A structured narrative review of clinical and experimental studies of the use of different positive end-expiratory pressure levels during thoracic surgery

Jiang Yueyi1 | Tan Jing2 | Gu Lianbing1,2

1The Affiliated Cancer Hospital of Nanjing Medical University, Nanjing, China
2Department of Anesthesiology, Jiangsu Cancer Hospital, Nanjing, China

Correspondence
Gu Lianbing, The Affiliated Cancer Hospital of Nanjing Medical University, Nanjing, China.
Email: 13951947684@163.com

Funding information
None.

Abstract
Objectives: This study aimed to present a review on the general effects of different positive end-expiratory pressure (PEEP) levels during thoracic surgery by qualitatively categorizing the effects into detrimental, beneficial, and inconclusive.

Data source: Literature search of Pubmed, CNKI, and Wanfang was made to find relative articles about PEEP levels during thoracic surgery. We used the following keywords as one-lung ventilation, PEEP, and thoracic surgery.

Results: We divide the non-individualized PEEP value into five grades, that is, less than 5, 5, 5–10, 10, and more than 10 cmH2O, among which 5 cmH2O is the most commonly used in clinic at present to maintain alveolar dilatation and reduce the shunt fraction and the occurrence of atelectasis, whereas individualized PEEP, adjusted by test titration or imaging method to adapt to patients’ personal characteristics, can effectively ameliorate intraoperative oxygenation and obtain optimal pulmonary compliance and better indexes relating to respiratory mechanics.

Conclusions: Available data suggest that PEEP might play an important role in one-lung ventilation, the understanding of which will help in exploring a simple and economical method to set the appropriate PEEP level.

KEYWORDS
lung protective ventilation, one-lung ventilation, positive end-expiratory pressure, thoracic

1 INTRODUCTION

Positive end-expiratory pressure (PEEP) is an auxiliary ventilation mode in which the airway pressure and alveolar pressure are higher than the atmospheric pressure through ventilator intervention in the expiratory phase. Applying a certain level of PEEP to the ventilated lung can promote lung recruitment, provide sufficient oxygenation and alveolar ventilation, increase functional residual capacity (FRC), reduce intrapulmonary shunt, and effectively improve alveolar compliance.1–6

One lung ventilation (OLV) realizes lung isolation and provides a good surgical field for surgical operation. However, OLV is a non-physiological ventilation mode, and unreasonable respiratory parameters often lead to ventilator-reduced lung injury.7 With the gradual...
improvement of the concept of lung-protective ventilation strategy (LPVs), LPVs is increasingly being used in thoracic surgery low tidal volume (VT) ventilation mode, PEEP, and recruitment maneuver strategy (RMS) are common strategies used in clinical practice.8–10 Currently, the concept of low tidal volume ventilation has been accepted and widely used. Although low tidal volume ventilation can reduce the risk of hyperinflation, the cyclic opening and closing of alveoli reduce the stability of alveoli, which may further lead to atelectasis.11–14 Therefore, the application of PEEP appears to be protective. It can dilate the collapsed alveoli during surgery and prevent the expanded alveoli from collapsing again throughout the respiratory cycle.15–17 It also plays a certain role in improving ventilation and oxygenation. Nevertheless, how to set the appropriate level of PEEP remains questionable and controversial even after a large number of animal experiments and clinical trials.

Most scholars adopted that PEEP at the level of 5 cmH2O is enough to keep the alveoli open, improve the oxygenation function of lung tissue, and reduce the shunt fraction.18–21 On the other hand, some scholars argued that it may not lead to excessive alveolar expansion and hemodynamic damage.22 They believed that 10 cmH2O PEEP can significantly increase the FRC, arterial oxygen partial pressure, and reduce the dead space fraction.23 Besides this, there exists several other points of views. More recently, the concept of optimal PEEP level has been put forward for it can improve intraoperative oxygenation and reduce the incidence of perioperative respiratory complications.24–27 To determine an optimal PEEP level that minimizes the harm caused by either insufficient or excessive distension, an individual approach may be needed.28 Overall, definitive evidence on the optimal PEEP value is not yet available. The review compared not only different PEEP levels but also possible optimal strategies during thoracic surgery.

