

Relation of the Static Compliance Curve and Positive End-expiratory Pressure to Oxygenation during One-lung Ventilation

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Background: Positive end-expiratory pressure (PEEP) is commonly applied to the ventilated lung to try to improve oxygenation during one-lung ventilation but is an unreliable therapy and occasionally causes arterial oxygen partial pressure (P_{aO_2}) to decrease further. The current study examined whether the effects of PEEP on oxygenation depend on the static compliance curve of the lung to which it is applied.

Methods: Forty-two adults undergoing thoracic surgery were studied during stable, open-chest, one-lung ventilation. Arterial blood gasses were measured during two-lung ventilation and one-lung ventilation before, during, and after the application of 5 cm H₂O PEEP to the ventilated lung. The plateau end-expiratory pressure and static compliance curve of the ventilated lung were measured with and without applied PEEP, and the lower inflection point was determined from the compliance curve.

Results: Mean (\pm SD) P_{aO_2} values, with a fraction of inspired oxygen of 1.0, were not different during one-lung ventilation before (192 ± 91 mmHg), during (190 ± 90), or after (205 ± 79) the addition of 5 cm H₂O PEEP. The mean plateau end-expiratory pressure increased from 4.2 to 6.8 cm H₂O with the application of 5 cm H₂O PEEP and decreased to 4.5 cm H₂O when 5 cm H₂O PEEP was removed. Six patients showed a clinically useful ($> 20\%$) increase in P_{aO_2} with 5 cm H₂O PEEP, and nine patients had a greater than 20% decrease in P_{aO_2} . The change in P_{aO_2} with the application of 5 cm H₂O PEEP correlated in an inverse fashion with the change in the gradient between the end-expiratory pressure and the pressure at the lower inflection point ($r = 0.76$). The subgroup of patients with a P_{aO_2} during two-lung ventilation that was less than the mean (365 mmHg) and an end-expiratory pressure during one-lung ventilation without applied PEEP less than the mean were more likely to have an increase in P_{aO_2} when 5 cm H₂O PEEP was applied.

Conclusions: The effects of the application of external 5 cm H₂O PEEP on oxygenation during one-lung ventilation correspond to individual changes in the relation between the plateau end-expiratory pressure and the inflection point of the static compliance curve. When the application of PEEP causes the end-expiratory pressure to increase from a low level toward the inflection point, oxygenation is likely to improve. Conversely, if the addition of PEEP causes an increased inflation of the ventilated lung that raises the equilibrium end-expiratory pres-

sure beyond the inflection point, oxygenation is likely to deteriorate.

HYPOXEMIA during one-lung ventilation (OLV) for thoracic surgery occurs in 7-10% of cases^{1,2} and remains a clinical problem. In most instances, this hypoxemia responds readily to the application of continuous positive airway pressure (CPAP) to the nonventilated lung.^{3,4} In a variety of clinical situations, CPAP is of no benefit or interferes with the surgery.⁵ The standard second line of therapy for hypoxemia when CPAP cannot be used or does not help is the application of positive end-expiratory pressure (PEEP) to the ventilated lung.⁶ In the majority of cases, PEEP does not improve oxygenation, and frequently it causes the arterial oxygen partial pressure (P_{aO_2}) to decrease even further.⁷ However, in a minority of cases, PEEP does cause a useful increase in P_{aO_2} during OLV.⁸ It has remained unclear which patients will benefit from PEEP and why PEEP works in some patients but not in others.

It is now appreciated that the majority of adults undergoing thoracic surgery develop an intrinsic PEEP (sometimes referred to as auto-PEEP) during OLV,⁹ and this intrinsic PEEP interacts with the external PEEP applied through the ventilator to produce the total PEEP to which the patients' lungs are actually subjected.¹⁰ In addition, it has recently been demonstrated that the static lung compliance curve can be used to understand the effects of PEEP on the respiratory mechanics of ventilated patients with acute respiratory distress syndrome and to guide ventilation therapy in the intensive care unit.¹¹ The aim of this study was to determine if the effects of PEEP on oxygenation during OLV are related to changes in lung mechanics as demonstrated by the static compliance curve and to find indicators that identify the subgroup of patients that benefit from the application of PEEP during OLV. The hypothesis tested was that improved oxygenation will occur when the application of PEEP causes the plateau end-expiratory pressure (EEP) to move toward the lower inflection point (IP) of the compliance curve.

