Evaluation of Effect of Lung Resection on Lobar Ventilation and Perfusion Using Intrabronchial Capnography*

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Intrabronchial capnography was applied in 11 lung cancer patients to investigate the effects of lobectomy on regional lung function. Spirometry and intrabronchial capnography were performed before surgery (PRE), and during the early (POST1, 19±5 POD) and late (POST2, 184±98 POD) postoperative periods. End-tidal carbon dioxide concentration (EtCO₂) and Smidt's velocity profile index (V-index) were calculated from each lobar capnogram obtained bronchoscopically. The V-index of lobes without cancer on the operated-on side increased after surgery (PRE, 10.7±5.0%; POST1, 14.3±9.4%, NS; POST2, 16.8±8.6%, p<0.05), while the V-index on the unoperated-on side decreased after surgery (PRE, 10.5±5.3%; POST1, 7.9±3.5%, p<0.05; POST2, 7.2±2.9%, p<0.05). EtCO₂ after surgery was lower on the operated-on side (POST1, 5.1±1.1%; POST2, 4.6±1.1%) than on the unoperated-on side (POST1, 5.4±0.9%, p<0.05; POST2, 5.0±0.9%, p<0.01). Since the V-index and EtCO₂ are compatible with the expiratory flow rate and the perfusion/ventilation ratio, respectively, we concluded that the air flow decreased on the operated-on side and increased on the unoperated-on side postoperatively and that perfusion on the operated-on side was more severely reduced than ventilation. These findings suggest that intrabronchial capnography is useful for assessing the ventilation and perfusion of the individual lobes as single units.

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CL=lung lobes with cancer; EtCO₂=end-inspiratory carbon dioxide concentration; EtCO₂=end-tidal carbon dioxide concentration; FRC=functional residual capacity; I:E=inspiratory-expiratory time ratio; NL=lung lobes on the unoperated-on side; NLA=neuroleptic analgesia; NS=not significant; OL=lung lobes on the operated-on side but without cancer; POD=postoperative day; POST1=first postoperative measurement; POST2=second postoperative measurement; PRE=before surgery; RR=respiratory rate; VC=vital capacity; V-index=velocity profile index

Key words: bronchoscopy; capnography; lung cancer; lung resection; regional lung function

Pulmonary function studies have been performed in thoracotomy patients mainly for the purpose of predicting postoperative morbidity and mortality.1,2 Reports of the physiologic effects of lobectomy on remaining lungs are relatively few.3-5 After lung resection, vital capacity (VC) and FEV₁ are generally reduced and the FEV₁/FVC%, calculated by FEV₁/FVC×100, increased.6 This restrictive disorder is a gross finding obtained from the entire remaining lung. When regional lung function in the operated-on and unoperated-on sides is compared using ¹³³Xe technique, an obstructive disorder is also recognized on the operated-on side.7,8

Regional lung function as measured by the ¹³³Xe technique does not represent the function of each lobe, but some area where radioactivity of ¹³³Xe is counted. To investigate the effect of lobectomy on the individual lobes, we applied intrabronchial capnography to patients who underwent lobectomy. Capnography was originally measured in the mouth. We modified this technique by combining it with a bronchoscope to enable capnographic measurements from each lobe and wave analysis as developed by Smidt et al.9 This technique was helpful in assessing regional lung function of individual lobes as single units.

MATERIALS AND METHODS

We studied 11 patients who underwent thoracotomy for primary lung cancer (Table 1). The 11 patients included 9 men and 2 women, ranging in age from 47 to 80 years (65±11 years). Tumors were located more peripherally than the subsegmental bronchus, and five were on the right side and six on the left. Mean tumor diameter was 3.7±2.4 cm. Operative procedures included lobectomy in nine patients and bilobectomy in two patients. Patients with major postoperative pulmonary or cardiac complications that might have affected postoperative pulmonary function were excluded from the study.

Both routine spirometry and intrabronchial capnography were performed once before surgery (PRE) and twice after surgery. The first postoperative measurement (POST1) was performed between 2 and 4 weeks after surgery, and the second postoperative...
Table 1—Patient Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disease</td>
<td></td>
</tr>
<tr>
<td>Primary lung cancer</td>
<td>11</td>
</tr>
<tr>
<td>Age, yr</td>
<td>65±11 (range, 47-80)</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>9</td>
</tr>
<tr>
<td>Female</td>
<td>2</td>
</tr>
<tr>
<td>Operation</td>
<td></td>
</tr>
<tr>
<td>Lobectomy</td>
<td>9</td>
</tr>
<tr>
<td>Bilobectomy</td>
<td>2</td>
</tr>
<tr>
<td>Tumor size, diameter, cm</td>
<td>3.7±2.4 (range, 1.3-7.5)</td>
</tr>
</tbody>
</table>

measurement (POST 2) was performed between 3 and 12 months after surgery.

