Bilateral pneumectomy (volume reduction) for chronic obstructive pulmonary disease

We undertook surgical bilateral lung volume reduction in 20 patients with severe chronic obstructive pulmonary disease to relieve thoracic distention and improve respiratory mechanics. The operation, done through median sternotomy, involves excision of 20% to 30% of the volume of each lung. The most affected portions are excised with the use of a linear stapling device fitted with strips of bovine pericardium attached to both the anvil and the cartridge to buttress the staple lines and eliminate air leakage through the staple holes. Preoperative and postoperative assessment of results has included grading of dyspnea and quality of life, exercise performance, and objective measurements of lung function by spirometry and plethysmography. There has been no early or late mortality and no requirement for immediate postoperative ventilatory assistance. Follow-up ranges from 1 to 15 months (mean 6.4 months). The mean forced expiratory volume in 1 second has improved by 82% and the reduction in total lung capacity, residual volume, and trapped gas has been highly significant. These changes have been associated with marked relief of dyspnea and improvement in exercise tolerance and quality of life. Although the follow-up period is short, these preliminary results suggest that bilateral surgical volume reduction may be of significant value for selected patients with severe chronic obstructive pulmonary disease. (*J THORAC CARDIOVASC SURG* 1995;109:106-19)

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Excision, plication, or decompression of large space-occupying bullae in patients with chronic obstructive pulmonary disease (COPD) may signifi-

cantly relieve symptoms of dyspnea and improve exercise tolerance.¹⁻⁴ Indications for operation have generally been accepted to be "incapacitating dyspnea with unequivocal compression of relatively normal underlying lung tissue."⁵ In such cases the presence of normal underlying compressed lung has been identified, traditionally, by pulmonary angiography or tomography and, more recently, by chest computed tomographic (CT) scan.

More than 35 years ago, Dr. Otto C. Brantigan reported his experience with an entirely different concept of pulmonary resection in patients with diffuse emphysema.⁶⁻⁸ He postulated that in patients with distended lungs caused by severe COPD, the normal outward circumferential pull on the bronchioles had been lost, causing their collapse during

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expiration. He proposed that reducing overall lung volume, by means of multiple wedge excisions or plications, would restore the outward elastic pull on the small airways and reduce expiratory airway obstruction.

Brantigan did his operation through a standard thoracotomy, performing multiple lung resections and plications, and incorporating radical hilar stripping to denervate the lung. This latter component, it was thought, reduced the production of tenacious sputum. Significant clinical improvement was reported in 75% of patients,⁸ and this improvement continued in some patients for more than 5 years. However, because the early mortality rate was 16%, and few objective data were reported to substantiate claims of subjective improvement, Brantigan's procedure never gained widespread acceptance. Six years ago, Brantigan's work was brought to the attention of one of us (J. D. C.), and subsequent observations made in patients who underwent lung transplantation for COPD suggested that in certain patients Brantigan's principles might apply. Fifteen months ago we began a prospective study to evaluate the merits of surgical bilateral lung volume reduction for such patients.

Methods

Patient population. Twenty patients with severe COPD were selected on the basis of the presence of a distended thorax and significant functional limitation despite maximum medical therapy. Patients who underwent operation for large emphysematous bullae, in the presence of normal underlying compressed lung, were excluded from this report. None of the patients in this series had α_1 -antitrypsin deficiency. Patients who continued to smoke were excluded from consideration. There were 11 men and 9 women, and the age range was 37 to 76 years with a mean of 56 years. Fourteen patients required supplemental oxygen with exertion, and of these five also required supplemental oxygen at rest. Eleven patients were taking regular doses of oral prednisone. One patient had previously undergone lobectomy for tuberculosis and another patient had undergone chemical pleurodesis for spontaneous pneumothorax. Two patients had previously been accepted for lung transplant and had accrued 5 and 12 months of waiting time, respectively, before being offered surgical volume reduction as an alternative. Another four patients were referred for lung transplantation and were thought to be suitable candidates for lung transplantation on the basis of the severity of their disease, the rate of progression, and limited life expectancy. These patients were offered surgical volume reduction as an alternative and chose the latter procedure.

Assessment

Physiologic. Assessment included standard pulmonary function studies, standardized 6-minute walk test, arterial

Table I. Modified Medical Research Council Dyspnea Scale

Grade	Symptoms
0	Not troubled with breathlessness except with strenuous exercise
1	Troubled by shortness of breath when hurrying on the level or walking up a slight hill
2	Walks slower than people of the same age on the level because of breathlessness or has to stop for breath when walking at own pace on the level
3	Stops for breath after walking about 100 yards or after a few minutes on the level
4	Too breathless to leave the house or breathless when dressing or undressing

blood gas values, quantitative nuclear lung perfusion and ventilation scan, catheterization of the right side of the heart, and lung volume measurements by plethysmography and by nitrogen washout. Whereas plethysmography gives accurate volumes in these patients, the nitrogen washout technique significantly underestimates the total lung capacity and the residual volume, and the discrepancy between these volumes measured by plethysmography and by nitrogen washout is a reflection of the volume of lung having no significant gas exchange during respiration.

Anatomic. Assessment included posteroanterior and lateral chest x-ray films taken in inspiration and expiration, chest CT scan, and, in some patients, dynamic magnetic resonance imaging evaluation of chest wall and diaphragmatic movement and coordination. If significant coronary artery disease was suspected, catheterization of the left side of the heart was also done at the same time as catheterization of the right side of the heart.