Materials and Methods

After obtaining approval from the Research Ethics Board of the University Health Network (Toronto, Ontario, Canada) and signed consent, patients were studied during stable open-chest OLV in the lateral decubitus

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position. Forty-two patients were studied based on a sample-size calculation¹² using the P_{aO_2} data from the study by Cohen and Eisenkraft.¹³ Based on these previous data, the potential significant treatment effect from the application of PEEP was designated as a 20% increase of P_{aO_2} and the SD of P_{aO_2} during OLV with PEEP as 28%. The α and β errors for the sample size were chosen as 0.05 and 0.1, respectively.

The study subjects were the consecutive consenting patients who met the study criteria of one surgeon (T. W.). The inclusion criterion was lung or esophageal surgery in the lateral position where the expected duration of OLV exceeded 1 h. Exclusion criteria were any contraindications to the application of PEEP (potentially increased intracranial pressure, lung bullae) or to the use of a left-sided double-lumen endobronchial tube (DLT), or to the use of any of the anesthetic drugs in the protocol. Patients underwent preoperative, outpatient pulmonary function testing (spirometry and plethysmography).

On admission to the operating room, patients had placement of standard anesthetic monitors plus intravenous and arterial catheters, and room-air arterial blood gas was drawn. Thoracic epidural catheters were placed in a midthoracic (T3–T7) level and tested with 3 ml of 2% lidocaine. No further epidural drugs were administered during the study period. Intravenous induction of anesthesia was performed with a titration of 1–4 mg midazolam, 0.01–0.02 $\mu\text{g}/\text{kg}$ sufentanil, 1–2 mg/kg propofol, and 0.6 mg/kg rocuronium. The patients' tracheas were intubated with a left-sided DLT, with tube position confirmed by fiberoptic bronchoscopy before and after turning the patient to the lateral position. The patients' lungs were ventilated with oxygen using a Siemens 900C Ventilator (Siemens Inc., Solna, Sweden) using a tidal volume of 10 ml/kg and a rate of 10 breaths/min, with inspiration equal to 33% of respiratory cycle time including a 10% end-inspiratory pause for both two-lung ventilation and OLV. Anesthesia was maintained with an intravenous infusion of 0.2–0.3 $\mu\text{g} \cdot \text{kg}^{-1} \cdot \text{h}^{-1}$ sufentanil and 100–150 $\mu\text{g} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ propofol titrated to keep the systolic blood pressure and heart rate within $\pm 20\%$ of preinduction values. Bolus doses of 0.2 mg/kg rocuronium were administered to maintain a neuromuscular blockade of greater than 90% reduction of initial twitch height. Nasopharyngeal temperature was maintained between 36.0 and 37.0°C with a Warm Touch forced air warmer (Mallinckrodt Inc., St. Louis, MO) applied to the lower body.

After induction of anesthesia, patients were placed in the lateral decubitus position for surgery. After opening the chest, an initial intraoperative arterial blood gas was drawn during two-lung ventilation, and the two-lung EEP was measured as the plateau airway pressure during a 10-s end-expiratory hold triggered with the ventilator, using a manometer calibrated against a water column

that was attached between the proximal end of the DLT and the anesthetic circuit using a T-connector.¹⁴ OLV was then commenced by clamping the lumen of the DLT to the nonventilated lung, and the bronchial cuff was inflated to abolish any leak from the ventilated to the nonventilated lung, confirmed by an underwater leak test.¹⁵ The maintenance of adequate lung isolation during OLV was monitored by observing for stable and comparable values for inspiratory and expiratory tidal volumes with a side-stream spirometer¹⁶ (Datex Inc., Helsinki, Finland).

