J Anesth (1994) 8:6–11

Journal of
Anesthesia

Preoperative estimation of pulmonary extravascular thermal volume in patients undergoing pneumonectomy

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Abstract: Pulmonary extravascular thermal volume (PETV) was measured during pulmonary artery occlusion in 18 patients preoperatively and 7 patients postoperatively who were undergoing pneumonectomy. We found that the PETV decreased from 6.6 ± 2.3 ml·kg^{-1} before occlusion to 4.1 ± 1.6 ml·kg^{-1} during occlusion. There was a significant correlation between the PETVs before and during occlusion multiplied by the fraction of pulmonary perfusion (r = 0.77, $P <$ 0.001). Although the PETV increased in two patients and decreased in four within 48 h after pneumonectomy, it returned to the value during occlusion at 3 weeks after pneumonectomy in seven patients. There was a significant correlation between the PETV during occlusion and that at 3 weeks after pneumonectomy (r = 0.66, $P < 0.05$). In conclusion, PETV during pulmonary artery occlusion is a reliable baseline value in the assessment of postoperative pneumonectomy values.

Key words: Thermal-dye dilution method, Unilateral pulmonary artery occlusion, PETV, Pneumonectomy

Introduction

The loss of pulmonary volume in patients undergoing pulmonary resection, is predicted primarily based on pulmonary function [1–4]. However, these studies did not determine the reduction of the pulmonary volume in the vascular bed. In relation to the pulmonary vascular bed, pulmonary hypertension [5] and pulmonary edema [6] are serious complications that can occur after pneumonectomy. These complications can only be detected by measurements of the vascular bed.

To determine pulmonary edema, a double indicator dilution method was demonstrated [7] and attempted using a variety of indicators [8,9]. Clinically, the pulmonary extravascular thermal volume (PETV) has been measured only in patients who underwent heart surgery [10,11], or at bedside assessment of pulmonary edema [12]. In those studies, there was no reduction of the pulmonary vascular bed caused by pulmonary resection. After a unilateral pulmonary artery occlusion test was designed that closely mimics the state following pneumonectomy [13], occlusion became part of the standard preoperative evaluation of thoracic patients [14,15] and the evaluation of the effects of acute pressure elevation on cardiopulmonary circulation [16].

In patients undergoing pulmonary resection, it was difficult to determine the baseline value of the PETV, since the volume was reduced as a direct result of lung resection. Thus, the first objective of this study was to determine whether the PETV during pulmonary artery occlusion provides a reliable baseline value for the assessment of the PETV after pneumonectomy. We measured the PETV during pulmonary artery occlusion before and after pneumonectomy, and then compared these values. The second objective was to determine the normal range of PETV values during the early postoperative period after pneumonectomy. In the early postoperative period, patient care should include some measurement that reflects changes of the pulmonary vascular bed. The third objective was to determine whether the PETV returns to the baseline level after pneumonectomy. To accomplish this, we measured the PETV at 3 weeks after pneumonectomy, when patients had returned to their normal daily life.

Methods

This study was approved by the Human Research Committee of Sendai Kosei Hospital, and informed consent was obtained from each patient.

Unilateral pulmonary artery occlusion

The unilateral pulmonary artery occlusion test was performed about 1 week before surgery in 18 patients

Address correspondence to: T. Sakuma
Received for publication on January 5, 1993; accepted on March 4, 1993

Table 1. Demographic features and fraction of perfusion in patients who underwent pulmonary artery occlusion

No	Disease	Location	Age years	Perfusion
1	Lung Cancer	Left	53	0.65
2	Lung Cancer	Left	56	0.55
3	Lung Cancer	Left	56	0.67
4	Lung Cancer	Left	59	0.78
5	Lung Cancer	Left	61	0.91
6	Lung Cancer	Left	62	0.85
7	Lung Cancer	Left	70	0.74
8	Lung Cancer	Left	77	0.63
9	Lung Cancer	Right	36	0.54
10	Lung Cancer	Right	59	0.50
11	Lung Cancer	Right	59	0.51
12	Lung Cancer	Right	66	0.46
13	Lung Cancer	Right	66	0.67
14	Lung Cancer	Right	67	0.54
15	Lung Cancer	Right	68	0.45
16	Metastatic tumor	Right	38	0.54
17	Tracheal tumor	Left	48	0.82
18	Aspergiloma	Right	59	0.55
Mean			59	0.63
SD			10	0.14