2 | SEARCH STRATEGY

Electronic databases were searched until March 2022 using a string of medical subject heading terms or related terms. The sensitive search strategy combined the following Medical Subject Headings and Keywords: “one-lung ventilation” OR “OLV” AND “positive end–expiratory pressure” OR “positive end expiratory pressure” OR “PEEP” AND “thoracic surgery.” Pubmed was used as a search engine for the Medline database and as the main source of information for this review. Furthermore, the China National Knowledge Infrastructure (CNKI) and Wanfang Database were also searched for relevant articles. The language was restricted to English and Chinese. The article type included clinical trials, animal experiments, observational studies, and review articles. In addition, we searched related articles in the reference lists of the included articles. Selection of clinical trials was restricted to those adult patients selective for thoracic surgery undergoing general anesthesia. Clinical trials in patients undergoing cardiac surgery and lung transplantation were excluded. A total of 160 articles were selected and analyzed in this review. Then, three authors reviewed these retrieved articles for suitability.

This narrative review provides a comprehensive literature of clinical trials and animal experiments that involved using PEEP in thoracic surgery, the application of which has its own advantages and disadvantages. When searching electronic databases, we found that a mass of clinical or animal research applied PEEP value of 5 or 10 cmH2O, with the remainder in between or less than 5 cmH2O or more than 10 cmH2O. The studies have come to different conclusions even though the same PEEP value used. Thus, we not only divided the non-individualized PEEP value into five grades, that is, less than 5, 5, 5–10, 10, and more than 10 cmH2O, divided the individualized PEEP value into two main setting approaches, test titration method and imaging method, but also qualitatively categorized the conclusions from the papers into detrimental, beneficial, and inconclusive. General effects of different PEEP levels during thoracic surgery are summarized in Table 1.

3 | NON-INDIVIDUALIZED PEEP VALUE

3.1 | PEEP < 5 cmH2O

The precise role of low-level PEEP has been less clearly defined. PEEP less than 5 cmH2O is rarely used in clinical practice, possibly because it cannot fully expand the alveoli or resist the patient’s intrinsic PEEP.29