Arterial blood gases were drawn after 20 and 30 min of OLV, and the initial one-lung EEP was measured at 30 min as the end-expiratory plateau pressure (EEP₁). OLV was resumed for 1 min after the EEP measurement, and then the DLT was disconnected from the circuit and the patients' lungs allowed to deflate to atmosphere for 12 s. A 3-l syringe was then connected to the lumen of the DLT from the dependent lung, and a repeat plateau pressure was recorded. The dependent lung was inflated in a stepwise fashion with 100-ml increments of oxygen every 4 s to a volume of 1,500 ml or a maximum airway pressure of 30 cm H₂O. The plateau pressure after each incremental inflation was recorded and used to construct an inspiratory compliance curve for the dependent (ventilated) lung.^{17,18} After this static inflation of the ventilated lung, 5 cm H₂O of external PEEP was added to the circuit at the ventilator, and OLV was continued for 10 min, at which time an arterial blood gas measurement was repeated, the EEP in the circuit was again measured (EEP₂), and the static compliance curve was again generated in an identical fashion after a 12-s expiration to atmosphere. The external PEEP was then withdrawn from the circuit, and after a further 10-min OLV without PEEP, all measurements were repeated (EEP₃). During the period of the study, no surgery was performed on the lung.

The static inspiratory compliance curves of the ventilated lung were constructed by manual plotting of volume *versus* pressure, and the lower IP of the curve was recorded as the pressure at the intersection of the linear extrapolations of the initial and the most compliant portions of the curve within the tidal volume range (figs. 1–3).^{19,20} If the increase in the slope of the compliance curve from the initial to the most compliant (steepest) portion was less than 30%, the compliance curve did not have a clinically relevant IP,²¹ and the IP pressure was assigned the initial equilibration pressure measured in the closed lung-syringe system at the end of the 12-s expiration when the 3-l syringe was attached to the lumen of the DLT from the dependent lung.

Statistics

Statistical analyses were performed with the aid of a computer program (SPSS 7.0 for Windows; SPSS Inc., Chicago, IL). Individual patient changes in P_{aO_2} during

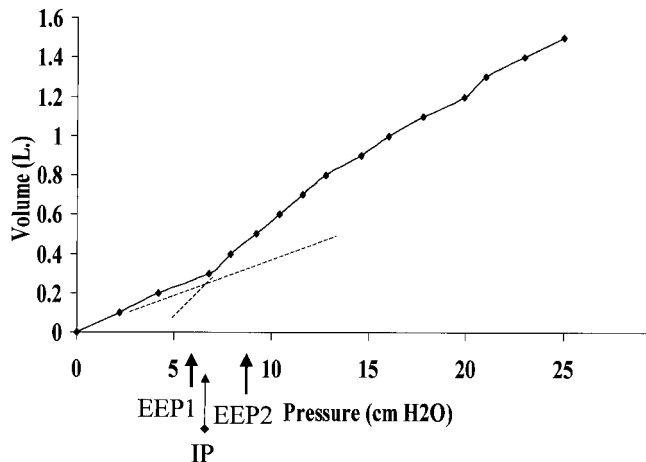


Fig 1. The initial static compliance curve of the dependent lung during one-lung ventilation for thoracotomy. The patient was a 57-yr-old woman with a preoperative forced expiratory volume in 1 s of 67% predicted. The inflection point (IP) was calculated as the pressure at the intersection of the linear extrapolations of the slopes of the initial and the most compliant portions of the curve within the tidal volume range. This is demonstrated by the thin dashed lines (in this patient, IP = 6.6 cm H₂O). The initial end-expiratory plateau pressure (EEP1) for this patient during one-lung ventilation was 6.1 cm H₂O, and the circuit end-expiratory pressure after the application of 5 cm H₂O PEEP through the ventilator (EEP2) was 8.7 cm H₂O. The compliance curve in this patient is typical of the majority of the patients studied. Positive end-expiratory pressure caused a net increase in the pressure gradient between the IP and EEP. In this patient, arterial oxygen partial pressure did not improve with positive end-expiratory pressure.

stable OLV associated with the addition or removal of external PEEP were compared with the changes in the pressure gradient for that patient between the plateau EEPs (EEP₁, EEP₂, and EEP₃) measured in the circuit and the IP pressure calculated from the compliance maneu-