Under modified neuroleptic analgesia (NLA) (pentazocine, 15 mg, diazepam, 10 mg IV) with topical administration of 2% lidocaine, intrabronchial capnography was performed using a flexible fiberoptic bronchoscope (Olympus type BF20) as the final procedure of routine bronchosscopic examination. During measurement, patients breathed room air spontaneously. A sampling tube (internal diameter, 0.5 mm; length, 1.7 m) was advanced through the operational channel of the bronchoscope into the orifice of each lobar bronchus and inspired and expired gases were collected continuously through the tube, and the carbon dioxide (CO2) concentration curve (Fig 1) was recorded using a side-stream type rapidly responding infrared CO2 analyzer (Nihondenki-Sanei model IH-28). End-tidal CO2 concentration (EtCO2), end-inspiratory CO2 concentration (EiCO2), respiratory rate (RR), and the inspiratory-expiratory time ratio (I:E ratio) were obtained from the CO2 concentration curve (Fig 1). The velocity profile index (V-index) was calculated as the percentage of the time (x) between 25% and 75% of full amplitude of CO2 concentration curve divided by the whole expiratory time (y) of a tidal breath (Fig 1). EtCO2, EiCO2, and the V-index in each lobe were expressed as mean values for more than three tidal breaths.

The lobes of each patient were classified into three categories as follows: (1) lobes with cancer (CL); (2) lobes on the operated-on side but without cancer (OL); or (3) lobes on the unoperated-on side (NL). EtCO2, EiCO2, and the V-index for each category were expressed as mean values of the parameters obtained from lobes in the same category. In a case in which lung cancer was located in the right upper lobe, for example, the right upper lobe was CL, the right middle and lower lobes OL, and left upper and lower lobes NL. EiCO2 of CL was therefore that of the right upper lobe, the EtCO2 of CL was the mean of those of the right middle and lower lobes, and the EtCO2 of NL was the mean of those of the left upper and lower lobes. The V-index for each category was obtained in the same manner. RR and I:E ratio were also determined in each patient.

The pattern observed in a capnogram depends on the sampling flow rate of the capnometer. Figure 2, left, shows three capnograms

![Figure 1](http://example.com/figure1.png)

**Figure 1.** Parameters obtained from intrabronchial capnogram. x=time between 25% and 75% of full amplitude (s); y=whole expiratory time (s); z=whole inspiratory time (s); RR (breaths/min)=60/(y+z); I:E ratio=y/z; V-index(%)=100x/y.

![Figure 2](http://example.com/figure2.png)

**Figure 2.** Left (a): Capnograms obtained at various sampling flow rates. Right (b): EtCO2, EiCO2, and V-index at various sampling flow rates. These capnograms were obtained from the middle lobe bronchus of a patient who underwent right lower lobectomy.
obtained at the right middle lobe bronchus in a patient who underwent right lower lobectomy. The sampling flow rates for the three capnograms were 5, 20, and 40 mL/min, respectively. The capnogram at a sampling flow rate of 5 mL/min is flatter than those at 20 and 40 mL/min. A small notch (shown by the arrows in Fig 2, left) was observed in the capnogram at 40 mL/min. The small notch appeared to be caused by aspiration of gas from another portion of the airway. EtCO₂, EtCO₂ and the V-index were also obtained at various sampling flow rates (Fig 2, right). Although EtCO₂ was not affected by sampling flow rates, a sampling flow rate of 20 mL/min or more was required to obtain stable values of EtCO₂ and the V-index. Based on these findings, a sampling flow rate of 20 mL/min was adopted for this study.

All values were described by means±SD. Repeated-measures analysis of variance was applied to differences among PRE, POST1, and POST2 or CL, OL, and NL; p less than 0.05 was regarded as statistically significant.

**Results**

Spirometry and intrabronchial capnography were performed within 1 month before surgery, on 19±5 postoperative days (POD) for POST1 and on 184±98 POD for POST2.

**Spirometry**

The results of spirometry are summarized in Table 2. VC, which is expressed as the percentage of the measured VC for the predicted normal VC, was 107.6±13.0% on PRE, 67.4±10.5% on POST1, and 79.8±15.2% on POST2. Percent VC was significantly reduced after surgery. FEV₁%, obtained by FEV₁/FVC×100, was 75.7±10.5% on PRE, 84.6±8.7% on POST1, and 82.1±5.3% on POST2. FEV₁% was significantly increased after surgery.