3.1.1 | Clinical research

In the Department of Thoracic Surgery, one-lung ventilation is widely used during operations. During one-lung ventilation, partial pressure of oxygen may decrease and peak airway pressure may increase. The application of PEEP levels of less than or equal to 5 cmH2O can improve oxygenation and to correct hypoxemia,20,30 while avoiding high airway pressure and lung injury caused by excessive alveolar expansion,31 thereby reducing the incidence of postoperative pulmonary
| PEEP      | Effect                | Clinical trials | Animal experiments | Predominant action |
|-----------|-----------------------|-----------------|-------------------|--------------------|
| <5 cmH₂O  | Oxygenation           | 20, 30          |                   | Inconclusive       |
|           |                       | 33              |                   |                    |
|           | Inflammation          |                 | 36, 38, 39        |                    |
|           | PPCs                  | 32              |                   |                    |
| 5 cmH₂O   | Oxygenation           | 18–21, 46       | 13, 69–71         | Beneficial         |
|           |                       | 19, 51–53       |                   |                    |
|           | Inflammation          | 60              |                   |                    |
|           |                       | 61–63           |                   |                    |
|           | PPCs                  | 56              |                   |                    |
|           |                       | 28, 64, 65      |                   |                    |
|           | Airway pressure       | 2243, 44        |                   |                    |
|           | Stable hemodynamic    | 6, 31, 47–50    | 68                |                    |
|           | CRS                   | 19, 51–53       |                   |                    |
|           | SrO₂                  | 35, 54          |                   |                    |
| 5–10 cmH₂O| Oxygenation           | 72, 73, 76, 80  | 13                | Inconclusive       |
|           |                       | 81              |                   |                    |
|           | PPCs                  | 10, 78          |                   |                    |
|           | Stable hemodynamic    | 60, 74–77       | 39                |                    |
|           | CRS                   | 80              | 81                |                    |
|           |                       | 60, 74, 77      |                   |                    |
| 10 cmH₂O  | Oxygenation           | 64              | 13, 88            | Inconclusive       |
|           |                       | 19, 30, 51, 52, 77 |                  |                    |
|           | Inflammation          | 60, 84          | 88                |                    |
|           |                       | 60, 85, 86      | 89                |                    |
|           | Stable hemodynamic    | 31, 52, 53, 87  |                   |                    |
|           |                       | 31, 52, 53, 87  |                   |                    |
|           | PPCs                  | 40              |                   |                    |
|           | CRS                   | 64, 83          |                   |                    |
| >10 cmH₂O | Oxygenation           | 65, 95          | 13, 102           | Detrimental        |
|           |                       | 72, 97, 98      |                   |                    |
|           | PPCs                  | 53, 100, 101    | 13, 102           |                    |
| Individual PEEP calculated by test titration | Oxygenation | 108, 112–114, 118, 119, 127, 132, 138 | 116 | Beneficial |
|           | Inflammation          | 117             |                   |                    |
|           | PPCs                  | 46, 109, 118, 119 |                  |                    |
|           | Stable hemodynamic    | 108, 132, 138   |                   |                    |
|           | CRS                   | 108, 115, 118, 119, 127, 132, 138 | 116 | Beneficial |
| Individual PEEP calculated by imaging method | Oxygenation | 151, 152, 160 |                   | Beneficial         |
|           | PPCs                  | 28, 143, 158    |                   |                    |
|           | Stable hemodynamic    | 142, 144, 153   |                   |                    |

Abbreviations: CRS, respiratory system compliance; PEEP, positive end-expiratory pressure; PPCs, postoperative pulmonary complications; SrO₂, cerebral oxygen saturation; ↑, represents activation; ↓, represents inhibition.
complications and facilitating the recovery of respiratory function.  

Nevertheless, a recent meta-analysis investigating the association between intraoperative PEEP settings and outcomes suggested that there were no significant differences between “low” PEEP (3–5 cmH2O) and “high” PEEP (8–10 cmH2O) in improving the intraoperative partial pressure of oxygen and the incidence of postoperative pulmonary complications, but lower incidence of intraoperative hypotension in the low-level PEEP group. The reason is that despite increasing the intrathoracic pressure, low-level PEEP may not affect venous return and cardiac filling Blank et al. have found that low levels of PEEP during OLV are associated with increased postoperative pulmonary complications and a higher mortality. Current evidence is insufficient to show the advantage of low PEEP. A randomized controlled trial, which compares high with low PEEP in patients receiving one-lung ventilation for thoracic surgery is going on. Further high-quality randomized controlled trials are needed to establish the clinical effect of low-level PEEP. When the results come out, we will further deepen our understanding.

### 3.1.2 | Animal research

In the rabbit lung model in vitro, Steinberg et al. found that 3 cmH2O PEEP could maintain the stability of alveoli, significantly reduce the level of inflammatory cytokines (IL-6), and cause less damage to lung tissue than 10 cmH2O PEEP. Another study showed that 1 cmH2O PEEP had lower levels of inflammatory cytokines associated with lung injury than 0 cmH2O PEEP. Naikas et al. performed one lung ventilation on lambs with different levels of PEEP. The results showed that compared with 0 and 7 cmH2O PEEP, 4 cmH2O PEEP could lower protein leakage, reduced mRNA expression of neutrophils and proinflammatory cytokines, which could minimize the pro-inflammatory response caused by ventilation and protect the lung from injury.