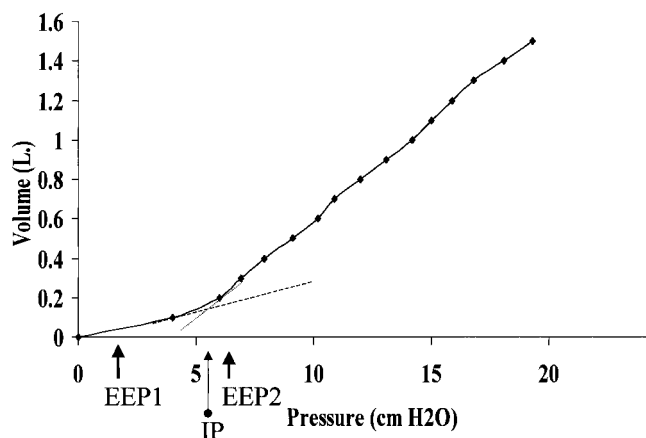


Fig 2. The initial one-lung ventilation static compliance curve of a 72-yr-old man with a preoperative forced expiratory volume in 1 s = 102% predicted. The application of positive end-expiratory pressure caused the end-expiratory pressure (EEP) to move closer to the inflection point (IP) in this patient (the net difference between EEP2 and IP was less than the initial difference between IP and EEP1). This was one of the few patients studied in whom positive end-expiratory pressure caused an increase in arterial oxygen partial pressure during one-lung ventilation.

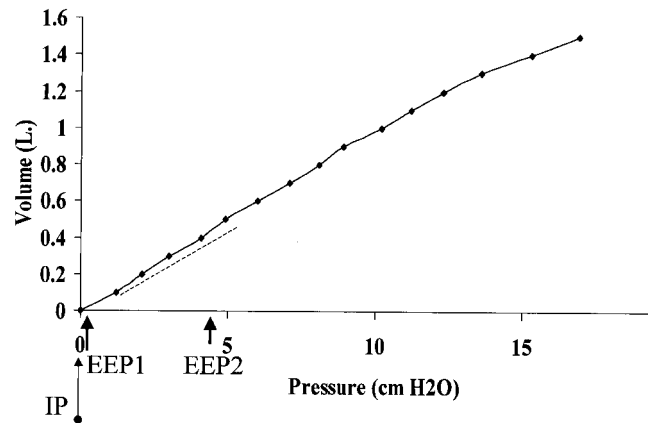


Fig 3. The initial one-lung ventilation static compliance curve of a 32-yr-old man with a forced expiratory volume in 1 s = 96%. This was one of the 10 patients initially studied whose curves did not show an inflection point (IP). The IP was assigned the value of the initial end-expiratory plateau pressure (EEP1) for calculation of the IP-EEP gradient. The application of 5 cm H₂O positive end-expiratory pressure from the ventilator resulted in a measured plateau EEP in the circuit (EEP2) of 4.2 cm H₂O; thus, the IP-EEP gradient increased. This patient did not have an increase in arterial oxygen partial pressure with positive end-expiratory pressure during one-lung ventilation.

ver (the IP-EEP gradient). These changes in Pao₂ during OLV were compared with changes in the IP-EEP gradient by linear correlation. Subgroups of patients were evaluated for a clinically useful (> 20%) increase in Pao₂ from the addition of PEEP during OLV by Fisher's exact test. Intraoperative gas exchange, ventilatory mechanics, and hemodynamic data for all patients during the stages of two-lung ventilation and OLV were compared by repeated-measures analysis of variance. Preoperative and intraoperative parametric data from patients who had a clinically useful increase in Pao₂ with the addition of PEEP during OLV were compared with those of patients who had a clinically important decrease in Pao₂ (> 20%) from PEEP during OLV by analysis of variance.

Table 1. Summary Data for All Patients Studied (n = 42)

	Mean (±SD)
Age (yr)	61 ± 13
Height (cm)	167 ± 10
Weight (kg)	68 ± 14
TLC (%)	116 ± 21
RV (%)	130 ± 33
FVC (%)	104 ± 27
FEV ₁ (%)	101 ± 27
Male/Female	23/19
Right/Left	24/18
Lobectomy	26
Esophagectomy	7
Biopsy	4
Pneumonectomy	2
Wedge	2
Bilobectomy	1

FEV₁ = forced expiratory volume in 1 s; FVC = forced vital capacity; RV = residual volume; TLC = total lung capacity.

Table 2. Mean Ventilation and Blood Gas Data from All Patients

	Two-lung Ventilation	OLV1	OLV2 (with PEEP ₅)	OLV3
P _{aw} peak (cm H ₂ O) ±SD	18.8 ± 3.4	29.3 ± 6.4*	29.7 ± 6.0*	28.5 ± 6.8*
P _{aw} plateau (cm H ₂ O)	14.1 ± 2.9	20.4 ± 4.6*	20.9 ± 4.7*	19.3 ± 4.8*
Total PEEP (cm H ₂ O)	1.2 ± 2.1	4.2 ± 3.4*	6.8 ± 1.8†	4.5 ± 3.3*
Pao ₂ (mmHg)	365 ± 23	192 ± 91*	190 ± 90*	205 ± 79*
Paco ₂ (mmHg)	35 ± 4	33 ± 4	33 ± 4	33 ± 4

* Significant difference versus 2LV, $P < 0.05$. † Significant difference versus OLV1 and OLV3, $P < 0.05$.

