Effect of Lung Resection on Exercise Capacity and on Carbon Monoxide Diffusing Capacity During Exercise*

Jeng-Shing Wang, MD, MSc, FCCP; Raja T. Abboud, MD; and Lee-Min Wang, MD

Objective: To evaluate the effect of lung resection on lung function and exercise capacity values, including diffusion capacity of the lung for carbon monoxide (DLCO), during exercise, and to determine whether postoperative lung function, including exercise capacity and DLCO during exercise, could be predicted from preoperative lung function and the number of functional segments resected.

Design: Prospective study.

Setting: Clinical pulmonary function laboratory in a university teaching hospital.

Patients: Twenty-eight patients undergoing lung resection at Vancouver General Hospital from October 1998 to May 1999, were studied preoperatively and 1-year postoperatively.

Interventions: We determined FEV₁ and FVC, and maximal oxygen uptake (V̇O₂max) and maximal workload (Wmax) achieved during incremental exercise testing. We used the three-equation modification of the single-breath DLCO technique to determine DLCO at rest (RDLCOR) and during steady-state exercise at 70% of Wmax, and the increase in DLCO from rest to exercise (ie, the mean increase in DLCO percent predicted at 70% of Wmax from resting DLCO percent predicted [(70%-R)DLCO]). We calculated the predicted postoperative (PPO) values for all the above parameters using the preoperative test data and the extent of functioning bronchopulmonary segments resected, and compared the results with the actual 1-year postoperative results.

Results: Following lung resection, there was a significant reduction in FEV₁, FVC, and DLCO with decreases of 12%, 13%, and 22% predicted, respectively. There were also significant decreases in V̇O₂max per kilogram of 2.1 mL/min/kg (8% of predicted V̇O₂max) and in Wmax of 12 W (7% of predicted Wmax). However, (70%-R)DLCO did not significantly decrease after lobectomy but decreased after pneumonectomy. The calculated PPO values significantly underestimated postoperative values after pneumonectomy but were acceptable for lobectomy.

Conclusions: Exercise tests may be better indicators of functional capacity after lung resection than measurements of FEV₁ and FVC or RDLCOR. PPO results calculated by estimating the functional contribution of the resected segments, are comparable with those obtained using ventilation-perfusion lung scanning and significantly underestimate postoperative lung function after pneumonectomy, but are acceptable for lobectomy. (CHEST 2006; 129:863–872)

Key words: exercise capacity; exercise diffusing capacity of the lung for carbon monoxide; lung function; lung resection; predicted postoperative value

Abbreviations: BR = breathing reserve; DLCO = diffusing capacity of the lung for carbon monoxide; HR = heart rate; HRR = heart rate reserve; MVV = maximal voluntary ventilation; PPO = predicted postoperative; RDLCOR = DLCO at rest; RER = respiratory exchange ratio; 70%DLCO = mean diffusing capacity of the lung for carbon monoxide at 70% of maximal workload; (70%-R)DLCO = mean increase in diffusing capacity of the lung for carbon monoxide at 70% of maximal workload from resting diffusing capacity of the lung for carbon monoxide; 3EQ-DLCO = three-equation DLCO technique; VEmax = volume of expired gas at maximal exercise; V̇O₂ = oxygen uptake; V̇O₂max = maximal oxygen uptake; Wmax = maximal workload

Despite recent advances in chemotherapy and radiotherapy, surgery offers the best chance of a cure in patients with nonmetastatic lung cancer. It has been recognized that such surgery may result in the impairment of lung function, which can reduce exercise capacity and affect quality of life. Several studies have predicted the change in exercise capacity after lung resection using perfusion lung:

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scanning. However, there are no published studies predicting postoperative exercise capacity after lung resection by estimating the contribution of the resected lung tissue to lung function without the use of perfusion lung scanning. Previous studies have shown that predicted postoperative (PPO) values for FEV₁ and single-breath diffusing capacity of the lung for carbon monoxide (DLco) can be predicted from the preoperative test values, and the number of resected segments and their estimated contribution to preoperative lung function, based on radiologic and bronchoscopic criteria using simple equations.  