(Table 1). None of the patients had been taking medication affecting cardiopulmonary function before the occlusion. The patients were supine and breathed room air. After local anesthesia with 10 ml of 1% lidocaine, a large occlusion balloon catheter (7Fr, Meditech, Watertown, MA) in the main pulmonary artery of the affected lung through the femoral vein. We also placed a Swan-Ganz thermodilution catheter (7Fr, Edwards, Irvine, CA) on the pulmonary artery in the normal lung. We also inserted a femoral artery lung water catheter (5Fr, Edwards) into the abdominal aorta through the right femoral artery. After a baseline period of 30 min, we inflated the balloon with the contrast media and occluded the pulmonary artery of the affected lung.

Pneumonectomy

Prior to pneumonectomy, a Swan-Ganz thermodilution catheter and a femoral artery lung water catheter were inserted. All patients were anesthetized with intravenous thiopental (4 mg/kg) followed by the muscle relaxant succinylcholine (1 mg/kg), intubated with double-lumen tubes, and then positioned in the lateral decubitus position. Anesthesia during surgery was maintained with 1%–3% halothane, nitrous oxide (3 l/min), and oxygen (3 l/min). The thorax was opened through posterolateral incision. First, the pulmonary veins and the main pulmonary artery were ligated and dissected. The main bronchus was clamped and pneumonectomy was performed. Then, mediastinal lymph nodes were dissected. After pneumonectomy, the patients were supine in bed and 30%–40% oxygen was supplied by oxygen mask to maintain PaO_2 over 100 mmHg for 48 h.

Pulmonary extravascular thermal volume

The PETV was measured by the thermal-dye dilution method as reported by Lewis and Elings [17]. Briefly, a 10 ml bolus of 5% dextrose solution, cooled to 0°C, containing 5 mg indocyanine green dye was injected through a swan-Ganz thermo-dilution catheter into the right atrium. Simultaneously, arterial blood was withdrawn at a volume of 30 $ml \cdot min^{-1}$ (SW-367, Dilution Pump, Waters, Rochester, MN) through the femoral artery lung water catheter. Then, a thermodilution curve was measured by the thermister located at the tip of the arterial catheter. The dye dilution curve was measured by a densitometer (D-402A, Waters). The PETV was calculated by a lung water computer (9310, Edwards). Three measurements were made at 5-min intervals in each time and averaged to obtain the PETV for that time. We measured the PETV before unilateral pulmonary artery occlusion and during occlusion prior to pneumonectomy. We also measured the thermal volume at 6, 24, 48 h, and at 3 weeks after pneumonectomy in 7 patients (Nos. 1, 2, 6, 7, 11, 13, and 17 in Table 1). In one case, we could not measure the PETV within 48 h after pneumonectomy because of difficulty with the lung water computer.

Hemodynamics

Pulmonary arterial pressure and pulmonary arterial wedge pressure were measured by a pressure transducer (P23ID, Gould, Oxnard, CA) and recorded on a polygraph (AP-600G, Nihon Koden, Tokyo Japan). Midaxillary line was set to be 0 mmHg. Cardiac output was measured by a thermodilution method using a cardiac output computer (COC9520, Edwards). Arterial blood gases were analyzed (ABL2, Radiometer, Copenhagen, Denmark). Colloid osmotic pressure was measured using a colloid osmometer (4100, Wescor, Logan, VT). In one case, we did not measure pulmonary hemodynamics within 48 h after pneumonectomy.

Fraction of pulmonary perfusion

The fraction of pulmonary perfusion was calculated using the distribution of ^{99m}Tc-macroaggregated albumin prior to unilateral pulmonary artery occlusion (Table 1). The radioisotope was injected through a cubital vein. Trapped ^{99m}Tc in capillaries of pulmonary artery was subsequently measured using a gamma camera (RC-IC-1025, Hitachi, Tokyo, Japan).