OLV = one-lung ventilation; PEEP = peak end-expiratory pressure; P_{aw} = inspiratory airway pressure; Pao₂ = arterial oxygen tension; Paco₂ = arterial carbon dioxide tension.

Results

Summary data for all patients studied are presented in tables 1–3. Examples of the initial compliance curves for three of the patients studied are shown in figures 1–3 along with the calculation of the IP. Overall the mean (\pm SD) Pao₂ (365 ± 23 mmHg) was higher during two-lung ventilation ($P < 0.001$) than at any time during OLV and was not significantly different between the initial period of OLV without PEEP (192 ± 91 mmHg) and the subsequent period with PEEP (190 ± 90 mmHg) or the final study period without PEEP (205 ± 79 mmHg). There was no significant difference between the mean Pao₂ after 20-min OLV (202 ± 98 mmHg) and after 30 min (range of changes for 20-min Pao₂–30-min Pao₂ = +25 to –17). There were no significant differences in arterial carbon dioxide partial pressure or pH between any of the periods of two-lung ventilation or OLV.

The mean EEP during two-lung ventilation (1.2 ± 2.1 cm H₂O) was lower than at any time during OLV ($P < 0.001$). The EEP measured in the circuit during OLV with added external 5 cm H₂O PEEP (6.8 ± 1.8 cm H₂O) was higher than during the preceding period of OLV without added PEEP (4.2 ± 3.4 cm H₂O) ($P < 0.01$) or the subsequent final study period of OLV without added PEEP (4.5 ± 3.5 cm H₂O) ($P = 0.01$). There was no significant difference in the EEP between the initial and final periods of OLV without added PEEP.

The individual changes in Pao₂ from the initial period of OLV without PEEP to the period of OLV with PEEP correlated in an inverse fashion with the changes in the IP-EEP gradient using the IP measured from the initial OLV compliance curve ($r = 0.76$, $P < 0.001$; fig. 4). When the application of PEEP during OLV caused the

pressure differential between the IP and EEP to decrease, the Pao₂ tended to increase. Conversely, if PEEP caused the EEP to move further away from the IP, increasing the gradient, then Pao₂ tended to decrease. No significant correlations could be found using the subsequent IP pressures measured from the compliance curves generated after the application of PEEP during OLV and subsequent changes in Pao₂ (OLV2 to OLV3).

The subgroup of patients who had a 20% increase in Pao₂ with PEEP during OLV ($n = 6$) had higher normalized preoperative spirometric pulmonary function values: forced vital capacity ($117 \pm 13\%$ predicted) than those who had a 20% decrease in Pao₂ ($n = 9$; forced vital capacity = $87 \pm 11\%$; $P = 0.005$) and also had a higher forced expiratory volume in 1 s ($120 \pm 13\%$ vs. $85 \pm 12\%$; $P = 0.004$). The subgroup of patients ($n = 10$) who had both a Pao₂ during two-lung ventilation that