Degree of dyspnea. Several additional studies were undertaken to evaluate the effectiveness of the procedure. These included determination of the dyspnea index (Mahler and associates⁹), assessment with the modified Medical Research Council of Great Britain Dyspnea Scale,¹⁰ and quality of life assessment with the Nottingham Health Profile (NHP)¹¹ and the Medical Outcomes Study 36-Item Short-Form Health Survey (MOS SF-36).¹²⁻¹³ The modified Medical Research Council Dyspnea Scale is illustrated in Table I. The second dyspnea index was based on work by Mahler and associates⁹ who developed a baseline dyspnea index to rate the severity of dyspnea at one point in time and a transition index to note changes from that baseline value at a later date. We used that part of the evaluation that deals with the degree of functional impairment, which has grades ranging from 0 to 4 as shown in Table II: grade 0 represents very severe impairment and grade 4 represents no impairment. The transition index, also shown in Table II, measures deterioration or improvement in functional impairment: 0 represents no change; -1, -2, and -3 represent, respectively, minor, moderate, and major deterioration; and +1,

Table II

<i>Baseline dyspnea scale</i>	
Functional impairment	
Grade 4:	No impairment. Able to do usual activities and occupation without shortness of breath.
Grade 3:	Slight impairment. Distinct impairment in at least one activity but no activities completely abandoned. Reduction in activity at work or in usual activities that seems slight or not clearly caused by shortness of breath.
Grade 2:	Moderate impairment. Patient has changed jobs or has abandoned at least one usual activity because of shortness of breath.
Grade 1:	Severe impairment. Patient unable to work or has given up most or all usual activities because of shortness of breath.
Grade 0:	Very severe impairment. Unable to work and has given up most or all usual activities because of shortness of breath.
<i>Transition dyspnea index</i>	
Change in functional impairment	
-3:	Major deterioration. Has deteriorated two grades or more from baseline status.
-2:	Moderate deterioration. Formerly working and has had to stop working or has completely abandoned some of usual activities because of shortness of breath.
-1:	Minor deterioration. Has changed to a lighter job or has reduced activities in number or duration because of shortness of breath. Any deterioration less than preceding categories.
0:	No change. No change in functional status caused by shortness of breath.
+1:	Minor improvement. Able to return to work at reduced pace or has resumed some customary activities with more vigor than previously because of improvement in shortness of breath.
+2:	Moderate improvement. Able to return to work at nearly usual pace or able to return to most activities with restriction only.
+3:	Major improvement. Able to return to work at former pace and able to return to full activities with only mild rest because of improvement of shortness of breath.

+2, and +3 represent, respectively, minor, moderate, and major improvement.

The NHP consists of a two-part questionnaire designed to measure perceived health problems and how such problems affect normal activities. Part I measures subjective health status concerning energy, pain, emotional reactions, sleep, social isolation, and physical mobility. Part II examines seven areas of task performance: job/work, looking after the house, social life, home life, sex life, interests and hobbies, and holidays. The patient answers *yes* or *no* to the various questions in both parts. The NHP was used to measure quality of life before operation and at 3 and 6 months after operation. The statistical method used in the analysis of data was repeated-measures analysis.

Along with the NHP, the MOS SF-36^{12, 13} was also used because of its ability to assess quality of life as it directly relates to the patients' disease and response to treatment. Repeated-measures analysis of variance was used and significant time effects were further analyzed by Tukey's pairwise comparisons.

After evaluation, all patients were enrolled in a structured, supervised, exercise rehabilitation program for a minimum of 6 weeks. The assessment data used for postoperative evaluation of objective and subjective improvement were the data obtained just before operation, after the period of exercise rehabilitation.

Technique of operation. A thoracic epidural catheter was placed immediately before the operation, thereby eliminating the need for intraoperative systemic narcotic agents. A left-sided double-lumen endotracheal tube was used. A standard median sternotomy incision was made and the side that showed the worst preoperative lung function, according to quantitative perfusion and ventilation scans, was done first. The pleura was incised longitudinally,

several centimeters posterior to the sternum to facilitate subsequent closure of the pleura at the end of the procedure. Care was taken to avoid incising the pleura too far cephalad to avoid injury to the phrenic nerve. The lung was deflated and one-lung ventilation directed to the contralateral side. Under these conditions, after a few minutes, the relatively more healthy portions of the lung undergo absorption atelectasis whereas the most destroyed portions often remain fully inflated because of poor or absent pulmonary blood flow. Several large, moist packs were placed posterior to the lung so as to elevate it anteriorly and facilitate the remainder of the procedure. Excision was directed to those portions of the lung that remained distended, which in most patients involved predominantly the upper lobes. This generally correlates with the previously recognized areas of severe destruction as gauged by the CT scans and quantitative nuclear lung scans. This was corroborated by visual inspection and palpation. Our goal has been to reduce the overall volume of each lung by 20% to 30%, concentrating on the most destroyed areas of lung. In some patients there was a mixture of bullous and nonbullous areas, whereas the majority of patients had diffuse changes with no apparent bullae. Successive applications of the linear stapling device were used to excise a significant portion of the upper lobe. In several patients, the emphysematous process was uniformly severe and portions of all lobes were excised. After excision of one or two pieces, the lung was reinflated to assess the adequacy of the volume reduction. If appropriate, the lung was again deflated and additional resection was done. The pulmonary ligament was divided.

In our initial experience, reinflation of the lung was associated with multiple small air leaks through the staple holes, which being located in severely emphysematous lung expanded or tore as the lung was reinflated. This

Fig. 1. Staple line through portion of left upper lobe with use of pericardial strips for buttressing. This technique has eliminated air leakage at staple line.

problem has been eliminated by the use of bovine pericardial strips to buttress the staple line as previously described (Fig. 1).¹⁴

It is important not only to reduce the volume of the lung but also to produce a lung shape that will fill the thorax and avoid postoperative air spaces. At the apex this is best accomplished by oblique rather than transverse excision of the superior portion of the upper lobe. If multiple bullae are present, the tendency to excise all of them must be avoided, inasmuch as this may result in excessive reduction of the lung volume with a resulting air space. On occasion, there was concern after excision about a possible apical air space. In such cases, a pleural tent was created that allowed the freed apical pleura to drop down to the upper surface of the remaining lung.

After the final excision, the lung was reinflated and inspected under water for air leaks. Every attempt was made to eliminate air leaks completely, inasmuch as even a small air leak from diffusely emphysematous lung may necessitate prolonged postoperative chest tube drainage. On completion of the first side, the lung was fully reinflated. The opposite lung was then deflated and an identical procedure done. Two chest tubes were placed on either side and the pleura was closed bilaterally before closure of the sternotomy. A typical operation takes 2 to 3 hours. Fig. 2 shows preoperative and immediate postoperative x-ray films from a typical case.