In a previous study, we have shown that preoperative DLco during exercise is a good predictor of postoperative complications. We also showed that PPO values, which were calculated from the estimated contribution of the resected lung to lung function, were a good predictor of postoperative complications. In this study, we sought to determine the effect of lung resection on postoperative exercise DLco in a subgroup of these patients, who were studied about 1 year postoperatively, and to evaluate whether postoperative function, including exercise capacity and exercise DLco, could be predicted from the preoperative values by taking into account the estimated contribution of the resected lung to these parameters. As in our previous study, we used the three-equation DLco technique (3EQ-DLCO) of Graham et al to determine DLco at rest (RDLCO) and during exercise following recovery from lung resection. This is the first study to evaluate the effect of lung resection on lung function and exercise capacity values, including DLco during exercise, and to determine whether postoperative lung function, including exercise capacity and DLco during exercise, could be predicted from the preoperative lung function and the number of functional segments resected.

*From the Section of Respiratory Medicine (Dr. J-S Wang), E-Da Hospital, Kaohsiung, Taiwan; Division of Respiratory Medicine (Dr. Abboud), University of British Columbia, Vancouver, BC, Canada; and the Division of Emergency Medicine (Dr. L-M Wang), Taipei Veterans General Hospital, Taipei, Taiwan. Dr. Wang was supported in part by a Fellowship from the British Columbia Lung Association and by funds from the Vancouver General Hospital Foundation. The analyzers and computer for the 3EQ-DLCO were obtained through a grant from the British Columbia Medical Services Foundation, while the SensorMedics exercise equipment was purchased with a major equipment grant from the Columbia Medical Services Foundation, while the SensorMedics; Yorba Linda, CA) and computerized breath-by-breath exercise testing equipment (V˙max 229; SensorMedics), as described previously in more detail. Heart rate (HR), ECG, and oxygen saturation by pulse oximetry were continuously monitored. Minute ventilation, tidal volume, respiratory rate, oxygen uptake (VO₂), CO₂ production, and respiratory exchange ratio (RER) were shown on the computer monitor during exercise. The exercise equipment was calibrated, and the calibration was verified daily. Maximal exercise capacity was determined using a step incremental protocol starting at a workload of 15 W, which was increased every minute by 15 W. Patients' subjective assessment of perceived effort during exercise and at peak exercise was assessed by the Borg scale, the subjects also indicated whether the reason for stopping the test was due to leg discomfort, dyspnea, or both. The maximal VO₂ (VO₂max) attained was taken to be the highest VO₂ at the maximal workload (Wmax) just before the end of exercise. We used the equations of Jones to determine the predicted VO₂max (in liters per minute) and expressed as milliliters per kilogram of body weight. The maximal predicted HR was calculated by subtracting two thirds of the patient's age from 210. The percentage of breathing reserve (BR) was determined as follows: maximal voluntary ventilation (MVV) = volume of expired gas at maximal exercise (VEmax) × the percentage of MVV. The MVV was considered to be equal to FEV₁ (in liters × 35). The percentage of HR reserve (HRR) is determined as follows: predicted maximal HR = HR at maximal exercise × the percent predicted maximal HR. The 3EQ-DLCO determinations during steady-state exercise were made with patients seated on a cycle ergometer while ECG, BP, and oxygen saturation were monitored. After cycling with no workload for 1 min to warm up, the workload was increased to 35% of the previously determined Wmax and was maintained for 3 min, and then the 3EQ-DLCO was determined at that Wmax. The workload was then increased to 70% of the patient's Wmax for another 3 min. The 3EQ-DLCO at steady-state exercise was then determined, and the measurement was repeated after another 1 min of exercise. It had been previously determined that this was an adequate length of time for the lung washout of carbon monoxide and CH4 from the preceding 3EQ-DLCO test, because of the increased ventilation during exercise.

Materials and Methods

In our previous study, a total of 57 patients with non-small cell lung cancer undergoing thoracotomy for lung resection at Vancouver General Hospital from October 1998 to May 1999 were evaluated preoperatively. The study was approved by the University of British Columbia Ethics Review Board, and all patients signed an informed consent form prior to participation.