### 3.2 | 5 cmH2O PEEP

Currently, 5 cmH2O PEEP has achieved much recognition through animal experiments and a large range of clinical studies. They believed that 5 cmH2O PEEP is enough to keep the alveoli open during OLV with not only improve the oxygenation function of lung tissue, reduce shunt fraction, ameliorate ventilation perfusion, and prevent hypoxemia but not lead to excessive expansion of alveoli and increase of airway pressure. The 5 cmH2O PEEP has been widely used during one lung ventilation in clinic. Based on their findings, the investigators consider that 5 cmH2O PEEP is safe with a trend of reducing the peak airway pressure, plateau airway pressure, driving pressure, and making the gas in the lung more evenly distributed. Peter D. Slinger et al. applied 5 cmH2O PEEP during one lung ventilation and then found the platform end-expiratory pressure moved to the inflection point of the static compliance curve, which may contribute to the improvement of oxygenation.

Hofman N et al. evaluated the role of 5 cmH2O PEEP on hemodynamics during OLV. Except for a slight decrease in stroke volume and cardiac output per minute, pulmonary artery pressure, mean arterial pressure, mixed venous oxygen saturation, and left ventricular ejection time had no significant changes. In a study involving 60 patients undergoing thoracoscopic bullectomy surgery, Li Wei et al. demonstrated no significant difference in the improvements in pulmonary dynamic compliance and arterial oxygenation between the 5 cmH2O PEEP and 10 cmH2O PEEP study groups by observing the changes of blood gas analysis and hemodynamics. And yet, 5 cmH2O PEEP appeared to improve cerebral perfusion, cerebral oxygenation, and reduce the decline of cerebral blood oxygen saturation, which is helpful to ameliorate postoperative delirium, postoperative pulmonary complications, and total complications. Consequently, it can be seen that the role of 5 cmH2O PEEP cannot be overemphasized in reducing the risk of ventilator-induced lung injury and postoperative respiratory complications and contributing to the rapid postoperative recovery of patients.

Otherwise, a few studies were reported the influence of 5 cmH2O PEEP on immunization. By monitoring surrogate markers of immunization, 5 cmH2O PEEP could reduce NK cells, CD3+ and CD4+ levels after operation, which may reduce the inhibition of postoperative cellular immune function.

Meanwhile, whether 5 cmH2O PEEP is effective in alleviating inflammatory response is currently unknown. The investigators compared ZEEP versus 5 cmH2O PEEP in patients undergoing esophageal surgery; they found significantly lower serum makers of inflammation (IL-1b, IL-6, and IL-8) in the 5 cmH2O PEEP group. The systemic pro-inflammatory response weakened, and the damage to alveolar epithelial cells reduced thereby. Nevertheless, other studies demonstrated that there were no major differences in carbon monoxide, interleukin-6,
and malondialdehyde. The 5 cmH2O PEEP does not appear to be beneficial in terms of oxidative stress, inflammatory response, or respiratory complications. When PEEP is 5 cmH2O, FRC can be increased by 500 ml. Theoretically, it can reduce the incidence of atelectasis caused by ventilation-perfusion (V/Q) mismatch and hypoxemia. On the contrary, some scholars have indicated that 5 cmH2O PEEP is not enough to keep the alveoli opening and prevent the occurrence of atelectasis. According to the study of Cylwik J et al., 87% of patients treated with 5 cmH2O PEEP have subpleural atelectasis. The presence of atelectasis has the potential to cause inflammation and alveolar injury, temporarily increase extravascular lung water, and induce pulmonary edema, thus increasing the risk for pneumonia. The 5 cmH2O PEEP applied during thoracic surgery is hemodynamically well tolerated; however, it does not improve oxygenation in all cases.

From the existing evidence, 5 cmH2O PEEP whose advantages outweigh disadvantages has many benefits such as dilate collapsed alveoli, maintain relatively normal end respiratory lung volume, ameliorate pulmonary gas diffusion, and correct hypoxia.