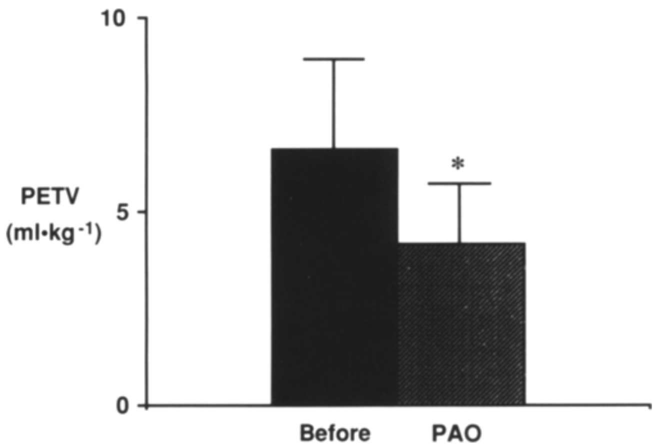

Fig. 1. Pulmonary extravascular thermal volume (*PETV*) in pulmonary artery occlusion (*PAO*) in 18 patients. The thermal volume during occlusion decreased from that before occlusion $^*P < 0.05$ *vs* thermal volume before occlusion

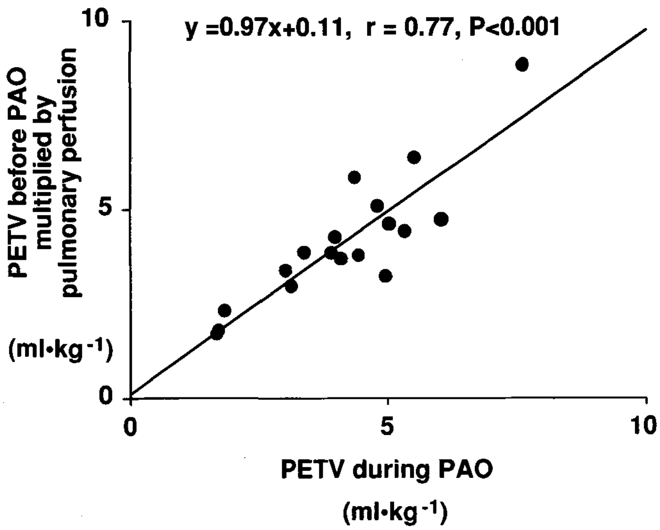

Fig. 2. Relationship between PETV before and during PAO. There was a significant correlation between PETV during PAO and that before occlusion multiplied by the fraction of pulmonary perfusion

Statistics

We used Student's paired *t*-test to compare the changes of PETV. We also used an analysis of correlation to compare the PETV during occlusion with the PETV before occlusion multiplied by the fraction of pulmonary perfusion, or with the PETV at 3 weeks after pneumonectomy. A *P* value less than 0.05 was considered statistically significant.

Results

Pulmonary extravascular thermal volume in unilateral pulmonary artery occlusion

The PETV decreased from 6.6 ± 2.3 ml·kg^{-1} before pulmonary artery occlusion to 4.2 ± 1.6 ml·kg^{-1} during occlusion (Fig. 1). There was a significant relation between the PETV during occlusion and the PETV before occlusion multiplied by the fraction of pulmonary perfusion (Fig. 2).

Hemodynamics in unilateral pulmonary artery occlusion

Pulmonary arterial pressure and pulmonary vascular resistance increased when the pulmonary artery was occluded (Fig. 3). However, pulmonary artery wedge pressure, cardiac output, and arterial oxygen tension during occlusion were not different from those before