The discrepancy between the enlarged thorax and the reduced lung size results in significant distending forces on the surface of the lung. To avoid excessive stress on the lung surface, therefore, the initial setting for the chest suction bottles was -10 cm of water pressure. This was

subsequently adjusted depending on the presence or absence of air leakage and the results of the portable chest x-ray film taken immediately on the transfer of the patient to the recovery area. All patients were extubated at the end of the procedure or shortly thereafter. One patient required reintubation and ventilation of the lungs overnight, with successful extubation on the following morning. Postoperative analgesia was provided by a mixture of 0.2% bupivacaine with 5 μ g/ml fentanyl administered through the thoracic epidural catheter with supplemental use of rectal indomethacin suppositories. The use of systemic narcotics was avoided for the first few days. Vigorous chest physiotherapy was instituted shortly after the procedure and administered frequently by the specially trained nursing staff and chest physiotherapists.

Results

Before operation the mean forced expiratory volume in 1 second (FEV_1) was 0.77 L or 25% of predicted. Eighteen of the 20 patients had an arterial oxygen tension measured on room air before operation with a range of 36 to 75 mm Hg and a mean of 64 ± 6.5 mm Hg. The condition of remaining two patients was too hypoxic to permit measurement of the oxygen tension on room air. The mean arterial carbon dioxide tension was 40 mm Hg (range 28 to 54 mm Hg). Three patients had a resting arterial carbon dioxide tension greater than 50 mm Hg. The mean pulmonary artery pressure

Fig. 2. Preoperative (*left*) and postoperative (*right*) x-ray film of 57-year old man. Endotracheal tube was removed immediately after chest x-ray film was taken. Film shows reconfiguration of chest and diaphragms. FEV₁ was 0.57 L before operation and 1.59 L at 3 months.

was 23 ± 5.1 mm Hg. No patient had a mean pulmonary arterial pressure higher than 35 mm Hg.

There have been no early or late deaths in this series. The hospital stay ranged from 6 to 49 days with a mean of 15 and a median of 13 days. Prolonged air leak (more than 7 days) was present in 11 patients including the 2 patients who had undergone previous thoracic procedures. Four patients required reexploration. One was because of bleeding from an apical adhesion. A second, early in the series, was because of persistent apical air space. A muscle-sparing lateral thoracotomy was done on the third postoperative day with creation of an apical pleural tent. In the remaining two patients, reexploration was done because of sudden development of massive bilateral air leakage. Both patients had virtually no air leakage at the end of the procedure. In one of these patients, subsequent extubation was associated with an explosive cough and the immediate development of massive air leakage. The patient underwent reexploration several hours later. The staple lines were intact, but a tiny rupture of the surface of the right lower lobe was found, which measured 1 to 2 mm in maximum diameter. This area was plicated with a staple line buttressed with bovine pericardium. The patient had no further air leakage and was discharged home the following week. The other patient became nauseated on the second postoperative day and had a violent emesis

immediately followed by massive bilateral air leak and apical pneumothoraces. She subsequently underwent reexploration and was found to have a small rupture on the surface of each lower lobe. These were plicated as in the first case, which resulted in no further air leakage and discharge from the hospital the following week. A postoperative phrenic nerve palsy has developed in two patients, including one patient with a fused pleural space from a previous pleurodesis. The nerve injury is thought to have resulted from traction during exposure of the pulmonary ligament.

The follow-up ranges from 1 to 15 months (mean 6.4 months) with 14 patients at 3 months or more and 8 patients at 6 months or more after the procedure. Objective and subjective assessment of results has been obtained 1, 3, 6, and 12 months after operation. In general, lung function continued to improve for at least 3 months, and in many patients further improvement was noted at 6 months.

Lung function studies. Table III demonstrates the improvement in spirometric and lung volume measurements. The total lung capacity and residual volumes shown were obtained by plethysmography. The trapped gas calculation is the difference between the total lung capacity as measured by plethysmography and that measured by the nitrogen washout technique. The postoperative measurements listed in Table III are those obtained at 6

months ($n = 8$) or between 1 and 6 months after operation ($n = 12$) for those who have not yet reached 6 months after operation.

Oxygen requirement. Four patients currently require oxygen with exercise, compared with 14 patients before operation. Of this number 3 also require oxygen at rest, compared with 5 patients before operation. Of the 14 patients evaluated at 3 months or more after operation, only 2 currently require supplemental oxygen with vigorous exercise.

Six-minute walk. The results of the 6-minute walk test are shown in Fig. 3. At the time the patients were first referred to us for treatment, the mean distance covered in 6 minutes was 958 feet and 12 of the patients required supplemental oxygen. After rehabilitation and just before operation, the mean distance had increased to 1220 feet and 14 patients required supplemental oxygen. At 1 month, postoperative results were similar to the preoperative values, but fewer patients required oxygen. Further improvement occurred at 3- and 6-month follow-up examinations.

Dyspnea

Medical Research Council Dyspnea Scale. Preoperative and postoperative data are available for 11 patients. The mean grade of dyspnea before operation was 2.9, which indicated that patients before operation stopped for breath after walking about 100 yards or after a few minutes on level ground. After operation the mean grade was 0.8, which indicated that patients were troubled by shortness of breath only when hurrying on level ground or walking up a slight hill.

Dyspnea index. Preoperative and postoperative data are available for 18 patients. The mean grade of dyspnea for functional impairment was 1.2 before operation, which indicated that patients before operation were severely impaired. They were unable to work or had given up most or all usual activities because of shortness of breath. Data for the patients' most recent postoperative assessment showed a mean change in functional impairment, as measured by the transition dyspnea index, of +2. This indicates moderate improvement. The patients have been able to work at nearly the usual pace or have been able to return to most activities with moderate restriction only (which in some cases is because the patient is in the early postoperative period).