### 3.2.2 Animal research

In a sheep model of pneumonectomy, a tidal volume of 6 ml/kg with 5 cmH2O PEEP did not increase significantly in extravascular lung water compared with ZEEP groups. Michelet et al. investigated the variation of oxygenation at different levels of PEEP in pigs with left-lung ventilation. The 5 cmH2O PEEP was pertinent to improving oxygenation and continuous lung recruitment and exerted no significant effects on hemodynamics. In some other animal studies, 5 cmH2O PEEP was considered to have more positive effect on oxygenation reduce shunt fraction and no further damage to cardiac function.

### 3.3 5 to 10 cmH2O PEEP

PEEP levels of 5 to 10 cmH2O are assumed to be relatively safe, reliable, and tolerable. In clinical work, we often choose 5 to 10 cmH2O PEEP for one-lung ventilation.

#### 3.3.1 Clinical research

The application of 5 to 10 cmH2O PEEP to the ventilated lung may ameliorate lung compliance, reduce the incidence of intraoperative hypoxemia, and has only a minor effect on cardiac output and dead space fraction. Compared with PEEP ≤ 5 cmH2O, 5 to 10 cmH2O PEEP could significantly improve oxygenation and lung compliance during OLV and have the potential to reduce lung injury in patients, which may be related to the fact that a higher level of PEEP could maintain more lung unit expansion. Marret et al. found that 5 to 8 cmH2O PEEP can reduce the incidence of acute lung injury in patients undergoing lobectomy, shorten the length of hospital stay, and improve the prognosis of patients with lung cancer. Li H et al. have observed that applying 6 cmH2O PEEP did not increase intra ocular pressure but enhanced dynamic compliance and oxygenation during OLV and reduce the incidence of postoperative pulmonary complications such as atelectasis and pulmonary inflammatory lesions. This may be due to the reduction of peak inspiratory pressure and plateau airway pressure during mechanical ventilation to balance the pressure between alveoli, so as to avoid alveolar collapse, increase air exchange, and reduce the effects of shear injury and inflammation, resulting in lung protection. In contrast, low-level PEEP group (PEEP ≤ 5 cmH2O) and high-level PEEP group (6 to 10 cmH2O PEEP) had no significant difference in the incidence of PPCs within 7 days after thoracoscopic pneumonectomy according to a randomized controlled clinical trial.

#### 3.3.2 Animal research

In a porcine sick lung model, different levels of PEEP were used for one-lung ventilation. It was found that moderate PEEP (5–10 cmH2O) helped to increase lung volume, improve oxygenation, and reduce intrapulmonary shunt. Conversely, Naik As et al. performed one-lung ventilation in sheep and found that 7 cmH2O PEEP can lead to excessive alveolar dilation, damage pulmonary capillaries, and adversely affect hemodynamics. This may be due to the latter experiment being conducted
in preterm lambs, and 7 cmH₂O PEEP may cause more distension of alveoli and elevated neutrophils and expression of proinflammatory cytokines relative to low-level PEEP.

### 3.4 | 10 cmH₂O PEEP

When PEEP increased from zero to 10 cmH₂O, the alveolar diameter increased in a positive proportion, while the thoracic pressure was almost constant. With the increase of the reopening alveolar, PaO₂ and lung compliance may be affected to some extent.

#### 3.4.1 | Clinical research

Based on previous findings, it suggested that lower levels of PEEP may not be sufficient to expand the collapsed alveoli and small airways. Some clinical studies have manifested that 10 cmH₂O PEEP can prevent lung collapse and has smaller dead space, better oxygenation, and compliance than conventional recommended 5 cmH₂O PEEP. When PEEP increased from zero to 10 cmH₂O, the alveolar diameter increased in a positive proportion, while the thoracic pressure was almost constant. With the increase of the reopening alveolar, PaO₂ and lung compliance may be affected to some extent.