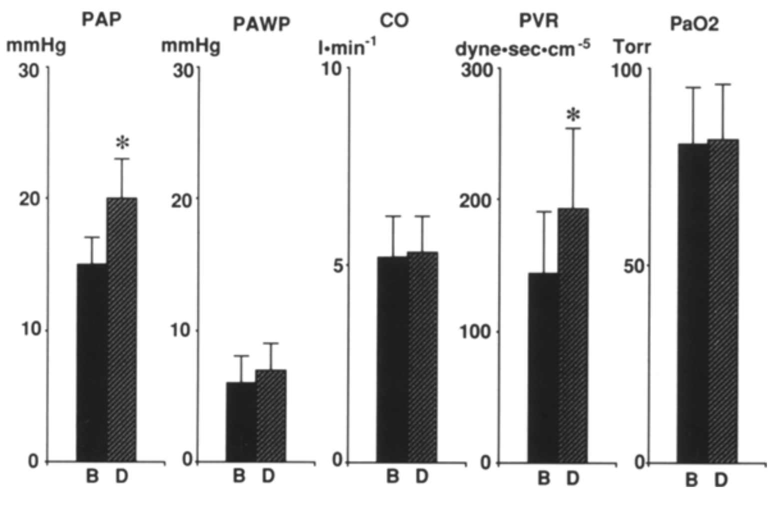

Fig. 3. Pulmonary hemodynamics and arterial oxygen tension in PAO. Pulmonary arterial pressure (*PAP*) and pulmonary vascular resistance (*PVR*) increased during occlusion (*D*) from those before occlusion (*B*). *PAWP*, pulmonary arterial wedge pressure; *CO*, cardiac output, PaO_2, arterial oxygen tension. $^*P < 0.05$ *vs* before occlusion

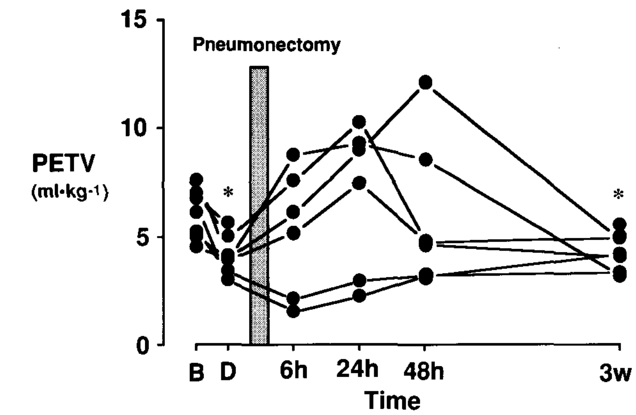

Fig. 4. PETV after pneumonectomy. Within 48 h after pneumonectomy, the thermal volume (*PETV*) decreased in two cases and increased in the other cases. At 3 weeks after pneumonectomy, the thermal volume returned to that during pulmonary artery occlusion. *B*, before occlusion; *D*, during occlusion. $*P < 0.05$ *vs* before occlusion

occlusion. Colloid osmotic pressure was more than 20 mmHg. There were no significant relations between the PETV before occlusion and each hemodynamic value before occlusion.

Pulmonary extravascular thermal volume after pneumonectomy

Values of the PETV were 6.0 ± 1.2, 4.1 ± 0.9, 5.2 ± 2.9, 6.9 ± 3.4, 6.1 ± 3.5, and 4.3 ± 0.9 ml·kg^{-1} before occlusion, during occlusion, at 6, 24, 48 h, and 3 weeks after pneumonectomy in the 7 patients tested postoperatively (Fig. 4). The PETV within 48 h after pneumonectomy decreased in two patients and increased in four. However, the PETV at 3 weeks after pneumonectomy re-

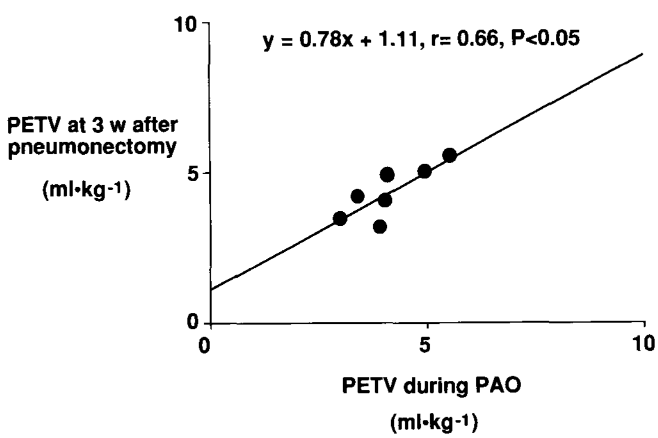

Fig. 5. Relationship between PETV during PAO and that after pneumonectomy. There was a significant correlation between the PETV during PAO and that at 3 weeks after pneumonectomy

turned to the value during occlusion in 7 patients. There was a significant relation between the PETV during occlusion and that at 3 weeks after pneumonectomy (Fig. 5).

Hemodynamics after pneumonectomy

Pulmonary arterial pressure, pulmonary arterial wedge pressure, cardiac output, and pulmonary vascular resistance after pneumonectomy did not differ significantly from those before pulmonary artery occlusion (Fig. 6).