Results of quality of life assessment

NHP. The preoperative and postoperative mean NHP dimension scores on parts I and II of the

Table III

	Before operation	After operation	Percent change	p Value
FEV ₁ in liters (% of predicted)	0.77 (25)	1.4 (44)	+82	<0.001
FVC in liters (% of predicted)	2.2 (56)	2.8 (73)	+27	<0.05
TLC in liters (% of predicted)	8.5 (140)	6.6 (110)	-22	<0.001
RV in liters (% predicted)	5.9 (288)	3.6 (177)	-39	<0.001
Trapped gas in liters	2.4	1.2	-50	<0.001
Pao ₂ in millimeters of mercury (room air)	64*	70		<0.05
Paco ₂ in millime- ters of mercury (room air)	40*	39		NS

FVC, Forced vital capacity; TLC, total lung capacity; RV, residual volume; NS, not significant.

*Two patients receiving oxygen excluded.

questionnaire are shown in Table IV. In Part I, patients noted significant improvement in energy, emotional reaction, and physical mobility at 3 months after operation when compared with preoperative data. Over the same period as noted in Part II, patients noted a significant reduction in problems related to health concerning job/work, looking after the house, social life, interests/hobbies, and holidays. The improvements in Part I and Part II were sustained or further improved at 6 months in the patients evaluable at that time.

MOS SF-36. The overall health transition improved by a significant amount ($p \leq 0.05$) from before operation to 3 months after operation. Those items that also increased by a significant amount were vitality, social functioning, physical functioning, general health, and an increase in the patients' ability to resume various roles in life.

Discussion

The traditional assumption underlying bullectomy for bullous emphysema is that the bullae enlarge to such a size as to crowd out normal, underlying lung tissue, which remains compressed or restricted. With the removal or decompression of such bullae, functional improvement is presumed to result from the restoration of function to the normal underlying lung. This has been emphasized in several reviews including those by Connolly and Wilson,⁴ Gaensler and associates,¹⁵ and Benfield and coworkers.¹⁶ Brantigan's notion, however, was entirely different:

Fig. 3. Results of 6-minute walk test. Patients are permitted to stop as often as required. Before operation (PRE-OP) 14 of 20 patients required oxygen (asterisk), whereas 2 of 15 patients studied at 3 months required oxygen (cross). EVAL, Evaluation period before start of rehabilitation program; MTH, months.

Table IV. Results of NHP

	Before operation (n = 16)	3 Months after operation (n = 11)	6 Months after operation (n = 7)
<i>Part I. Mean dimension score. The higher the score the more difficulty with these variables.</i>			
Energy	60	20*	9†
Pain	14	3	0
Emotional reaction	29	11*	13
Sleep	30	30	30
Social isolation	17	9	0
Physical mobility	21	11*	6†
<i>Part II. Percent of patients having health problems relating to these areas. The higher the percentage the more problems perceived.</i>			
Job/work	53	9	0†
Working about house	88	46*	0†
Social life	75	27*	14†
Home life	44	9	0
Sex life	69	30	14
Interests/hobbies	81	18*	0†
Holiday	75	18*	0†

* $p < 0.05$ before operation to 3 months after operation.

† $p < 0.05$ before operation to 6 months after operation.

he proposed multiple wedge resections of peripheral lung tissue to reduce lung volume and to restore circumferential traction on small airways. Gaensler and associates,¹⁷ commenting on Brantigan's observations, observed that "it is difficult to believe that a disease characterized by diffuse loss of lung parenchyma could be effectively treated by resection of functioning lung."

Several observations made in lung transplant re-

cipients suggested to us the possible validity of Brantigan's observations. When bilateral lung transplantation was first undertaken as a treatment for emphysema, we were concerned that the donor lungs might not adequately fill the large thorax, resulting in persistent air spaces. This concern proved groundless, because the thoracic configuration was found to rapidly return toward normal after the transplant. This suggested that a similar result

might be produced by surgical volume reduction. A second observation was that in the course of more than 50 single lung transplants for severe emphysema, gas exchange with one-lung ventilation has always been adequate. No patient has required use of cardiopulmonary bypass support, except in one case in which bypass was required to repair an injury to the pulmonary artery. That decompression of one lung, and ventilation of the opposite lung, has always resulted in perfectly satisfactory gas exchange has been a surprising finding and, one that indicates that a lung severely destroyed by emphysema nonetheless has the capacity for satisfactory gas exchange if adequately ventilated.

We decided to use median sternotomy and bilateral resection for this procedure to achieve maximum benefit at one operation, with a minimum of morbidity. We, and others, have previously used this approach for the resection of emphysematous bullae with good success.¹⁵ At the outset of this series, consideration was given to the possible role of a video-assisted approach to minimize morbidity. However, we have not adopted this approach because of several factors, including the desire to operate on both lungs at one sitting with a minimum of anesthesia time, the inability to palpate and examine all areas of the lung before selecting areas for resection, and the ability with an open procedure to minimize air leaks and to more accurately identify and secure any air leaks that do occur during the procedure. Indeed recent reports of thoracoscopic treatment of bullae including use of laser ablation have justified our reservations. These reports have generally dealt with patients with bullous disease whose conditions were more favorable rather than with patients with more complicated problems associated with nonbullous disease. Barker and associates¹⁸ have reported an early experience with unilateral video-assisted thoracoscopic laser bullectomy in which they observed prolonged anesthesia time, universal and significant postoperative air leakage, routine requirement for postoperative ventilatory assistance, prolonged intensive care unit stay, and a significant mortality rate. Furthermore, data relating to objective assessment of results have been limited, and those that have been available fail to show the same degree of improvement observed with the procedure described in this paper.^{19, 20} Paradoxically, therefore, the seemingly more radical approach that we have adopted has in fact produced superior results in terms of morbidity, mortality, and overall improvement than has the video-assisted approach.