Details of the lung function tests and exercise studies have been described previously. A computerized dry rolling seal spirometer was used for spirometry, according to the American Thoracic Society criteria. The 3EQ-DLCO system used in this study is identical to the one described in detail in our previous study and is similar to the original systems with slight modifications.

For determination of the resting 3EQ-DLCO, patients rested in a seated position for 15 min to minimize the effect of any prior activity on DLco. To familiarize the patients with the breathing template, several practice runs of the breathing maneuver were performed with the patients breathing room air from the bag-in-box system; flow rates were adjusted according to the lung function of the patients. Then, the 3EQ-DLCO measurements were made at least 5 min apart; the mean of three measurements agreeing to within 10% of each other was taken as the resting 3EQ-DLCO (ie, RDLCO).

Exercise testing was performed using a cycle ergometer (model 800; SensorMedics; Yorba Linda, CA) and computerized breath-by-breath exercise testing equipment (V˙max 229; SensorMedics), as described previously in more detail. Heart rate (HR), ECG, and oxygen saturation by pulse oximetry were continuously monitored. Minute ventilation, tidal volume, respiratory rate, oxygen uptake (VO₂), CO₂ production, and respiratory exchange ratio (RER) were shown on the computer monitor during exercise. The exercise equipment was calibrated, and the calibration was verified daily. Maximal exercise capacity was determined using a step incremental protocol starting at a workload of 15 W, which was increased every minute by 15 W. Patients' subjective assessment of perceived effort during exercise and at peak exercise was assessed by the Borg scale, the subjects also indicated whether the reason for stopping the test was due to leg discomfort, dyspnea, or both. The maximal VO₂ (VO₂max) attained was taken to be the highest VO₂ at the maximal workload (Wmax) just before the end of exercise. We used the equations of Jones to determine the predicted VO₂max (in liters per minute) and expressed as milliliters per kilogram of body weight. The maximal predicted HR was calculated by subtracting two thirds of the patient's age from 210. The percentage of breathing reserve (BR) was determined as follows: maximal voluntary ventilation (MVV) = volume of expired gas at maximal exercise (VEmax) × the percentage of MVV. The MVV was considered to be equal to FEV₁ (in liters × 35). The percentage of HR reserve (HRR) is determined as follows: predicted maximal HR = HR at maximal exercise × the percent predicted maximal HR. The 3EQ-DLCO determinations during steady-state exercise were made with patients seated on the cycle ergometer while ECG, BP, and oxygen saturation were monitored. After cycling with no workload for 1 min to warm up, the workload was increased to 35% of the previously determined Wmax and was maintained for 3 min, and then the 3EQ-DLCO was determined at that Wmax. The workload was then increased to 70% of the patient's Wmax for another 3 min. The 3EQ-DLCO at steady-state exercise was then determined, and the measurement was repeated after another 1 min of exercise. It had been previously determined that this was an adequate length of time for the lung washout of carbon monoxide and CH4 from the preceding 3EQ-DLCO test, because of the increased ventilation during exercise.
The PPO values for FEV\textsubscript{1}, FVC, RD\textsubscript{LCO}, VO\textsubscript{2}\textsubscript{max} per kilogram, W\textsubscript{max}, and exercise DL\textsubscript{CO} were calculated using the preoperative test data and the number of resected bronchopulmonary segments, according to the following equation,\textsuperscript{7} which takes into account lung segments that were nonfunctional due to endobronchial obstruction, atelectasis, or consolidation:

\[
PPO \text{ value} = \text{preoperative value} \times \left[1 - \left( \frac{S - N}{19 - N} \right)\right]
\]

where \(S\) is the number of resected segments, \(N\) is the number of obstructed or consolidated segments resected, and 19 indicates the total number of segments in both lungs. It is assumed that the number of bronchopulmonary segments is 3, 2, 5, 5, and 4 respectively, in the right upper, right middle, right lower, left upper, and left lower lobes, and that each of the 19 bronchopulmonary segments in the normal lung contributes equally to lung function. The \(N\) value was determined based on the findings of preoperative chest radiography, chest CT scan, and bronchoscopy. For a segment with a \(\geq 75\%\) narrowing, \(N\) was considered to equal 1, while a segment with stenosis of between 75\% and 50\% was counted as 0.5, and milder stenosis was ignored.\textsuperscript{8}