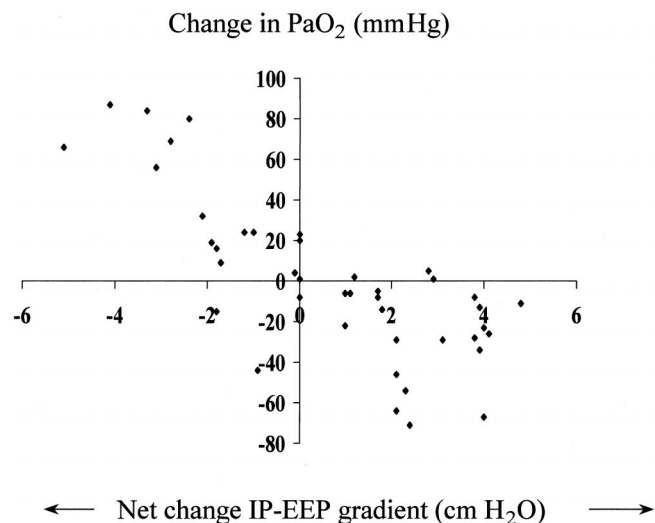


Fig. 4. The changes in arterial oxygen partial pressure (Pao₂) and in the gradient between the lower inflection point of the static lung inflation compliance curve (IP) and the plateau end-expiratory pressure (EEP) associated with the application of 5 cm H₂O positive end-expiratory pressure during one-lung ventilation in 42 patients. There was a significant inverse correlation ($r = 0.76$, $P < 0.001$). In the patients ($n = 6$) in whom positive end-expiratory pressure had the most effect to move the EEP closer to the IP, the Pao₂ improved. In the majority of patients, positive end-expiratory pressure caused no change or increased the IP-EEP gradient, and Pao₂ either did not change or decreased.

Table 3. Lower Inflection Point (IP) Data from the Static Compliance Curves during OLV

	OLV1	OLV2 (with PEEP)	OLV3
IP mean \pm SD	4.5 \pm 3.5 (cm H ₂ O)	4.5 \pm 1.7	4.1 \pm 3.0
No. patients with no IP	10/42	13/42	8/42

No statistically significant differences between the three time periods.

OLV = one-lung ventilation; PEEP = peak end-expiratory pressure.

was lower than the mean (365 mmHg) for the entire study group and who had an EEP_1 during the initial period of OLV lower than the mean (4.2 cm H₂O) were significantly more likely to have a greater than 20% increase in Pao_2 with the application of 5 cm H₂O PEEP during OLV than the other patients ($P = 0.001$).

Peak and plateau inspiratory airway pressures were lower during two-lung ventilation than at any time during OLV ($P < 0.001$). These pressures were not statistically different during the periods of OLV with or without added PEEP (table 2). There was a significant effect of the side of the operation on Pao_2 during OLV but not during two-lung ventilation. Left-sided surgery was associated with a higher mean Pao_2 (224 ± 89 mmHg) than right-sided (171 ± 69 mmHg; $P < 0.05$) over the period of OLV. There were no correlations between side of surgery and changes in Pao_2 with PEEP. Heart rate and blood pressure were not statistically different between the periods of two-lung ventilation and OLV.

Discussion

Prevention and treatment of hypoxemia during OLV for thoracic surgery can be a difficult clinical problem. Although the application of CPAP to the nonventilated lung is usually beneficial, it requires reinflation of the lung for optimal effect.³ This is not possible in cases in which the bronchus of the operative lung is obstructed or if the ipsilateral lower airway is open to atmosphere, as in bronchial surgery or in the case of a bronchopleural fistula. In addition, CPAP frequently makes surgery more difficult as the reinflated lung impedes exposure. This is particularly a serious clinical problem during thoracoscopy, when the surgeon does not have the ability to retract the lung out of the surgical field,⁵ and video-assisted thoracoscopic surgery is continually increasing in frequency. For these reasons, there is a need to understand and improve the other options available to improve oxygenation during OLV. The application of PEEP to the ventilated lung in this clinical situation is a therapy that is recommended in standard texts of anesthesia.^{6,22} The majority of studies of the use of PEEP to the ventilated lung during OLV have shown that it is of no benefit or that it causes a decrease in mean Pao_2 during OLV.^{4,7,8} However, there are some patients who benefit from PEEP.¹³

The current study found that the application of 5 cm H₂O PEEP through the ventilator circuit caused a clinically useful increase ($> 20\%$) in Pao_2 during a stable period of OLV in only 6 of 42 patients. The majority of patients had no clinically important change in Pao_2 during the application of PEEP, and in 9 of 42 patients there was a greater than 20% decrease in Pao_2 . The changes in Pao_2 with PEEP correlated inversely with changes in the gradient between the plateau end-expiratory airway pressure and the pressure at the lower IP measured from

the inspiratory static compliance curve of the ventilated lung. The EEP measured when no external PEEP is applied is sometimes referred as *auto-PEEP* or *intrinsic PEEP*.¹⁰ In the majority of patients who had EEP levels greater than 4 cm, adding PEEP elevated the plateau EEP beyond the IP and increased the EEP-IP gradient. The subgroup of patients who had both a lower than mean Pao_2 during two-lung ventilation and a lower level of EEP during OLV are most likely to benefit from 5 cm H₂O PEEP during OLV. The group of patients who showed improved Pao_2 values with PEEP during OLV had better preoperative spirometric pulmonary function than those in whom PEEP caused a decrease in Pao_2 .