In our first few patients, persistent air leaks at the staple line presented a troublesome problem and a prolonged hospital stay. For excision of emphysematous bullae, we had previously used a technique of incision of the bullae along the longitudinal axis with eversion of the bullous wall, to buttress the staple line that was then applied at the base of the bullae.²¹ This technique was not applicable for patients with diffuse emphysema. We therefore sought a suitable material for buttressing the staple line that would provide strong, supple backing that was easily cut by the knife blade of the stapler and thin enough to allow overlapping staple lines so that a second staple line could cut across the first without difficulty. The previously described uses of Teflon felt strips,²² polyglycolic acid fabric,²³ and polydioxanone ribbon²⁴ were evaluated and found not to be suitable for this particular application. With the use of the bovine pericardial strips, air leakage at the suture line has been completely eliminated, though air leakage from torn adhesions between the lobes or injury to the lung during manipulation and dissection may still occur. These other possible sources of air leakage during operation for emphysema have been emphasized by Crosa-Dorado and associates,²⁵ who also designed a special instrument used to roll up and suture portions of the lung for purposes of controlling parenchymal air leaks when portions of emphysematous lungs are excised.

Whereas our initial 10 patients had a mean hospital stay of 20 days this has been reduced to 13 days for the most recent 10 patients, in part because of reduction of postoperative air leakage.

How to evaluate results is a central issue in the assessment of this or any procedure designed to improve function in patients with COPD. Improvement in dyspnea was a consistent finding in our patients much as has been observed in patients after bullectomy.^{26, 27} It is recognized, however, that dyspnea is a subjective sensation and its apparent severity may or may not correlate with physiologic measurements.⁹ For these studies, we used three indices of overall lung function: subjective improvement was reflected in the dyspnea index and the quality of life assessment, performance was evaluated by means of the 6-minute walk test, and direct measurements of function were made by means of spirometry and plethysmography. By all three indices, the early results reflected in our data have been gratifying.

Such objective improvement has not always been apparent after standard decompressive bullectomy

for emphysema. Boushy and colleagues²⁶ noted only slight improvement in spirometric studies and Benfield and colleagues¹⁶ noted that "reliable correlation between subjective improvement and objective evidence on the basis of spirometric data has not been obtained." FitzGerald and colleagues,²⁷ on the other hand, documented an 81% improvement in the FEV₁ in six patients who had excision of bullae that occupied 70% to 100% of the chest whereas the improvement was only 18% when the bullae occupied between 40% and 70% of the chest.

Improvement, after bullectomy, is generally attributed to postoperative expansion of normal, underlying, compressed lung. Indeed, patient selection for bullectomy has primarily been based on this criterion.^{1, 17, 28} In contrast, Brantigan's concept was not based on the presumption of compression of underlying normal lung, but rather on the notion of restoring outward elastic forces on collapsible bronchioles. We have based selection of candidates for surgical bilateral volume reduction primarily on Brantigan's concept, choosing patients with hyperexpansion of the chest and flattening of the diaphragm. After surgical volume reduction, there is expansion of the remaining lung in addition to reduction of the overall thoracic volume, and it is probable that some areas of relative compression have been reexpanded. Both procedures likely owe their success to a combination of improved respiratory mechanics and improved redistribution of ventilation and perfusion in the remaining lung. The unifying principle then would be the presence of an overdistended chest, coupled with specific regions of the lungs with marked hyperexpansion and relatively absent ventilation and perfusion, be these areas bullous or nonbullous in nature. Undoubtedly, the ideal patient for this treatment is one who has thoracic distention and heterogeneity in the distribution of the emphysematous changes. This provides "target" areas of lung that can be sacrificed with little loss of functioning lung tissue to improve the function of the remaining, less diseased lung. Whether these target areas have bullous changes or not is probably unimportant.

We have yet to define rigorous criteria for patient selection. Initially, we chose only those patients who could not be considered for lung transplantation, either because of age or other contraindication or because the FEV₁ exceeded 20% of predicted, which is our upper limit of acceptance for transplantation for patients with emphysema. However, the consistently satisfactory early results obtained led us

to consider this procedure as a possible alternative to lung transplantation for selected patients, recognizing that this procedure might well serve as a "bridge" to transplantation at a later date, if and when subsequent deterioration occurred.

The improved pulmonary function, depicted in Table III, understates the overall results, because six of the postoperative measurements were made before 3 months of recovery. Analysis of the findings in patients 3 or more months after operation indicates that the results of these measurements continue to improve for a minimum of 3 months after operation. Nonetheless, the 82% improvement in the FEV₁ already achieved by the overall group of patients is quite gratifying. Similarly the reductions in the total lung capacity by 1.9 L, in the residual volume by 2.3 L, and in the trapped gas calculation by 1.2 L all confirm the underlying principle of this procedure; namely, elimination of functionless lung, which is merely occupying volume and taking up needed space. It was for this reason that we have somewhat fancifully chosen the term *pneumectomy* to describe this operation. The use of this term is based on an exchange that occurred between Dr. Evarts Graham and Dr. Howard Lilienthal at the 1933 Annual Meeting of The American Association for Thoracic Surgery. At that meeting, Dr. Lilienthal presented his experience with the attempted removal of an entire lung for a lung tumor (sarcoma) and referred to the procedure as a *pneumectomy*. Dr. Evarts Graham, in discussing this paper, indicated that he too had just recently done a similar operation, noting that "in my case, however, fortunately the result was successful." Dr. Graham continued, "I do not call it pneumectomy, as Dr. Lilienthal does, because I have the support of the Oxford dictionary and various other dictionaries to call it pneumectomy instead of pneumectomy." The discussion was continued by Dr. Pol Coryllos of New York who, illustrating on the blackboard, reviewed the Greek derivation of the various terms and concluded that the correct term should be *pneumectomy* as proposed by Dr. Lilienthal. Dr. Coryllos pointed out that the term *pneumectomy* means "resection of air," which is an apt description of the goal of surgical volume reduction.