One year after lung resection, patients were contacted and invited to return for follow-up lung function and exercise testing, as was done preoperatively; a total of 28 patients who had undergone lung resection participated in this follow-up study. The actual postoperative FEV\textsubscript{1}, FVC, RD\textsubscript{LCO}, exercise capacity, and exercise DL\textsubscript{CO} values determined 1 year after surgery were compared with the preoperative data and with the calculated PPO values. Analysis of the data was done using a spreadsheet program (Excel 97; Microsoft; Redmond, WA) and a statistical software package (SPSS; SPSS; Chicago, IL) using a personal computer. Comparisons for continuous variables before and after surgery were made using a two-tailed paired Student \(t\) test, while the \(\chi^2\) test was used for categoric variables. A \(p\) value of \(< 0.05\) was considered to be statistically significant. The PPO values and the actual postoperative values were also compared by plotting them against the line of identity. To check the level of agreement,\textsuperscript{16} the differences between PPO and actual postoperative values were plotted against the actual postoperative values, and the mean and SD of the differences were determined.

**Results**

The 28 patients who had undergone follow-up studies 1 year after undergoing lung resection had a mean (± SD) age of 64.6 ± 10 years; 17 patients (61\%) were men, and 11 patients (39\%) were women. The mean height was 168 ± 10 cm, and the mean weight was 71 ± 14 kg. The surgical interventions that had been performed were pneumonectomy (5 patients), lobectomy (19 patients), and segmental resection (4 patients). Preoperative data on these 28 patients are shown in Table 1 and are similar to those of the remaining 29 patients who did not undergo follow-up (data not shown). The mean FEV\textsubscript{1} was 86 ± 18\% predicted; some patients had mild or moderate obstructive ventilatory impairment. The Mean FVC was 92 ± 13\% predicted, but some patients had mild restrictive ventilatory impairment. Maximal exercise capacity (in terms of VO\textsubscript{2}\textsubscript{max} per kilogram) was reduced to < 75\% predicted in about two thirds of patients, with a mean VO\textsubscript{2}\textsubscript{max} of 18.5 ± 4.0 mL/min/kg, which is equivalent to 77.5 ± 13.4\% predicted. The mean W\textsubscript{max} was 111 ± 31 W (or 87.5 ± 29.2\% predicted). To adjust for differences in sex, age, and height in different patients, the 3EQ-DL\textsubscript{CO} results at rest and after exercise were expressed as the percent predicted resting single-breath DL\textsubscript{CO}. The mean RD\textsubscript{LCO} was 22.8 ± 8.4 mL/min/mm Hg (or 93 ± 33\% predicted). The mean DL\textsubscript{CO} at 70\% of W\textsubscript{max} (70\%DL\textsubscript{CO}) was 28.9 ± 10.8 mL/min/mm Hg (119 ± 43\% predicted RD\textsubscript{LCO}). The mean increase in 70\%DL\textsubscript{CO} from RD\textsubscript{LCO} (70\%-RDL\textsubscript{CO}) was 29.2 ± 18.0\% predicted, with a significant interpatient variability.

From postoperative lung function and exercise test results obtained 1 year after surgery, lung capacity was compared with the results of preoperative tests (Table 1). As expected, following lung resection there was a significant (\(p < 0.001\)) reduction in lung function with mean decreases in FEV\textsubscript{1}, FVC, and resting 3EQ-DL\textsubscript{CO} of 12\%, 13\%, and 22\% predicted, respectively. There was also a significant decrease in exercise capacity (\(p < 0.001\)), which was indicated both by a mean decrease in VO\textsubscript{2}\textsubscript{max} of 2.2 mL/min/kg (equivalent to a decrease of 10\% of the predicted VO\textsubscript{2}\textsubscript{max}) and by a mean decrease in W\textsubscript{max} of 12 W (equivalent to a decrease of 10\% of the predicted W\textsubscript{max}). The postoperative exercise 70\%DL\textsubscript{CO} was significantly reduced (\(p < 0.001\)). However, because the RD\textsubscript{LCO} was also reduced by almost the same extent, the postoperative increase in DL\textsubscript{CO} during exercise was not significantly reduced compared with the preoperative results, with a mean decrease of only 2\% of the predicted RD\textsubscript{LCO} (\(p = 0.27\)).