Wolthuis Ek et al. found that, regardless of the left or right lying position, the respiratory compliance was the highest when PEEP was 10 cmH₂O. Spadaro et al. reported in 41 patients undergoing video-assisted thoracoscopic lobectomy or lung resection that 10 cmH₂O PEEP may increase the oxygenation index and lower driving pressure without causing excessive alveolar expansion and increasing dead space compared with 5 cmH₂O PEEP. These scholars seemed to be in favor of the application of 10 cmH₂O PEEP in clinical work.

Besides improving respiratory compliance and driving pressure, 10 cmH₂O PEEP would lower inflammatory factors such as interleukin-8 as reported by three studies. Wrigge et al. examined the effects of 10 cmH₂O PEEP and ZEEP on intraoperative oxygenation and postoperative inflammatory mediator in patients undergoing thoracotomy. However, no difference was observed. Owing to increasing the pulmonary vascular resistance and redistributing the blood flow, 10 cmH₂O PEEP may increase intrapulmonary shunt, thereby not conducive to the operation. In addition, it has potential hemodynamic hazards such as reducing cardiac output and pleural fluid composition and increasing myocardial acceleration index. It can be seen that 10 cmH₂O PEEP should be applied with caution especially when patients have poor cardiac function or compensation. The benefits of 10 cmH₂O PEEP are warranted to be further confirmed by prospective studies.

#### 3.4.2 | Animal research

Sacramento EMF et al. applied 2, 5, and 10 cmH₂O PEEP respectively to Sprague-Dawley male rats during lung transplantation. It was found that 10 cmH₂O PEEP group was pertinent to improving oxygenation and hemodynamics as well as reducing the incidence of atelectasis of rats. The findings of Michelet et al. were consistent with it by analyzing the arterial blood gas of pigs at different levels of PEEP during one lung ventilation. In addition, they found 10 cmH₂O PEEP would reduce ventricular preload and cardiac output.

### 3.5 | PEEP > 10 cmH₂O

High-level PEEP would cause alveolar hyperinflation, thus increasing lung parenchyma stress and strain and systemic organ injury. PEEP greater than 10 cmH₂O is rarely used in clinical practice except at the beginning of a few operations to fully expand the alveoli.

#### 3.5.1 | Clinical research

On one hand, high PEEP may correct hypoxemia and promote more homogenous ventilation by preventing atelectasis. On the other hand, it would indirectly contribute to circulatory depression by reducing venous/lymphatic drainage.

In the study of Cylwik J, it was found that 91.9% of patients can successfully dilate the atelectasis area with an average PEEP of 17 cmH₂O. It appears that atelectotrauma may be alleviated due to reducing the need for high concentration oxygen and the occurrence of ventilation-perfusion mismatch. Nevertheless, Jo et al. reported that PEEP greater than 11 cmH₂O affected the stability of hemodynamics. High-level PEEP would lead to intrapulmonary pressure increased and the venous return blood volume and the cardiac output reduced, which induced an reduction of the pulmonary blood perfusion and gas exchange. Some other studies demonstrated that there was a downward trend in lung compliance with the potential risk of barotrauma and bacterial translocation when PEEP value applied was excessively high. In light of these limitations, PEEP greater than 10 cmH₂O is rarely employed. It ought to be applied with a close control of cardiovascular hemodynamics, respiratory function and gas exchange.

#### 3.5.2 | Animal research

One randomized controlled experiment comparing different levels of PEEP during one lung ventilation in a
pig model showed that lung compliance decreased and oxygenation worsened significantly when PEEP greater than or equal to 15 cmH$_2$O. Similar to the results of the study above, He Fang et al. found that PEEP exceeded 10 cmH$_2$O would induce reducing lung compliance and increasing intrapulmonary shunt, thereby affecting the tissue oxygen supply.\textsuperscript{102}

## 4 | EXPLORE THE OPTIMAL INDIVIDUALIZED PEEP VALUE

The effect of PEEP is dual: on one hand, high-level PEEP may lead to excessive alveolar expansion; on the other hand, the collapsed alveoli could not be fully opened if the PEEP value is too small. At the same time, the existence of individual heterogeneity in patients’ physique, BMI, and physiological structure of lung makes the homogenized PEEP value not optimal for each individual patient. PEEP is then individually titrated to optimize lung compliance and minimize driving pressure when the elements above are taken into account.

