Lung Volume Reduction Surgery

Technique, Operative Mortality, and Morbidity

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The objective of lung volume reduction surgery (LVRS) is the safe, effective, and durable palliation of dyspnea in appropriately selected patients with moderate to severe emphysema. Appropriate patient selection and preoperative preparation are prerequisites for successful LVRS. An effective LVRS program requires participation by and communication between experts from pulmonary medicine, thoracic surgery, thoracic anesthesiology, critical care medicine, rehabilitation medicine, respiratory therapy, chest radiology, and nursing. The critical analysis of perioperative outcomes has influenced details of the conduct of the procedure and has established a bilateral, stapled approach as the standard of care for LVRS. The National Emphysema Treatment Trial (NETT) remains the world's largest multi-center, randomized trial comparing LVRS to maximal medical therapy. NETT purposely enrolled a broad spectrum of anatomic patterns of emphysema. This, along with the prospective, audited collection of extensive demographic, physiologic, radiographic, surgical and quality-of-life data, has positioned NETT as the most robust repository of evidence to guide the refinement of patient selection criteria for LVRS, to assist surgeons in providing optimal intraoperative and postoperative care, and to establish benchmarks for survival, complication rates, return to independent living, and durability of response. This article reviews the evolution of current LVRS practice with a particular emphasis on technical aspects of the operation, including the predictors and consequences of its most common complications.

Keywords: emphysema; surgery; complications; outcomes

Pneumectomy or the nonanatomic resection of emphysematous lung by thoracotomy to palliate chronic dyspnea was proposed and tested by Otto Brantigan in the 1950s (1). While the physiologic principles of the procedure appeared to benefit survivors, operative morbidity and mortality proved prohibitive and relegated the procedure to the obscure pages of the history of surgery for emphysema, where it lay alongside costochondrectomy, phrenic nerve lysis, and glomectomy (2). Joel Cooper and colleagues resurrected the concept of partial pneumectomy nearly four decades later, advocating a bilateral, nonanatomic, stapled resection through a median sternotomy. Forty years of advances in anesthesia, critical care, pulmonary rehabilitation, and surgical instrumentation, along with the expertise of the Washington University group, yielded a considerable reduction in operative

morbidity and mortality, and lung volume reduction surgery (LVRS) was (re)born (3).

The objective of LVRS is the safe, effective, and durable palliation of dyspnea in appropriately selected patients with moderate to severe emphysema. Before the National Emphysema Treatment Trial (NETT), there were several reported single institutional, case-controlled series of LVRS demonstrating encouraging results with regard to *mean* improvements in spirometry, 6-minute-walk distance, self-reported dyspnea, and supplemental oxygen use (3–13). While these reports involved more than 700 patients, many individual series were small. Operative mortality varied substantially from 2.5 to 10%, with a few series reporting mortality as high as 19% (4–6, 10, 14, 15). Observational claims data for more than 700 Medicare patients having LVRS between October 1995 and January 1996 revealed a bleaker picture, with a 90-day mortality rate of 14.4%. Twenty-three percent of operated patients died in the first year after surgery (16). Despite such disparate mortality outcomes, each report emphasized the importance of an experienced multi-disciplinary team of pulmonary physicians, thoracic surgeons, anesthesiologists, respiratory and rehabilitation specialists, chest radiologists, and experienced nurses to achieve successful LVRS.

PATIENT SELECTION

NETT was designed with this specific team approach incorporated into a randomized trial comparing LVRS with maximal medical therapy for severe emphysema (17). The details of evaluating, selecting, and optimizing patients for LVRS are central to the success of any LVRS program and are detailed elsewhere in this symposium (*see* DeCamp and coworkers, pages 427–431 [43]; and Sharafkhaneh and coworkers, pages 438–441 [44]). Briefly, based on NETT results and the observations of others, patients are selected according to the morphology of emphysema (upper-lobe predominant versus other patterns), its physiologic severity (FEV₁, DL_{CO}, Ppa), the patient's fitness (6-minute/shuttle walk, cycle ergometry), the patient's perception/expectation regarding quality of life, and the presence of important co-morbidities such as coronary ischemia, pulmonary hypertension, sputum production, or ongoing tobacco abuse. The majority of patients with emphysema referred to experienced programs but excluded from receiving LVRS are rejected based on objective criteria (Table 1). Physician and surgeon clinical judgment remain important considerations, but accounted for only 7.2% of the ineligibilities in NETT. The purpose of this contribution is to review the technical aspects of LVRS, including the predictors and consequences of its most common complications.