Figure 1 compares postoperative and preoperative results in FEV\textsubscript{1}, FVC, and DL\textsubscript{CO} (all expressed as percent predicted) for each type of lung resection. The postoperative FEV\textsubscript{1} was significantly decreased after pneumonectomy (\(p < 0.001\)), lobectomy

### Table 1—Comparison of Preoperative, Postoperative, and PPO Values for Lung Function and Exercise Capacity

<table>
<thead>
<tr>
<th>Test</th>
<th>Preoperative</th>
<th>Postoperative</th>
<th>PPO</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEV\textsubscript{1}</td>
<td>86 ± 18</td>
<td>74 ± 15†</td>
<td>66 ± 20†</td>
</tr>
<tr>
<td>FVC</td>
<td>86 ± 13</td>
<td>74 ± 14†</td>
<td>70 ± 16†</td>
</tr>
<tr>
<td>RD\textsubscript{LCO}</td>
<td>103 ± 35</td>
<td>81 ± 26†</td>
<td>79 ± 32</td>
</tr>
<tr>
<td>VO\textsubscript{2}\textsubscript{max}</td>
<td>18.5 ± 4.0</td>
<td>16.3 ± 4.8†</td>
<td>15.2 ± 4.8†</td>
</tr>
<tr>
<td>W\textsubscript{max} W</td>
<td>113 ± 31</td>
<td>99 ± 36†</td>
<td>84 ± 12†</td>
</tr>
<tr>
<td>(70%-RDL\textsubscript{CO})</td>
<td>29 ± 18</td>
<td>27 ± 18</td>
<td>23 ± 16</td>
</tr>
</tbody>
</table>

*Values are given as the mean ± SD. \(\*\)\(p < 0.001\) (preoperative vs postoperative). \(\†\)\(p < 0.001\) (postoperative vs PPO).
(p < 0.01), and segmentectomy (p < 0.01) by 23%, 9%, and 10% predicted, respectively, from the preoperative values. The postoperative FVC was significantly decreased (p < 0.001) after both pneumonectomy and lobectomy by 28% and 13% predicted, respectively, but there was no significant change after segmentectomy (mean decrease, 0.8% predicted). The postoperative RDLDco was significantly

**Figure 1.** Lung function variables (top left, A: FEV1; middle left, B: FVC; and bottom left, C: RDLDco) and exercise capacity variables (top right, D: VO2max; middle right, E: Wmax, and bottom right, F: [70%-%RDLDco]) before and 1 year after patients underwent lung resection. The postoperative lung function decrease was shown. * = p < 0.05 (comparison to previous test results); ** = p < 0.01 (comparison to previous test results); *** = p < 0.001 (comparison to previous test results); ♦ = pneumonectomy; ■ = lobectomy; ▲ = segmentectomy.
FEV1, FVC, and RD

2 compares individual calculated PPO results for FEV1, FVC, and VO2max with the corresponding actual postoperative values plotted on the x axes. There is scatter around the line of identity; the PPO values were lower than postoperative values, especially for patients who had undergone pneumonectomy, with only a minimal difference for the four patients who had undergone segmentectomy. Figure 2 also shows the differences between PPO and actual postoperative results for the same tests plotted against the actual postoperative results. It also indicates the mean difference and the limits of agreement for all cases (±2 SDs from the mean difference) between calculated PPO results and actual postoperative results. Similarly, Figure 3 compares PPO values with actual postoperative results for VO2max, Wmax, and (70%-R)DLco; it also shows the differences between PPO and postoperative values. The calculated PPO values for pneumonectomy patients significantly underestimated the postoperative results, but the lobectomy PPO values generally only slightly underestimated postoperative results. A comparison of postoperative and PPO results in pneumonectomy and lobectomy patients are shown separately in Table 2. This shows that whereas PPO values grossly underestimate postoperative lung function in patients who had undergone pneumonectomy, the underestimation in lobectomy cases is on the order of 10 to 15% for FEV1, FVC, and VO2max, and is negligible for RDLCO and DLCO during exercise, suggesting that the calculation of PPO values by the equation given in the “Materials and Methods” section would be acceptable for lobectomy patients, but not for pneumonectomy patients.