One of the major goals of anesthetic management during OLV is to improve oxygenation by maximizing the pulmonary vascular resistance of the nonventilated lung while minimizing the resistance to flow through the ventilated lung. The pulmonary vascular resistance is normally at its lowest when the lung volume is at its functional residual capacity (FRC).²³ During OLV, a variety of pathophysiologic changes tend to interfere with the ability of the ventilated lung to maintain its normal FRC. In the lateral position with the hemithorax open, the loss of the elastic recoil of the chest wall and the weight of the mediastinum will tend to decrease the FRC of the ventilated lung, whereas the increased airway resistance to expiration through one lumen of a DLT and the use of a relatively large tidal volume for a single lung will tend to increase EEP²⁴ and increase FRC. Because of underlying mechanical differences in the respiratory systems of the variety of patients who present for thoracic surgery, it is difficult to develop one ventilation method that is ideal for all. Theoretically, it would be best to measure the FRC of the ventilated lung and to manipulate the ventilation to keep that lung as close to its FRC as possible. It is very difficult to obtain a reliable measure of FRC during OLV because of the difficulty of the clinical measurement and the persistence of end-expiratory flow in most patients.²⁵ However, the FRC can be estimated from the lower IP of the static lung compliance curve.²⁶

The minority of patients who benefit from PEEP during OLV seem to be patients with good elastic recoil as suggested by normal spirometry. Presumably, these patients expire down to an EEP that is below their FRC and are prone to develop atelectasis in the dependent lung,²⁷ which would explain the tendency of these patients to have lower Pao_2 values in the lateral position during two-lung ventilation. This would also explain the common clinical observation that patients with normal mechanical lung function often are less tolerant of OLV.²⁸ Conversely, patients with poor elastic recoil or increased airway resistance may be expected to have higher levels of EEP during OLV, and this would explain the observation that they tend to have better oxygenation.²⁹ The mechanism by which PEEP caused improved arterial

oxygenation in patients with an EEP below their IP during OLV is not certain. PEEP may cause recruitment of collapsed alveoli. However, this could be expected to be demonstrable by a change in the shape of the compliance curve after the application of PEEP, which was not seen in this study. Other possible mechanisms by which PEEP could improve P_{aO_2} in this subgroup of patients include allowing more homogeneous ventilation-perfusion matching in the ventilated lung or by altering the distribution of pulmonary blood flow between the ventilated and nonventilated lungs.

The technique of measurement of compliance curves with stepwise inflation from a 3-l syringe was performed as previously described.^{17,18,20} If the slope of the compliance curve does not increase by 30% from its first measured portion ($n = 10$), it is assumed that there is no lung recruitment over the course of the static inflation maneuver.²¹ Based on a pilot study, it was determined that if the compliance curve was measured starting at the end of a normal expiratory period (4 s), when the majority of patients still demonstrate persistent expiratory flow,^{9,25} only a minority of patients could be shown to have an IP in their compliance curve. The use of a triple expiratory period (12 s) before the compliance measurement was chosen as a compromise so that the majority of patients would have time to reach an equilibrium lung volume at end expiration without starting to develop atelectasis.

The level of external applied PEEP studied (5 cm H_2O) was selected as a value that has been reported to be of benefit in some patients but has not been shown to interfere with cardiac output during OLV,⁸ which is another important determinant of oxygenation during thoracotomy.³⁰ Although it may be best to individualize the level of PEEP applied depending on lung mechanics when trying to optimize ventilation for a specific patient, for purposes of standardization of the study and to demonstrate the interaction of PEEP with the compliance curve, the same level of PEEP was applied to all subjects.

Unlike the pattern of changes in oxygenation with the application of PEEP, no pattern could be identified in the changes in oxygenation that occurred when PEEP was withdrawn during OLV. This may be a result of the fact that the period allowed to return to steady state OLV without PEEP was only 10 min, and the recruitment of lung regions from PEEP can persist for up to 45 min after it is removed.³¹ Higher P_{aO_2} levels during left- versus right-sided thoracotomy have been documented in previous studies¹ and are thought to be related to a lower level of intrapulmonary shunt when the smaller left lung is collapsed.