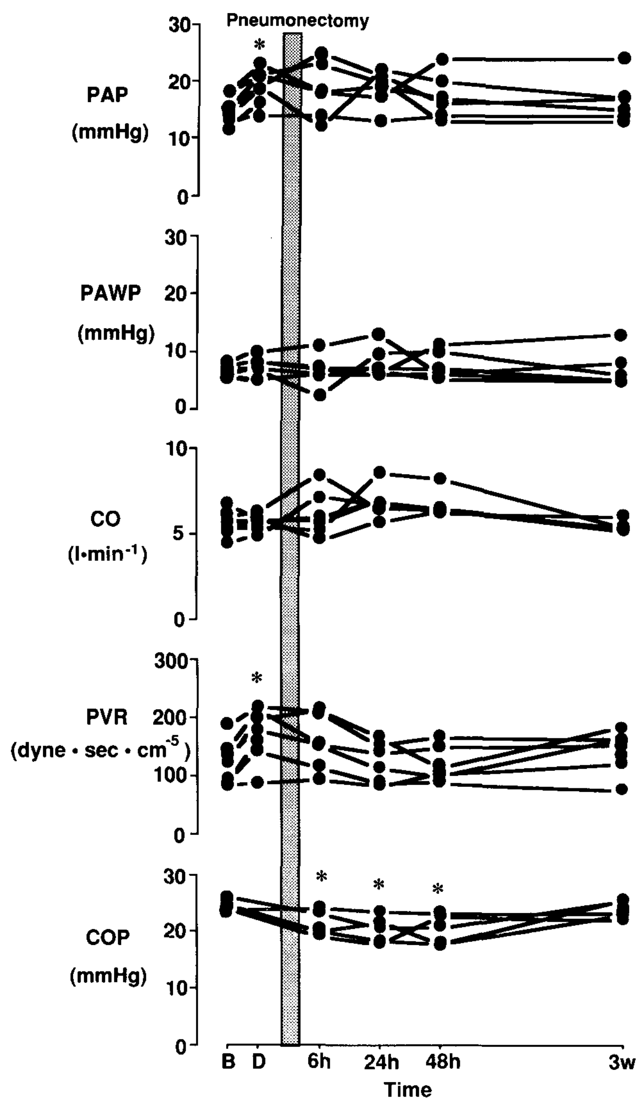

Fig. 6. Pulmonary hemodynamics and colloid osmotic pressure after pneumonectomy. After pneumonectomy, pulmonary arterial pressure (*PAP*), pulmonary arterial wedge pressure (*PAWP*), cardiac output (*CO*), and pulmonary vascular resistance (*PVR*) did not significantly differ from those before occlusion. Colloid osmotic pressure (*COP*) decreased from that before occlusion within 48 h, then returned to that before occlusion at 3 weeks after pneumonectomy. *B*, before occlusion; *D*, during occlusion. $*P < 0.05$ *vs* before occlusion

However, these values were not constant in each case after pneumonectomy. Colloid osmotic pressure decreased within 48 h after pneumonectomy from that in occlusion, then returned to that in occlusion at 3 weeks after pneumonectomy. Arterial oxygen tension increased within 48 h after pneumonectomy from that during occlusion, since patients breathed air with 30%–40% oxygen.

Discussion

The first finding in this study is that the PETV during unilateral pulmonary artery occlusion is reliable as a baseline value in the measurement of the PETV after pneumonectomy. There was a significant relation between the PETV measured during occlusion and at 3 weeks after pneumonectomy. Previous studies [1–4] focused mainly on the ventilatory predictions in the management of patients after pulmonary resection. Indeed, there are many complications related mainly to the airway system such as atelectasis, hypersecretion from the bronchial gland, pneumonia, bronchospasm, and airway edema [18]. However, it is also very important to measure changes in the pulmonary vascular system when managing the postoperative complications involving pulmonary vessels. Previously, the pulmonary arterial pressure, pulmonary artery wedge pressure, cardiac output, blood gases, and colloid osmotic pressure were measured after pneumonectomy. In this study, no significant relationship was found between the PETV and hemodynamic variables in pulmonary artery occlusion. This suggests that the hemodynamic parameters we used in the past after pneumonectomy were not reliable for the measurement of the PETV changes.