**Intrabronchial Capnography**

Conditions of respiration during intrabronchial capnography are shown in Table 3. There was no significant difference in RR or the I:E ratio between PRE and POST1 or POST2.

| Table 2—Preoperative and Postoperative Pulmonary Function Findings* |
|-----------------|--------|--------|
| PRE             | POST1  | POST2  |
| %VC             | 107.6±13.0 | 67.4±10.5 | 79.8±15.2 |
| FEV₁%           | 75.7±10.5  | 84.6±8.7  | 82.1±5.3  |

*POST1=19±5 POD; POST2=184±98 POD.

| Table 3—Respiratory Conditions During Intrabronchial Capnography |
|-----------------|--------|--------|
| RR, breaths/min | 20.9±5.0 | 18.7±3.4 | 19.3±2.5 |
| I:E ratio       | 1.95±0.39 | 2.03±0.18 | 2.02±0.44 |

*Abbreviations are as in Table 2.

Intrabronchial capnographic variables for three categorized lung fields are summarized in Table 4 and illustrated in Figures 3 and 4.

The PRE V-index was 13.4±4.9% in CL, 10.7±5.0% in OL, and 10.5±5.3% in NL. There was no significant difference in PRE V-index among the three categorized lung fields. The V-index in OL increased after surgery, and was significantly increased on POST2 (16.8±8.6%). In contrast, the V-index in NL was significantly decreased after surgery on both POST1 and POST2. As a result, the POST2 V-index was significantly larger in OL than in NL.

PRE EtCO₂ was 5.0±0.9% in CL, 5.1±0.8% in OL, and 5.3±0.9% in NL. There was no significant difference in PRE EtCO₂ among CL, OL, and NL. EtCO₂ in OL became lower after surgery, but not significantly...
so. However, EtCO₂ after surgery was significantly lower in OL than in NL.

**DISCUSSION**

Capnography is now widely used to monitor the ventilatory status of patients under anesthesia, since EtCO₂ is well correlated with arterial CO₂ pressure. Wave analysis of capnograms also yields important information concerning lung function.

There are three methods for wave analysis of gas washout curves. Greve, calculated the slope of the alveolar plateau of expiratory helium curves as the change in partial pressure per second in percentage of the initial end-tidal amplitude during washout of helium gas. Van Meerten reported the method for direct measurement of the time constant of expiration. He calculated the minimum radius of curvature of capnograms. Smidt used the V-index, which was the time interval between 25% and 75% of the end-tidal amplitude expressed in percentage of the time for the whole expiratory time interval. The most sensitive parameter for the expression of expiratory flow rate is Van Meerten’s. However, his parameter is inferior to the other two in objectivity and reproducibility. Greve’s parameter is inferior to the others in sensitivity. The value of Smidt’s parameter expresses the expiratory flow rate of small airways and becomes smaller as flow increases. Smidt reported that the V-index was negatively correlated with FEV₁% in COPD patients.

These methods of the wave analysis were developed using gas washout curves obtained in the mouth. Some investigators attempted to obtain capnograms in the bronchus by using a bronchoscope, but they have not analyzed the waveforms of such capnograms. We combined these two techniques to investigate the effect of lobectomy on the individual lobes. For wave analysis, we used Smidt’s method with a small modification, in which the full amplitude of CO₂ was obtained as a difference between EtCO₂ and EICO₂.

In the beginning of our study, we determined the adequate sampling flow rate. A low sampling flow rate made the waveform flat due to longitudinal dispersion of CO₂ in the sampling tube. However, high sampling flow rate causes aspiration of gas from other portions of the airway. These phenomena are illustrated in Figure 2, right. In our measuring system, 20 mL/min was the best sampling flow rate for obtaining a proper waveform and a stable V-index shown in Figure 2, right. These parameters are also affected by respiratory conditions. With sufficient premedication and modified NLA, the patients studied maintained stable respiration both preoperatively and postoperatively, as shown in Table 2. Thus the same waveform was obtained in the bronchus as that in the mouth.

Tis demonstrated the disturbance of perfusion and ventilation in lung with tumor compared with other portions of the lung without tumor by the radioisotopic method. In our study, however, there was no significant difference in V-index or EtCO₂ between lobes with tumor and lobes without tumor. Since our patients had cancer in the peripheral portions of the airway, the effects of tumor occupation of lung seemed to be too small to be detected by intrabronchial capnography.