Application of PEEP selectively to the dependent lung during two-lung ventilation with the chest closed in the lateral position has been shown by other investigators to improve oxygenation and compliance of the dependent lung.^{32,33} Previously it has been assumed that the compliance curve of the lung would maintain its normal

configuration during OLV and that the ventilated lung would move to a different FRC on this curve.³⁴ These assumptions about the changes in the compliance curve during OLV have largely been extrapolations based on measurements in closed-chest subjects. The compliance curves in this study rarely showed an upper IP even though the volume approached the total capacity for a single lung (figs. 1–3). The mechanical behavior of the respiratory system during open-chest OLV as demonstrated by the compliance curves in this study is very different than previously suggested. Compliance curves are normally the product of a complex interaction between the elastic forces of the lungs, the chest wall, and the abdomen. The shapes of the compliance curves generated in this study suggest that this interaction is different in the open-chest OLV situation when the contributions of the opposite lung, chest wall, and abdomen are modified compared with the curves in closed-chest patients. There would seem to be a potential in many patients to inflate the dependent lung to potentially dangerous high volumes without any detectable decrease in compliance.

The change in P_{aO_2} for an individual patient with the application of PEEP during OLV in previous studies has been extremely variable and unpredictable. There are a minority of patients, often those with lower P_{aO_2} values, who do benefit from PEEP.¹³ However, in clinical practice, it would be preferable to be able to predict which patients would benefit from PEEP and to use it prophylactically rather than to wait until the patient desaturates to begin treatment. In a series of patients, Inomata *et al.*²⁴ showed that application of external PEEP to the dependent lung with a value equal to the measured level of auto-PEEP improved the mean P_{aO_2} by 28 mmHg during OLV. Total PEEP values and compliance were not measured in that study. Intrinsic PEEP and external applied PEEP interact in an unpredictable fashion during OLV to produce the EEP to which the patients' lungs are exposed.¹⁰ It was previously thought that there would be no significant interaction between intrinsic PEEP and external PEEP and that the mechanical effects of the larger pressure would be predominant and determine the upstream equilibrium pressure and volume of the lung; this was termed the *waterfall effect*.³⁵ It has subsequently been shown, during two-lung ventilation, that there is an individual critical level for added external PEEP (approximately 50–75% of the intrinsic PEEP) above which added external PEEP will begin to increase the EEP and cause dynamic hyperinflation.³⁶ It has been shown in a lung model that for equivalent PEEP levels, applied PEEP may result in a better distribution of ventilation than intrinsic PEEP.³⁷ The patients in the study by Inomata *et al.*²⁴ are the only OLV study group that has demonstrated an improvement in mean P_{aO_2} with PEEP. This may be related to the small number of patients studied ($n = 8$) or the patient population that was

selected (nonobese and without obstructive airways disease).

This study demonstrates that the changes in oxygenation during stable OLV associated with the application of PEEP correspond to changes in the relation between the EEP and the static compliance curve of the lung. However, the method of constructing the compliance curves used in this study is not readily applicable in standard clinical practice. It is possible that with improved ventilation monitoring technology, automated construction of compliance curves and derived variables will be available intraoperatively.³⁷ As has been previously demonstrated during mechanical two-lung ventilation of patients in the intensive care unit, oxygenation is improved if the application of PEEP moves the end-expiratory plateau pressure closer to the pressure at the lower IP of the compliance curve.^{11,38} However, if the added PEEP results in the net increase of an already elevated EEP beyond the IP pressure, oxygenation will deteriorate. Presumably this is because the resulting increased inflation of ventilated lung regions results in a redistribution of pulmonary blood flow to poorly or nonventilated lung areas. This is similar to the concept of the open lung approach used to ventilate patients with acute respiratory distress syndrome and other conditions resulting in abnormal respiratory mechanics.^{19,39} The subgroup of patients who will benefit from the application of PEEP to the ventilated lung during OLV can be identified prospectively, rather than by trial and error as in the past, and these data can be used to guide anesthetic ventilation management for thoracic surgery. Patients who tended to have P_{aO_2} values lower than the mean during two-lung ventilation in the lateral position and who developed lower than mean levels of EEP during OLV showed improved oxygenation with a low level (5 cm H_2O) of applied PEEP during OLV.

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