TECHNICAL CONSIDERATIONS

The specifics of perioperative and anesthetic management in LVRS are delineated in the contributions of Brister and colleagues (pages 432–437, this symposium [45]) and Sharafkhaneh and coworkers (pages 438–441, this symposium [44]) in this symposium. The keys to achieving better early post-surgical outcomes and minimizing perioperative complications lie in having the pa-

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TABLE 1. COMMON INCLUSION AND EXCLUSION CRITERIA FOR LUNG VOLUME REDUCTION SURGERY

Inclusion Criteria	
Radiographic evidence of emphysema, especially involving upper lobes	
Hyperinflation	
FEV ₁ > 20 and < 45% predicted (post-bronchodilator)	
D _{LCO} > 20% predicted	
Severe dyspnea	
Restricted activities of daily living	
Decreased quality of life	
Abstinence from tobacco	
Exclusion Criteria	
Active smoking	
Bronchiectasis	
Pulmonary nodule requiring evaluation	
Excessive daily sputum production	
Previous thoracotomy	
Obvious pleural disease	
Active or inducible coronary ischemia	
Pulmonary hypertension	
Depressed LVEF(< 45%)	
Obesity	
Systemic steroids ≥ 20 mg prednisone/d	

Definition of abbreviations: D_{LCO} = diffusion capacity for carbon monoxide; LVEF = left ventricular ejection fraction.

tient compliant with all aspects of preoperative rehabilitation, minimizing inhalational anesthesia, effective epidural analgesia, immediate extubation, and early ambulation.

Unilateral versus Bilateral LVRS

Video-assisted thoracic surgery (VATS) became popular among general thoracic surgeons concurrent with Cooper's reports of bilateral LVRS via median sternotomy. Surgeons with early VATS experience reported unilateral LVRS results with morbidity, mortality, and hospital lengths of stay similar to those described by Cooper (Table 2, References 7–10). The consistent criticism of unilateral LVRS was an underwhelming physiologic benefit, with mean improvement in FEV₁ often half that reported after a bilateral intervention. Some unilateral enthusiasts argued that the short duration of benefit after LVRS (2–3 years) argued for a staged unilateral LVRS strategy to provide a longer overall period of palliation (20).

As surgeons gained more VATS experience in the 1990s, reports of bilateral thoracoscopic LVRS emerged with mortality and morbidity similar to that of the unilateral or median sternotomy groups. These investigators also reported physiologic improvements similar to those observed after a bilateral intervention via sternotomy (4, 11–13). Given hospital lengths of stay after bilateral LVRS via either sternotomy or VATS equivalent to those for unilateral LVRS, the costs of two separate

TABLE 2. UNILATERAL VERSUS BILATERAL LUNG VOLUME REDUCTION SURGERY

Author	Year	n	Technique	Mortality (%)	LOS (d)	Change in FEV ₁
McKenna (8)	1996	87	Unilateral	3	11.4	31%
Naunheim (7)	1996	50	Unilateral	2	13	35%
Keenan (9)	1996	57	Unilateral	2	17	27%
Cooper (10)	1996	150	Bilateral	4	13.5	51%
Kotloff (4)	1996	80	Bilateral	13.8	22	41%
Argenziano (5)	1996	85	Bilateral	7	17	61%
McKenna (11)	1997	154	Bilateral	4	11	52%
Kotloff (4)	1996	40	Bilateral	2.5	15	41%
NETT (18, 19)	2003/4	511	Bilateral	2.2	10	NR

Definition of abbreviations: LOS = length of stay; NETT = National Emphysema Treatment Trial; NR = not reported.

TABLE 3. INDICATIONS FOR UNILATERAL LUNG VOLUME REDUCTION SURGERY

Unilateral or severely asymmetric emphysema
Contralateral pleurodesis
Contralateral thoracotomy with or without prior lung resection
Ipsilateral lung cancer resection with contralateral LVRS for a patient with limited lung function
Hemodynamic instability during the first side of planned bilateral LVRS
Massive air leak during the first side of planned bilateral LVRS
Severe native lung hyperinflation following single lung transplantation for emphysema

Definition of abbreviation: LVRS = lung volume reduction surgery.

procedures and two hospitalizations became prohibitive. Bilateral LVRS became the standard of care for patients seeking relief of dyspnea from moderate to severe emphysema.

Unusual clinical conditions do arise for which unilateral LVRS may be appropriate. These are summarized in Table 3. Unilateral LVRS is best accomplished with the patient in the lateral decubitus position, allowing for either a standard posterolateral or muscle-sparing thoracotomy or VATS. The lateral position typically provides ample open or video exposure of the anterior, lateral, and posterior pleural surfaces and is superior to sternotomy for accessing the lower lobes (21).