Berend and colleagues investigated the effects of lobectomy by comprehensive lung function testing, including spirometry and determination of lung volumes, the pressure-volume curve, lung resistance, diffusing capacity, and so on. They concluded that most of the changes in lung function after lobectomy could be explained simply on the basis of changes in lung volume. These results were gross findings for the entire remaining lung.

More recently, regional lung function after lobectomy was assessed with the Xe technique by Fleetham and colleagues. They reported that regional lung expansion at residual volume (RV), functional residual capacity (FRC), and lung volumes above FRC were greater on the operated-on side than on the unoperated-on side, and that washout of gas was delayed on the operated-on side compared with the unoperated-on side. Although the effect of volume reduction by lobectomy was manifested in the lung on the unoperated-on side as a decrease in static lung compliance, this effect was larger on the operated-on side than on the unoperated-on side. Xe has been utilized for the study of regional lung
function. We first used intrabronchial capnography for this purpose. Intrabronchial capnography has certain advantages over the $^{133}$Xe technique. Since capnography can be performed for each lobe, findings for a given lobe obtained before and after surgery can be compared. This kind of comparison cannot be made with the $^{133}$Xe technique. Furthermore, since a good correlation exists between the V-index and FEV$_1$%, the V-index can be considered to reflect local air flow. Thus, Figure 3 shows that the air flow is decreased on the operated-on side and, on the other hand, increased on the unoperated-on side. The increase in FEV$_1$% after lobectomy appears to be due to the increase in air flow on the unoperated-on side, and disturbance of air flow on the operated-on side appears to be masked. In analysis of regional lung function with the $^{133}$Xe technique, lung function on the unoperated-on side has been considered normal and used as a control.$^7,8$ Limitations of the $^{133}$Xe technique have led to this incorrect hypothesis.

There are several reasons for the difference in air flow between the operated-on side and unoperated-on side. Since the lung is more hyperinflated at FRC on the operated-on side than on the unoperated-on side, the compliance of the lung may be lower on the operated-on side than the unoperated-on side. If the same intrathoracic pressure is loaded on both sides during inspiration, more air per lung volume is inspired in the unoperated-on side due to the difference of the compliance. During expiration, more air per lung volume must exit from the unoperated-on side. As a result, the air flow is higher on the unoperated-on side and lower on the operated-on side. Emphysematous changes in the hyperinflated lung$^4,20$ or stenosis of the bronchus, which occur due to dislocation of the remaining lung on the operated-on side, may contribute to an obstructive disorder.

Ali and his colleagues$^{22}$ reported that loss in both overall pulmonary function (FVC and FEV$_1$) and regional function (V, V, and Q) obtained by the $^{133}$Xe technique in the short term after lobectomy was followed by significant improvement with time, as shown in Table 2. However, they also demonstrated that the increase in volume (V) of the remaining lobe in the long term was significantly higher than either V or Q. They explained this mechanism in which the remaining lobe resulted in a hyperinflated, relatively hypoventilated and hypoperfused lobe. Our results shown in Figure 3 seemed to be compatible with their latter findings.

Minakata and his colleagues$^{23}$ applied the same measuring system as ours to patients with lung cancer or pulmonary embolism. ET$\text{CO}_2$ was lower in the involved lobes of lung cancer patients with a disturbance of perfusion diagnosed by perfusion scan than that obtained in the normal lobes and trachea. They also demonstrated that lowered ET$\text{CO}_2$ detected in the lobes with embolism returned to normal after treatment. These findings revealed that perfusion/ventilation ratio is well reflected on ET$\text{CO}_2$ obtained by intrabronchial capnography. The significant reduction in ET$\text{CO}_2$ on the operated-on side compared with unoperated-on side, shown in Figure 4, suggested that perfusion in the lung on the operated-on side was more severely reduced than ventilation. This finding is supported by the observations of Hatakeyama et al$^6$ with the $^{133}$Xe technique. Denervation of the vagal nerve in the remaining lung on the operated-on side, which is often associated with the lung cancer operation, may be one of the main causes of the decrease in the perfusion.$^{24}$ Furthermore, because the capillaries in the alveolar walls are stretched and thinned out in the hyperinflated lung, this phenomenon may be another cause of the decrease in the perfusion.$^{22}$

Intrabronchial capnography was first applied for investigating the effects of lobectomy on the regional lung function. We concluded that air flow in the remaining lung was decreased on the operated-on side and increased on the unoperated-on side, and that the perfusion in the remaining lung on the operated-on side was more severely reduced than ventilation. This new technique appears to be useful for assessing the ventilation and perfusion of individual lobes as single units.

REFERENCES