The objective exercise parameters, which may indicate a limitation of exercise capacity before and after surgery, are shown in Table 3. The VEmax tended to be lower after pneumonectomy only, but this did not achieve statistical significance. The BR at maximal exercise was decreased postoperatively after pneumonectomy and lobectomy by a mean of 27% and 11%, respectively. However, the postoperative oxygen pulse, which depends on cardiac stroke volume, was significantly decreased only in pneumonectomy patients (2.5 mL/beat), but there was no change in the maximal HR reached with exercise.

The subjective factors limiting exercise capacity before and after surgery are shown in Table 4. Before surgery, most patients could not continue exercise because of leg fatigue. After recovery from pneumonectomy, three of five patients were limited by dyspnea, compared to only one patient preoperatively, while only one patient was limited by leg fatigue compared with three patients preoperatively. However, for the lobectomy and segmentectomy patients, there was no significant change in the proportion of patients stopping exercise because of dyspnea or leg fatigue.

DISCUSSION

The main findings in this study were as follows: (1) the increase in DLCO with exercise was preserved after lobectomy; and (2) the calculation of PPO values for lung function and exercise test results from preoperative test data and the extent of functioning of the resected bronchopulmonary segments yielded acceptable results after lobectomy. Although there was a slight decrease in maximal exercise capacity after lobectomy, there was preservation of the (70%-R)DLCO after lobectomy, indicating that the capacity of the pulmonary capillary bed to expand with exercise was preserved.

As expected, there was a greater and more signif-
ificant decrease in lung function and exercise capacity after pneumonectomy, compared with after lobectomy. The decreases from preoperative values for FVC, FEV₁, and RDLCO were 30%, 28%, and 39%, respectively, after pneumonectomy, and 13%, 8%, and 20%, respectively, after lobectomy. After pneumonectomy, the indexes of maximal exercise capacity, VO₂max and Wmax, were reduced by 28% and 20%, respectively, of the preoperative values, while after lobectomy they were reduced by 12% and 8%,
respectively, of the preoperative values. Our findings are similar to those of Larsen et al, who reported a 6-month postoperative decrease in FEV$_1$ of 23% after pneumonectomy and 8% after lobectomy, while exercise capacity decreased by 16% after pneumonectomy and 13% after lobectomy. Our results are also similar to those of Bolliger et al who reported decreases in FVC of 36% after pneumonectomy and 8% after lobectomy.

Figure 3. Predictive and actual exercise capacity variables (top left, A: VO$_{2}$max; middle left, B: Wmax; bottom left, C: [70%-R]DLCO) were shown around the line of identity, and they (top right, D: VO$_{2}$max; middle right, E: Wmax; bottom right, F: [70%-R]DLCO) were plotted as the differences between the predictive and actual variables over the averages. The calculated PPO and actual postoperative exercise capacity values were well-correlated and had good agreement. Diagonal line = line of identity; horizontal line = mean ± 2 SDs; ♦ = pneumonectomy; ■ = lobectomy; ▲ = segmentectomy.
lobectomy and 6% after lobectomy, while the decreases in $V_{O2max}$ were 20% and 1%, respectively. In this study, the mean increase in DLCO with exercise after pneumonectomy was only 51% of the preoperative value, but was 96% of the preoperative value after lobectomy. The findings for exercise DLCO are consistent with a reduced capacity of the pulmonary capillary bed to increase with exercise after pneumonectomy and with a preserved capacity after lobectomy. In our previous study,9 the increase in DLCO after pneumonectomy and 6% after lobectomy, while the decrease in $V_{O2max}$ was 12.8 ± 1.9 mL/min/kg, the relative increase in $V_{O2max}$ was 54% after lobectomy. The findings for exercise after pneumonectomy were only 51% of the preoperative value, but was 96% of the preoperative value after lobectomy. The findings for exercise after pneumonectomy were only 51% of the preoperative value, but was 96% of the preoperative value after lobectomy.