Our report contains preliminary results and clearly must be viewed in this context. Undoubtedly these patients will by and large show further progression of the disease, though it is likely that many will achieve years of improved function. What will ultimately define the value of this procedure will be

the balance between the early morbidity and mortality of the procedure on the one hand, and the magnitude and duration of benefit achieved on the other. It would be premature to speculate at this time, except to note that the lower the operative risk can be kept, the more likely it is that the ultimate balance will be tipped in favor of the merits of this procedure. The successful results achieved to date are entirely the fruits of the efforts of a dedicated team of anesthesiologists, nursing staff, physiotherapists, and respiratory therapists who have years of experience caring for the more than 200 patients with severe end-stage lung disease who have undergone lung transplantation at this institution.

We acknowledge the essential contributions made to this work by the cardiothoracic anesthesia staff, the pain service under the direction of Dr. Robert Swarm, the cardiothoracic fellows, the nursing staff of the thoracic operating rooms and thoracic surgical clinical unit, the chest physiotherapy team, the respiratory therapists, Dotie Biggar, RN, and the staff of the pulmonary rehabilitation team, and all other members of the cardiothoracic service who worked so diligently to provide experienced and superior care to this complicated group of patients. We also wish to acknowledge the statistical support provided by Mr. Brad Wilson and the expert secretarial support of Ms. Kathy Stroud.

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Discussion

Dr. Charles Brantigan (*Denver, Colo.*). Otto Brantigan's research interests and publications were eclectic and diverse. He published more than 110 medical articles during his career, which covered such diverse subjects as gonococcal strictures, knee joint anatomy, and cardiothoracic surgery. The emphysema work described today began with the first procedure in 1950 and continued until he retired in 1976. As a surgeon myself, I cannot imagine doing such a procedure under conditions as primitive as they were in 1950.

As you have heard today, the operation was based on an understanding of pulmonary physiology. Whereas the operation consistently improved vital capacity and recreated a difference between inspiration and expiration on chest roentgenogram, my father had few additional objective measurements available to him. I was too young to appreciate his early attempts at measurement. While I was in college and medical school he shared with me his struggles to come up with these objective measurements. In 1963, for example, he saw a pH meter in the chemistry lab where I was working and saw immense potential for pH and blood gas measurements in clinical medicine, if only those were available to him. The following year, while he was explaining to me the relationship of surface tension of the lung to pulmonary emphysema, I showed him the Langmuir surface balance, which he then used to study the subject. Denervation of the lung, it turns out, produced a decrease in surface tension. His thought that the microvasculature was somehow important in emphysema led to early work with lung scanning, which proved insufficiently sensitive, and to beautiful corrosion castings of the lung, which now reside in my basement, but never led to a publication. From my younger brother he obtained a mass spectrometer originally designed for the space flight program, and he discovered that gas measurements by themselves were unable to document differences in a patient's functional capacity.

He asked for help from physiologists: most poignantly at the American Medical Association Clinical Congress in Washington in 1960. They were no more interested in studying these patients than they had been in studying the renal transplants that he had done in dogs in the 1940s. They knew that the pulmonary operation would not work with the same certainty that they knew that a transplanted kidney would never function. The result of this lack of measurements and the inherent difficulty of the operation was that the operation died with him.

My father believed that he had received great blessing throughout his career. He felt the need to pass on what he had learned. The highest honor a teacher can have is to have his pupil exceed his highest accomplishments. "If

someone criticizes your work," he said, "then publish the results. Your work will stand or fall on its own merits."

Three weeks ago the Denver Brass and the Colorado Symphony brass section performed, to great acclaim, a new composition that celebrated the life of a particular person. What an honor my father would have considered himself to have received today. He believed that the greatest honor that he could receive would be for someone to critically examine and confirm his work.

My family and I are indebted to Dr. Cooper and his colleagues and congratulate them on their fine work.

Dr. Joseph S. McLaughlin (*Baltimore, Md.*). I first met Otto Brantigan nearly 40 years ago when I took his course in clinical and surgical anatomy at the University of Maryland. This was a required course for sophomore medical students and for most of the surgical residents matriculating through the 14 surgical residency programs in Baltimore at that time.

Dr. Brantigan had an interesting career at the University of Maryland. He was a professor of anatomy, but in addition, he was professor of clinical surgery, professor of thoracic surgery, and chief of surgery at the old Baltimore City Hospital, which was a big hospital in those days. He maintained an enormous private practice in thoracic surgery and was then the premier thoracic surgeon in Baltimore. The last time I saw him was a few years before he died in 1981. He and Mrs. Brantigan and I came to New York as part of the Baltimore contingent for a combined meeting of the Baltimore, Philadelphia, and New York Surgical Societies. He indicated that he had always regretted that his work had not been accepted in this particular area because it was physiologic and not anatomic in nature. He is still quoted in orthopedic texts because of his anatomic descriptions of the knee.

The physiologic principle that Dr. Cooper described so well today is a simple one. Removal of areas of the emphysematous lung that are nonfunctional allows those areas that have the potential to exchange air to expand and realize this potential. This was contrary to the conventional wisdom of the time: that emphysema was a diffuse disease only. He had developed an operation that had an almost 20% mortality rate. He had no physiologic measurements as we know them today, which were so well presented by Dr. Cooper. So the work generally was rejected and, of historical interest, was rejected by some very distinguished members of this Society.

I believe it is fitting that Dr. Brantigan has been vindicated by the very thing that he said was necessary: by the development of physiologic studies that could prove his hypothesis. Dr. Kress, the other gentleman on the paper, was a pulmonologist in Baltimore who had an enormous practice. They operated on more than 30 patients with what appeared to be excellent clinical results. I am sure that Dr. Brantigan and Dr. Kress and the young man, Muller, who was a resident, would have been pleased to be here today to hear that Dr. Cooper, a member of this Society, has vindicated their work, which I believe is a significant contribution to our understanding and surgical treatment of emphysema.

Dr. Akio Wakabayashi (*Orange, Calif.*). Last October when I participated, pro and con, at a thoracic surgery session, one of the old doctors came up to me after the

session and said, "Dr. Brantigan was as courageous and innovative as you, but he eventually ruined his career." I am glad he did not ruin his career.