Bilateral LVRS is usually accomplished using either a median sternotomy or via VATS. Either approach is preferable to bilateral thoracotomies, which divide more muscle and are generally more painful. A median sternotomy is simple and quick to perform. As it is a midline incision, no muscle is divided, making it less painful during postoperative convalescence. This incision provides excellent exposure to anterior, medial, and apical disease, though posterior adhesions and lower lobe targets of disease remain difficult to visualize, dissect, and/or resect.

A VATS approach to bilateral LVRS can be performed with staged lateral approaches under one anesthetic or in a single stage fashion with the patient supine. A 30-degree video-telescope enhances visualization in either patient position. The presence of posterior pleural adhesions or an LVRS plan, which involves resection of portions of the lower lobes, mandates the use of the lateral position. The patient will need to be repositioned, repped, and draped to achieve bilateral lung volume reduction, which adds time and expense to the procedure. Care must also be taken to ensure the chest drains after LVRS in the first pleural space remain unobstructed during contralateral LVRS to avoid tension pneumothorax and intraoperative cardiovascular and/or respiratory collapse.

When the targets for LVRS are predominantly upper lobe and a bilateral VATS procedure is planned, many surgeons prefer to have the patient supine supported on blanket rolls or a beanbag beneath the spine, shoulder, and hips. This allows the arms to be strapped to a padded ether screen over the patient's head and, with the patient elevated off the operating table, frees the anterior and lateral chest wall up to the axillae bilaterally for port placement. This position has also been described for bilateral sequential single lung transplantation using either bilateral anterior thoracotomies or a clamshell bilateral sternothoracotomy. Single stage positioning allows the surgeon to move between the two pleural spaces more quickly during bilateral LVRS and may shorten operative and anesthetic time. Immediate access to either pleural space is also useful should significant bleeding or intraoperative air-leak arise (22).

Stapled versus Laser LVRS

As LVRS achieved popular acclaim in the early and mid-1990s, most of the resected lung was excised via sternotomy using mechanical staplers originally developed for gastrointestinal

surgery. As VATS was being introduced and before the widespread availability of endoscopic staplers, thoracic surgeons used carbon dioxide (23) and neodymium: yttrium-aluminum garnet (Nd-YAG) (24) lasers to perform VATS LVRS.

Initial results were encouraging, but there was an alarming rate of delayed pneumothorax, approaching 20% in laser-treated patients. These were presumably related to sloughing of the laser-induced pleural eschar at the site of volume reduction and often occurred well after hospital discharge, requiring urgent readmission. McKenna and colleagues performed a randomized trial comparing laser to stapled LVRS, and confirmed a higher rate of morbidity in the laser-treated group, with inferior physiologic improvement and minimal durability (25). Hazelrigg and coworkers' experience with 144 laser-treated patients corroborated these findings (26). Such poor results and the subsequent widespread availability of endoscopic staplers has caused laser LVRS to be abandoned. The NETT mandated a bilateral stapled approach to LVRS (17).

Median Sternotomy versus VATS

Before NETT there was conflicting data regarding the optimal approach to stapled bilateral LVRS. Two small, single institutional, retrospective series reported equivalent mean physiologic improvements when patients who had undergone sternotomy were compared with those who had undergone VATS. One trial demonstrated higher morbidity for sternotomy (4), while the other reported similar operative morbidity but a quicker realization of physiologic improvement after VATS (15). Cooper and colleagues (10) and McKenna and coworkers (11) each published large ($n \geq 150$ patients), single institutional case series of bilateral LVRS via sternotomy and VATS, respectively. Both authors operated on patients with similar severity of emphysema and achieved remarkably similar results in terms of 90-day mortality and mean improvement in FEV₁.

A major strength of NETT was the prospective design mandating that centers designate themselves as sternotomy sites, VATS sites, or sites willing to internally randomize to either approach. Overall, 511 non-high-risk patients had LVRS in NETT; 359 underwent median sternotomy, while 152 patients had a bilateral VATS approach. Within the internally randomized surgical patients, 77 had a sternotomy and 71 had VATS. This is the largest direct comparison of LVRS by sternotomy and VATS and the only study to date with a subset of patients randomly assigned to the two surgical approaches.

NETT surgeons found that the two approaches resulted in similar early and late mortality, similar types and rates of complications, and produced similar improvements in spirometry, exercise capacity, and quality of life extending to 24 months of follow-up (19). The operative results alone are impressive with a 90-day mortality in NETT between 4.6% (VATS) and 5.9% (sternotomy) versus the pre-NETT Medicare 90-day mortality rate of 14.4% (16). It is important to note that NETT achieved these outcomes across 17 centers with surgical volumes ranging from 19 to 50 cases performed over the 4.5 years of the trial.