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Table 2—Comparison of Postoperative Value With PPO Values After Pneumonectomy and Lobectomy*

<table>
<thead>
<tr>
<th>Variables</th>
<th>Pneumonectomy</th>
<th>Lobectomy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Postoperative</td>
<td>PPO</td>
</tr>
<tr>
<td>$FEV_1, %$</td>
<td>59 ± 14</td>
<td>44 ± 11</td>
</tr>
<tr>
<td>$FVC, %$</td>
<td>63 ± 12</td>
<td>48 ± 8†</td>
</tr>
<tr>
<td>$RDLC, %$</td>
<td>68 ± 22</td>
<td>54 ± 17†</td>
</tr>
<tr>
<td>$V_{O2max}, mL/min/kg$</td>
<td>12.8 ± 1.9</td>
<td>8.6 ± 9.8†</td>
</tr>
<tr>
<td>$W_{max}, W$</td>
<td>80 ± 9</td>
<td>59 ± 7</td>
</tr>
<tr>
<td>$(70%-R)DLCO, %$</td>
<td>10 ± 12</td>
<td>9 ± 8</td>
</tr>
</tbody>
</table>

*pValues are given as the mean ± SD.
†p < 0.01 (postoperative vs PPO).
‡p < 0.05 (postoperative vs PPO).

Our study indicates that the evaluation of the contribution of the resected lung to function from the total number of functional lung segments resected using a simple equation, the modified formula of Nakahara et al,7 in conjunction with preoperative function and exercise testing, yields a good estimate of postoperative lung function and exercise capacity after lobectomy but significantly underestimates the results after pneumonectomy. Only a few of our patients underwent quantitative radionuclide lung scans. However, we have compared our calculated PPO values for lung function and exercise variables relative to the actual postoperative values obtained in our study with those from the studies of Bolliger et al,5 and Larsen et al,6 both of whom used radionuclide scanning to calculate PPO results. The correlation between PPO and postoperative results, the underestimation of postoperative results by PPO.

Table 4—Subjective Factors Limiting Exercise Capacity Before and After Surgery*

<table>
<thead>
<tr>
<th>Reason</th>
<th>Preoperation Values</th>
<th>Postoperation Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dyspnea</td>
<td>1/5 (20)</td>
<td>3/5 (60)†</td>
</tr>
<tr>
<td>Pneumonectomy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lobectomy</td>
<td>2/9 (11)</td>
<td>3/9 (16)</td>
</tr>
<tr>
<td>Segmentectomy</td>
<td>0/4 (0)</td>
<td>0/4 (0)</td>
</tr>
<tr>
<td>Leg fatigue</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pneumonectomy</td>
<td>3/5 (60)</td>
<td>1/5 (20)†</td>
</tr>
<tr>
<td>Lobectomy</td>
<td>11/19 (58)</td>
<td>9/19 (47)</td>
</tr>
<tr>
<td>Segmentectomy</td>
<td>3/4 (75)</td>
<td>3/4 (75)</td>
</tr>
<tr>
<td>Combined</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pneumonectomy</td>
<td>1/5 (20)</td>
<td>1/5 (20)</td>
</tr>
<tr>
<td>Lobectomy</td>
<td>6/19 (32)</td>
<td>7/19 (37)</td>
</tr>
<tr>
<td>Segmentectomy</td>
<td>1/4 (25)</td>
<td>1/4 (25)</td>
</tr>
</tbody>
</table>

*pValues are given as the No. of patients with that factors/No. of patients in that group (%).
†p < 0.05 (preoperative vs postoperative).
values, and the scatter of data around the line of identity are similar in these two studies and ours. These comparisons indicate that the modified formula of Nakahara et al \(^7\) can predict the postoperative lung function and exercise capacity values as well as the calculations using ventilation-perfusion lung scanning, although more definitive conclusions would require a comparison of both methods in a larger number of patients in a prospective study.