On today's topics, I have a few comments and two questions. Median sternotomy is a poor approach to the emphysematous lungs. If you do not inflate the lungs you cannot see the bullae, and if you inflate the lungs you cannot see the lungs, especially the posterior portion of the lungs. Also bilateral procedures are dangerous. If you have massive air leaks from both lungs, it is difficult to manage the ventilation after operation. Also, a stapling device should be used with extreme caution because it tends to cut too much lung tissue. Although I use stapling in almost every case, and I have done more than 740 cases of laser bullectomy, I use it carefully to limit the very weak portion of the lung, removing the weak portion of the lung after laser contraction of bullae to prevent future rupture. Whatever technique we use, the goal is to improve the breathing of the patient. We have to preserve lung parenchyma as much as possible.

My first question is this: what is your patient selection criteria for the pneumectomy operation? Second, how do you define the line of stapling in a diffusely emphysematous lung?

Dr. Cooper. I think that the comparison between Dr. Wakabayashi's procedure and mine offers a wonderful paradigm for the problem of focusing on technique rather than results. He believes that these patients are too ill to undergo a proper operation, and therefore, according to all of the published reports by his anesthetists and pulmonologists, he does a small operation: 5 to 6 hours of one lung deflation, uniform massive air leaks after operation, an average hospital stay of 16 days, a mortality rate that was initially 20% and then subsequently declined after several hundred cases to 5% and no documented measured significant improvement. We believe that these patients are much too ill to undergo an unsatisfactory procedure. You have to achieve the maximum benefit with the least morbidity. Therefore we choose the "big" operation. Yes, you can see all parts of the lung, the operation can be conducted in about 2 hours, maximum improvement is accomplished, and I think that we just have to let the results speak for themselves. Dr. Wakabayashi's argument emphasizes to me the inappropriate emphasis placed on methods. I do not really care about methods. I care about taking a group of patients who have started off with a significant problem and seeing them end up much improved. And I have no doubt that surgeons in the audience today will find refinements, improvements, and better ways of accomplishing the goal and I would certainly applaud that. Unfortunately, his procedure to date has not accomplished that.

The patients are selected on the basis of disabling dyspnea: symptoms that interfere with their quality of life. Many studies are done to measured distension of the chest, the degree of heterogeneity, and target areas of lung that can be removed, so as to remove the parts without much function. The manuscript will go into further details. We have excluded from this report all of the patients with bullous emphysema and underlying compressed lung. They do so well that it would be unfair to include them in this particular series.

When we open the chest, we collapse the worst lung first as shown by the preoperative scans. You all know that when a lung no longer receives ventilation absorption atelectasis occurs and the lung begins to shrink. What shrinks first? The best lung, that is, the areas with well-preserved vasculature. And so after about 5 minutes, the best parts of the lung are all atelectatic and the most diseased parts are still distended. That helps choose the areas, which usually correspond to areas previously targeted on CT scans and other scans.

Dr. Rodney J. Landreneau (Pittsburgh, Pa.). Dr. Cooper will certainly go down in history as a fine and innovative thoracic surgeon. His contributions to general thoracic surgery and pulmonary transplantation have been substantial. Likewise, we have honored a man, Dr. Brantigan, who was also an innovator and explorer. But I think it is also important to recognize other persons, such as Dr. Deslauriers and, yes, Dr. Wakabayashi, who have also earnestly explored this area of surgical treatment for emphysema. I believe that we should strive to work together in exploring this clinical problem. Certainly, the primary goals of this organization, which are aimed at advancing thoracic surgical knowledge and promoting fellowship, should be honored rather than increasing division within our ranks.

This present study was done by a group intimately involved in lung transplantation and pulmonary rehabilitation. I would like to ask Dr. Cooper if he believes this lung reduction procedure, done by thoracoscopy or done by sternotomy, will ultimately be able to be transferred to the community setting?

Dr. Cooper. I certainly apologize if I have been divisive here. It was not my intention to do so, other than to divide fact from fiction. And, as I have always said, all of us stand on the shoulders of giants who went before us. Of course, many people did make important contributions, not the least of whom are my associates.

As to where this operation should be done, I would like to first emphasize that it needs to come with a warning label attached. It is not a cure for emphysema. The patients still have emphysema and require medications. It does not apply to the vast majority of patients who have emphysema. Medical management is the proper treatment for emphysema. This operation should be used only when medical management fails and only in a highly selected group of patients. The results to date represent early short-term follow-up. The duration of improved function is yet to be determined.

And, finally, though the operation itself is easy to perform, the results reported today were made possible, as Dr. Landreneau pointed out, by the concerted efforts of a large team of highly experienced cardiothoracic anesthesiologists, physicians, chest physiotherapists, respiratory therapists, and others who have cared for more than 200 lung transplant patients. It is they who are responsible for the success that I report today in this difficult group of patients. Yes, the operation can be done anywhere technically, but unless it is done as a program with proper preoperative preparation, proper attention to detail, and proper experience, I am afraid it will get a bad name.

Dr. John R. Benfield (St. Louis, Mo.). Dr. Cooper, was

this approved by your Institutional Review Board as a research project?

Dr. Cooper. I did not apply to the Institutional Review Board because I believed that this was an extension of a widely accepted principle of excising lung from patients with emphysema to improve function. What I did do was propose, and had accepted by the Institutional Review Board, the studies that these patients are undergoing to document the benefit of the procedure.

Dr. Richard M. Peters (*Palo Alto, Calif.*). It seems to me that the concentration of respiratory function studies always centers on the lungs even for an operation such as pneumectomy, which has the major effect of improving ventilatory muscle function by decreasing the end expiratory chest cage volume and increasing the preload of ventilatory muscles so they can work more efficiently. Have you made any simple ventilatory function measurements such as maximum inspiratory pressure before and after operation? To complement your elegant dynamic magnetic resonance imaging scans have you also measured esophageal pressure? Did pneumectomy make the pleural pressure more negative (subatmospheric)? I am confident that the postoperative intrapleural pressures would be more negative.

