not amenable to scientific resolution but rather are value judgments and social issues. These issues are as follows: (1) How do we avoid abuse of the procedure by both physicians and patients? (2) Is improvement for 2 or 4 years worth the cost? (3) How impaired must a patient be before he or she can be considered a surgical candidate? (4) What is the role of LVRS in relation to lung transplantation? These are particularly difficult to answer in an era when the health-care environment is so dominated by the drive for spending less, and increasingly by for-profit managed-care organizations, all of which create an environment hostile to innovative patient care. In the past, these value decisions were made predominantly by patients and their physicians which, when left uncontrolled, tended to lead to overuse and occasionally outright abuse. Currently these decisions will be made by third parties who may well have a



conflict of interest in evaluating the "worthwhileness" of a new therapy.

To provide both the scientific basis so necessary to establish the position of LVRS in the care of the patient with COPD and to reassure both patients and their insurance carriers that appropriate use will be made of the resources devoted to LVRS, it is important that centers of excellence be established at which LVRS may be undertaken. A national registry should be initiated to collect multicenter data to commence answering the scientific questions. The criteria for selecting centers of excellence should be the center's (1) prior experience with complicated thoracic surgery, if not prior experience with LVRS, (2) potential avenues for referral of patients for evaluation for lung transplantation when this is an alternative to LVRS, and (3) clinical and scholarly excellence in pulmonary medicine and thoracic surgery. While human value issues need to be decided by society, input of appropriate information and non-self-serving guidance from the medical community is needed. As physicians and surgeons, we must be effective advocates for patient care, and if we meet our responsibilities to our patients, LVRS will find its correct place in the medical armamentarium.

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