The postoperative values for FEV\(_1\), FVC, and DLCO were somewhat more decreased (by 12%, 13%, and 22%, respectively) than those for VO\(_{2}\max\) (by 2.1 mL/min/kg or 8%) and W\(_{\text{max}}\) (decreased by 12 W or 7%), as shown in Table 1. However, the DLCO increase during exercise was not significantly decreased postoperatively compared with preoperatively, although the mean values were slightly lower. These findings suggest that lung function tests performed at rest may overestimate the functional loss, but additional studies will be required to determine whether this will be a better parameter in estimating functional capacity after lung resection.

Postoperative lung function was significantly decreased after lobectomy by a mean of 9% for FEV\(_1\), 13% for FVC, and 22% for DLCO, and after pneumonectomy by 23% for FEV\(_1\), 28% for FVC, and 33% for DLCO, as indicated in Figure 1. The mean postoperative exercise capacity as determined by W\(_{\text{max}}\) (Fig 1) was decreased after lobectomy by 7 W (or 6%), while VO\(_{2}\max\) decreased by 2.2 mL/min/kg (or 7%). After pneumonectomy, W\(_{\text{max}}\) decreased by 31 W (or 20%), while VO\(_{2}\max\) decreased by 3.4 mL/min/kg (or 20%), as indicated in Figure 1. However, the DLCO increase during exercise was decreased only after pneumonectomy by 8% (Fig 1).

The increase in DLCO with exercise may also be a useful indicator of exercise functional capacity after lung resection.

Objectively, the mean R\(_E\)R at peak exercise was > 1.10; an R\(_E\)R of > 1.05 is considered to be evidence of enough motivation for the exercise test.\(^1\)\(^7\) There were significant decreases in the breathing reserve after pneumonectomy and lobectomy (Table 3). There was also a significant decrease in oxygen pulse after pneumonectomy, but not after lobectomy (Table 3), suggesting a decrease in cardiac stroke volume during exercise after pneumonectomy. These findings suggest that ventilatory capacity\(^1\)\(^8\) after both lobectomy and pneumonectomy may be limiting exercise, while circulatory capacity\(^1\)\(^9\)\(^,\)\(^2\)\(^0\) may be limiting exercise capacity after pneumonectomy. Circulatory limitation could be a more important limiting factor for exercise capacity,\(^1\)\(^9\)\(^,\)\(^2\)\(^0\) and may be due to the impaired filling of the left ventricle caused by the limitation of the increase in pulmonary blood flow with exercise. Oxygen pulse and the DLCO increase with exercise 1 year after lobectomy were similar to the preoperative values but were lower after pneumonectomy. The recovery in exercise capacity after lobectomy is most likely due to the expansion of the remaining lung on the side of the lung that was operated on, compensating for the resected lung tissue lost during lobectomy.

Prior to lung resection, most patients felt that their exercise capacity was limited by leg fatigue (Table 4). After segmental or lobar resection, leg fatigue was still the main factor limiting exercise after the operation, but the pneumonectomy patients were mostly limited by dyspnea postoperatively (Table 4). Leg fatigue before the operation indicates deconditioning, as supported by a large breathing reserve and HRR. Dyspnea and exercise limitation after pneumonectomy could be due to the decreased postoperative ventilatory and circulatory capacities, as indicated by the decreased BR and oxygen pulse. The degree of impairment in lung function after pulmonary resection may be dependent on the timing of postoperative testing. Larsen et al\(^8\) showed that there is improvement in lung function 6 months after undergoing lobectomy compared with 3 months after undergoing pneumonectomy. Veneskoski et al\(^2\)\(^1\) showed that 6 months after surgery there was no significant change in the impairment in lung function, and we selected 1 year as the time for our evaluation. Our results were obtained in a relatively small group of patients and may need confirmation in a larger number of patients.

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