Why did the PETV in the normal lung not increase during unilateral pulmonary artery occlusion? One explanation is that the surface area of pulmonary vascular bed in the normal lung was not increased when the whole ejected blood flow in the lung. Luepker et al. [19] reported that the increased PETV at rest was clearly related to increased left atrial and pulmonary artery pressures but not to the blood flow or pulmonary vascular resistance. Since pulmonary arterial wedge pressure did not increase during occlusion, the increase of pulmonary artery pressure was probably insufficient to increase the pulmonary vascular bed in this study. The minor influence of cardiac output on the PETV [20,21] and on precapillary vessel tone without a concomitant rise in pulmonary capillary hydrostatic pressure [6] support our results. The other explanation is that extravascular lung water was insufficient to increase the PETV during pulmonary artery occlusion. Since pulmonary arterial pressure and pulmonary vascular pressure increased, Starling's law [22] indicates that the filtration of fluid from pulmonary vascular spaces into pulmonary interstitium must have increased. The thermal-dye dilution technique accurately measures the filtrated extravascular lung water gravimetrically [23,24]. If the fluid filtration exceeds the capacity of the lymphatic pump removing fluid, the PETV would increase. The absence of a decrease in arterial oxygen tension during occlusion supports the possibility that extravascular lung water did not increase enough to increase the PETV.

The PETV measured by the thermal-dye dilution technique reflects the reduction of pulmonary perfusion in humans. There was a significant relation between the PETV during occlusion and the PETV before occlusion multiplied by the fraction of pulmonary perfusion. Levine et al. [25] reported that the double indicator-dilution technique provides a measure of the fraction of pulmonary perfusion in dogs. In the study, balloon occlusion of the left pulmonary artery resulted in a 50% reduction of the thermal volume. However, in humans with bronchogenic carcinoma, the degree of pulmonary perfusion in the affected lung is not 50% but rather is widely distributed, as shown in Table 1. Accordingly, it was necessary to determine whether the PETV decrease coincided with the reduction of pulmonary perfusion.

The PETV during pulmonary artery occlusion can be predicted by the thermal volume of both lungs and pulmonary perfusion. Therefore, PETV can be measured indirectly in hospitals where pulmonary artery occlusion is not available. The fraction of pulmonary perfusion estimated by a quantitative technetium macroaggregate lung scan (^{99m}TC) has been used as a preoperative split pulmonary function study [2,3]. Similarly, the pulmonary perfusion scan is useful to predict the baseline value for the PETV volume after pneumonectomy.

The second finding in this study is that the PETV is variable within 48 h after pneumonectomy. Since pulmonary edema often occurs between 24 and 48 h after pneumonectomy [6], we measured the thermal volume within 48 h as the PETV in acute postoperative period. In two cases, the PETV decreased from the value during pulmonary artery occlusion, but there was no apparent atelectasis that reduced the pulmonary vascular bed. Previously, the PETV was decreased in the embolization by air [26] or by glass beads [27]. Although chest X-ray could not reveal any findings suggestive of a reduction of the pulmonary bed, it may simply be the case that the decrease was below the limits of detection. In the other cases, the PETV increased two- to threefold of the PETV during occlusion. There are two possible explanations for the increase of the PETV after pneumonectomy. The first is that the filtration gradient may have increased. Although we maintained a negative water balance after pneumonectomy, decreased colloid osmotic pressure might have increased the filtration gradient. Secondly, the dissection of mediastinal lymph node combined with pneumonectomy may have limited the lymphatic pump capacity whereas it remained unaffected during occlusion.

The third finding is that the PETV at 3 weeks after pneumonectomy usually returns to the value during preoperative pulmonary artery occlusion. The PETV was constant in the normal lung before occlusion, during occlusion, and at 3 weeks after pneumonectomy. The observation that no significant change occurred in the regional pulmonary function distribution within the remaining lung [28] supports the contention that PETV at 3 weeks after pneumonectomy returned to the value during pulmonary artery occlusion. Although we did not measure the PETV and hemodynamics between 48 h and 3 weeks after pneumonectomy, it is possible that these variables return to the values before pneumonectomy earlier than 3 weeks.

We conclude that the PETV during pulmonary artery occlusion provides a reliable baseline value in the measurement of the PETV after pneumonectomy. The PETV is variable within 48 h after pneumonectomy, and it returns to the baseline level at 3 weeks after pneumonectomy.

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