The emphasis on change in FEV₁ as an indication of improve function uses an accepted criterion but is non-specific in these cases. Pneumectomy improves ventilatory function by making the end expiratory chest volume smaller, which improves the efficiency of the ventilatory muscles. Pneumectomy has removed mostly nonfunctioning peripheral portions of the lung to make the lungs smaller. Most of the remaining lung is still hyper-expanded. The symptom of dyspnea indicates fatigue of the ventilatory muscles. Pneumectomy makes it easier for the patient to perform the required ventilatory work. The muscles are more efficient, which delays fatigue and removes the need for oxygen. We always concentrate on the lungs, which your operation must damage. Pneumectomy improves the ventilatory pump efficiency more than it hurts the lungs.

Dr. Cooper. I think that is true, Dr. Peters. We did not do compliance measurements, although I would have liked to. I spoke with Peter Macklin and some other physiologists, who discouraged me as far as the accuracy of such studies. We have only recently added maximum inspiratory force to this. We do have many other physiologic studies, of course, including the cardiopulmonary exercise study and other data that I did not have time to cover. I, too, thought that the improvement would be a pure mechanical one. But then I have trouble explaining how two thirds or more of the patients no longer require oxygen. I did not expect that. So I think that there are two components: improved mechanics and improved ventilation/perfusion distribution to the remaining lung.

I have learned a good deal about chest wall mechanics in the past few months with the use of these magnetic resonance imaging scans. I have only shown you some. We have axial, coronal, sagittal, and other different planes, and they are being mathematically analyzed. I have learned more about the movement of the diaphragm and the chest and its coordination of the past few months than in the entire previous part of my career, and I hope that

we will be able to learn something of value and to promulgate our findings.

Dr. Jean Deslauriers (*Sainte-Foy, Quebec, Canada*). There are several points to be made about this paper. The first is that in Dr. Cooper's group of patients there are no selection criteria for operation other than the presence of diffuse and severe emphysema as documented by imaging and physiologic studies. In our own studies and those of others, hemodynamic evidence of reduced cardiac output during end expiration is used to select patients for surgical volume reduction. The second important aspect of Dr. Cooper's presentation is the emphasis he makes on optimal preoperative preparation. This level of preparation (6 weeks) is absolutely critical in the success of these procedures. It would be a mistake for surgeons to go home and start doing volume reductions without taking appropriate time for investigation and preoperative preparation.

By doing simultaneous bilateral parenchymal volume reduction, Dr. Cooper has introduced a concept that is controversial in operation for bullous lung disease: most surgeons recommend doing only one side at a time because bilateral bullectomy does not appear to give better functional results than unilateral bullectomy. By contrast, this paper shows that in diffuse nonbullous emphysema, it may be better to do both sides at once to avoid overexpansion of the remaining lung. I would finally like to point out that despite the excellent results presented today, these are only consistent with those of phase II trial. In the literature on operation for emphysema, several procedures have had excellent early results, but the results did not persist for more than 2 or 3 years after operation. This is not a criticism, but a warning to be cautious in interpreting this information.

From my point of view the future of operation for emphysema is based on (1) the availability of an experimental model in which physiologic parameters of success could be evaluated, (2) the identification of parameters indicative of good results, (3) the analysis of medium and long-term results to document whether they are consistent with the results of operation for bullous emphysema where improvement lasts for up to 5 years, and (4) the production of phase III studies in which operation could be compared with standard medical treatment. As long as we do not have better information, volume reduction should probably be considered an experimental procedure.

Dr. Cooper. Dr. Deslauriers, I usually play the role of skeptic and critic, and you know that I greatly value your opinion in this matter. As I have acknowledged, it was you who brought to my attention Dr. Brantigan's work, for which I am very grateful.

I regret that we are not able to show the selection criteria, partly because, you are correct, they were not rigidly defined. We have been racing to try to define it as rigidly as possible. There are many measurements that have been made. The trapped gas calculation is an extremely important calculation in my opinion. The body box plethysmography versus the nitrogen washout technique plays a central role in our selection. We only select perhaps one out of every five or six patients who we think might be appropriate. Whether or not our selection process is correct, it is certainly not broadly applied. Many

other studies have been done, such as flow volume loops and the various lung function studies, and the results will be reported.

You are right about the rehabilitation. For the 6-minute walk, we gave three data points. What happened during rehabilitation is very important. The patients were first, of course, treated not only medically to a maximum point, but also then subjected to a rigorous nutrition and exercise program, and only after that was any further measured improvement resulting from the operation reported. I think that this is an extremely important point.

I think the ultimate risk/benefit ratio of this procedure will be defined by the risk, that is, the morbidity and mortality, versus the benefit, in terms of the magnitude of improvement and the duration of improvement. It is clearly too soon to make a judgment, but if the risk, that is, the morbidity and mortality, can be kept low enough, then even 2 or 3 years of improved quality of life may in fact be sufficient to justify the procedure. I think time will tell. I agree with all of your comments.

Dr. Harold C. Urschel (*Dallas, Tex.*). Spending several weekends during the past 2 years in St. Louis finishing our *Atlas in Thoracic Surgery*, I was impressed with Dr. Cooper's enthusiasm for this procedure. We have done two cases. The significant point for the practicing thoracic surgeon is that bovine pericardium does prevent many air

leaks. This is an important key to the success of this operation. It is also good for any operation on the lung to prevent air leaks. It is much better than glue, argon beam cautery, and prayer. Regardless of whether you agree or do not agree with the experimental principles, you can take home what I did: this bovine pericardium works beautifully.

Dr. Cooper. I have two brief remarks. First, regarding the previous comment, I do think it is important to do both sides at once, because if you study the mechanics of the chest, you will find that what changes the configuration of the rib cage is bringing the sternum down to a more normal configuration. If you keep one distended lung in the chest, it keeps the anteroposterior diameter of the chest increased to such a point that you may not get the maximum benefit from improvement in the configuration of the contralateral rib cage. It cannot downhinge as much if the other lung is forcing the sternum up and out.

Finally, I too want to acknowledge the contribution of wives, including Mrs. Brantigan in this case. Many of you who know me know that my career has had the constant support and encouragement of my wife. She will never travel when any of the children are in school and she could not be here today, but I want to acknowledge her constant support.

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