The NETT surgical experience did find that VATS LVRS allowed for a statistically significant shorter hospital stay and earlier recovery, with more VATS patients living independently 30 days after surgery. These outcomes also translated into a statistically significant mean cost savings of about \$8,000 for the hospitalization and \$10,000 for the subsequent 6 months of care for patients in the VATS group (19).

Buttressing

Air leak is common after pulmonary surgery and essentially universal after LVRS. In NETT, 90% of operated patients

developed an air leak with a median duration of 7 days (27). The use of reinforcing materials to buttress suture or staple lines has been proposed as a remedy for this problem. Surprisingly little data exists to support or refute its efficacy. A small, two-institution, randomized trial of buttressing with bovine pericardium ($n = 58$) versus no buttressing ($n = 65$) was reported in 1997 and demonstrated a 2- to 3-day reduction in hospital stay for the buttressed group. Despite this shorter stay, hospital charges for the two groups were identical, suggesting that the cost of the buttress offsets potential savings (28). Stammberger and colleagues reported a statistically significant reduction in air leak duration with bilateral, buttressed VATS LVRS ($n = 65$ patients randomized), but no reduction in overall hospital stay (29).

Despite the lack of evidence to firmly support buttressing, surgeons performing LVRS have typically used either bovine pericardium or expanded polytetrafluoroethylene (ePTFE) routinely. Of the 522 surgical patients who had use of one of these two materials, there was no demonstrable benefit of one over the other. Only 4.7% of NETT patients had unbuttressed LVRS (27). Given this paucity of unbuttressed LVRS, an unbiased comparison between buttressed and unbuttressed patients would be impossible.

MORTALITY

Operative mortality and morbidity after LVRS is higher than that seen after most other elective general thoracic procedures. The severity of their lung disease makes such patients extremely fragile both anatomically and physiologically. Identification of factors that accurately and consistently predict adverse outcome is necessary to develop evidence-based exclusion criteria. Many series of LVRS have reported a variety of demographic, radiologic, and/or physiologic characteristics that predicted higher operative risk (Table 4) (9, 30–39). Unfortunately, most were small, retrospective, single-institution, case-controlled series with selection bias and incomplete or inconsistent data collection.

NETT, with its rigorous prospective study design and audited data collection, was better equipped to elucidate valid factors predictive of both salutary outcomes as well as those associated with increased operative mortality and/or morbidity. NETT has better defined the value of LVRS as well as helped optimize patient selection for the procedure itself.

Operative mortality within NETT was defined as occurring within 90 days of LVRS rather than the customary 30 days used in most reports of surgical mortality. Given available critical care expertise and the chronic nature of respiratory failure in the population with emphysema, the 3-month horizon was felt to be a more realistic time period to account for deaths attributable to the operation. Despite this expanded definition, the 90-day mortality of the non-high-risk patients in NETT

TABLE 4. PREDICTORS OF MORTALITY FOLLOWING LUNG VOLUME REDUCTION SURGERY

Factor	Published Series
Advancing age	Naunheim (30), Glaspole (31)
Male sex	Naunheim (30), Ciccone (32)
Declining exercise tolerance	Szekely (33), Naunheim (30), Geddes (34), Ciccone (32)
Increasing PaCO ₂	Szekely (33), O'Brien (35), Keenan (9)
Decreasing FEV ₁	NETT (36), Ciccone (32)
Decreasing DLCO	NETT (36), Geddes (34), Keenan (9)
Imaging studies	NETT (36), Slone (37), Wisser (38), Weder (39)

Definition of abbreviations: DLCO = diffusion capacity for carbon monoxide; NETT = National Emphysema Treatment Trial.

undergoing LVRS was only 5.5% ($n = 28$ patients). Death after LVRS in NETT was primarily respiratory in 43% of cases, cardiovascular in 18%, multiple organ failure in 7%, cerebrovascular in 4%, septic in 4%, and unclassified in 25%. In multivariate analysis, only a non-upper-lobe predominant pattern of emphysema was independently predictive of 90-day mortality (odds ratio, 2.99; $P = 0.009$) (40).

MORBIDITY

Complications associated with surgery can occur intraoperatively or during the postoperative period. Within NETT, 91% of patients experienced no intraoperative complications; however, almost 60% developed one or more postoperative problems requiring intervention. Major pulmonary morbidity was defined as the need for reintubation, tracheostomy, ventilator support for more than 2 days, or pneumonia within 30 days of operation. This was the most common category of morbidity, affecting nearly 30% of patients. Major cardiovascular morbidity was defined as arrhythmia requiring chemical or electrophysiologic treatment, myocardial infarction, or pulmonary embolus. Twenty percent of patients having LVRS within NETT experienced one of these major cardiac events. A tabulation of complications within NETT is organized around these two major categories and presented in Table 5.

Naunheim and colleagues on behalf of the NETT investigators performed an exhaustive univariate and multivariate analysis of more than 20 demographic, physical, biochemical, pharmacologic, radiographic, physiologic, exercise, and quality of life measures to identify independent predictors of major pulmonary and/or cardiac morbidity after LVRS. Three continuous variables were defined as independent predictors of pulmonary morbidity. These were advancing age, declining FEV₁, and declining DL_{CO}. Advancing age was also independently predictive of major cardiac morbidity, as was the use of oral

corticosteroids at the time of surgery and the presence of a non-upper-lobe predominant pattern of emphysema (40).

Air leak lasting more than 7 days is a familiar complication after LVRS (4, 5, 10, 14, 15). Its influence on outcome in NETT was purposefully omitted in Naunheim and coworkers' consideration of perioperative mortality and morbidity to allow DeCamp and colleagues to identify risk factors for the occurrence, duration and consequences of air leak (27). Within NETT, 90% of patients experienced some air leak with a median duration of 7 days. Sixty-six patients had a persistent air leak 30 days after surgery. Both the prevalence and duration of leak were associated with patient factors (use of inhaled steroids, declining lung function, distribution of emphysema, and degree of pleural adhesions) and not with institutional surgical volume, approach to LVRS (sternotomy or VATS), brand of stapler, type of buttress material, or the use of pleural tenting. Analysis of 54 propensity-matched pairs of patients (41) demonstrated that despite having similar mortality risk, those patients experiencing an air leak had more overall complications, were more likely to develop postoperative pneumonia, were more likely to be readmitted to the ICU, and had nearly a 4-day longer hospital length of stay.

CLINICAL INFERENCES

How can we use these data to enhance our clinical judgment? The absence of other independent predictors of adverse outcomes in the NETT data is a testament to the rigorous selection criteria applied by these investigators and serve as a validated template from which LVRS should continue. Advancing age must always be considered when weighing risk versus benefit of any palliative surgical intervention. Declining FEV₁ and DL_{CO} define the most severe cohort of patients with emphysema and have already been shown to engender excessive operative risk (36). The observation that a non-upper-lobe predominant pattern of emphysema was independently associated with increased operative mortality and major cardiovascular morbidity lends support to a more conservative program of LVRS, which focuses primarily on patients with heterogeneous disease located in the upper lobes. Despite the Medicare coverage decision to allow for reimbursement for LVRS for some patients with non-upper-lobe predominant disease, the risks of LVRS in this subset appear to be substantial and the functional benefits with mature follow-up appear limited (42).

For those patients satisfying each of these qualified inclusion and exclusion criteria for LVRS, the NETT experience would suggest an attempt to wean and discontinue both inhaled and systemic steroids perioperatively to minimize cardiovascular and air leak morbidity, respectively. The surgeon should also carefully examine the cross-sectional imaging of older candidates with marginal physiology (FEV₁ and/or DL_{CO}) with particular attention to the presence of pleural thickening suggestive of dense adhesions.

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TABLE 5. COMPLICATIONS FOLLOWING LUNG VOLUME REDUCTION SURGERY IN NETT ($n = 511$)

Intraoperative	
None	91%
Hypotension	0.4%
Arrhythmia	1.2%
Hypoxemia	2.2%
Cardiac arrest	0.4%
Uncontrolled air leak	1.0%
Postoperative (within 30 d of surgery)	
None	41.3%
Major pulmonary morbidity*	29.8%
Failure to wean	8.0%
Tracheostomy	8.2%
Pneumonia	18.2%
Reintubation	21.8%
Ventilation > 2 d	13.6%
Major cardiovascular morbidity*	20.0%
Arrhythmia requiring Rx	18.6%
Myocardial infarction	1.0%
Pulmonary embolus	0.8%
Reoperation for air leak	3.3%
Readmit to ICU	11.7%
Mediastinitis	0.6%
Sternal debridement	0.6%
Sepsis	2.5%
Epidural catheter complications	0.8%
Readmit to hospital	2.5%
Urinary retention	3.5%

Information from Reference 40. Patients may have more than one complication.

Definition of abbreviations: ICU = intensive care unit; NETT = National Emphysema Treatment Trial; Rx = therapy.

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