Several targets have been proposed for individualized titration, including improving intraoperative oxygenation and hemodynamics, providing optimal pulmonary compliance,\textsuperscript{26,95,103–108} and reducing the incidence of postoperative pulmonary complications.\textsuperscript{24–27,109,110} An animal experiment also confirmed the importance of individualized PEEP, in which Reiniush et al. obtained the appropriate range of PEEP according to oxygenation, driving pressure and cardiac output. PEEP exceeded this range would cause ventilation/perfusion mismatch of the ventilated lung.\textsuperscript{111} The optimal PEEP remains a matter of considerable debate. This uncertainty has fostered various setting approaches. Some believe it should be titrated, whereas others advocate imaging methods. The following describes several methods.

### 4.1 | Test titration

In clinical practice, PEEP titration could allow personalized application of optimal PEEP to achieve optimize lung function while matching the highest dynamic lung compliance, the best oxygenation index, and the minimum driving pressure.

#### 4.1.1 | Dynamic compliance

Patients undergoing thoracic surgery often have potential differences in respiratory compliance due to the size or location of the mass or the existing lung disease.\textsuperscript{109} Dynamic pulmonary compliance (Cdyn) can reflect the number of ventilated alveoli. Maximum alveoli opening was attained at the PEEP associated with the highest Cdyn. When the PEEP value is lower than this level, the lungs begin to collapse. We hypothesized that a decremental PEEP trial might provide an appropriate means of PEEP thereby improving oxygenation and reducing right ventricular load\textsuperscript{112,113} and the risk of ventilator-induced lung injury.\textsuperscript{46} Several studies supported the hypothesis. Luecke T et al. found that compared with standardized 5 cmH$_2$O, PEEP titration guided by Cdyn was shown to be more effective in improving oxygenation and respiratory mechanics.\textsuperscript{114} Xu D et al. compared different PEEP titration strategies and found it seemed to be inconsistent with the studies above in some way that the dynamic compliance method could lower driving pressure and improve dynamic compliance but does not adequately improve arterial oxygenation and intrapulmonary shunt.\textsuperscript{115} Suarez-Sipmann et al. also demonstrated the role of dynamic lung compliance in setting the optimal PEEP value using animal models.\textsuperscript{116} The respiratory parameters displayed on anesthesia machine include pulmonary dynamic compliance. The method is simple, easy to apply, and offers great potential for larger prospective studies clearly support Cdyn-guided PEEP during thoracic surgery.

#### 4.1.2 | Pressure–volume curve

The pressure–volume curve (P–V curve) reflects the compliance and resilience of the lung. PEEP above the low inflection point (LIP) of the P–V curve was thought to recruit a large number of alveoli to protect lung from shear injury. Liu Wenjun et al. recommended that PEEP set at LIP + 2 cmH$_2$O was optimal to reduce the traction stimulation and inflammatory response of lung tissue.\textsuperscript{117} Others hold different suggestions that PEEP corresponding to the inflection point on the expiratory branch of the P–V curve was effective in meliorating lung function and arterial oxygenation and reducing the occurrence of acute lung injury.\textsuperscript{118,119} The method is convenient and suitable in the operating room. Whether the P–V curve can provide useful information about optimal PEEP is still in doubt. We are conducting a clinical trial comparing individualized PEEP based on P–V curve with 5 cmH$_2$O PEEP and 10 cmH$_2$O PEEP. Our pre-experimental results indicated individualized PEEP was associated with a downward trend of the incidence of postoperative pulmonary complications. It may add new information about the rational of using individualized PEEP during OLV.

#### 4.1.3 | Intrinsic PEEP

Intrinsic PEEP (PEEP$_i$) resulting from restriction to airflow in the bronchioles during exhalation reflect the
residual pressure, which may reduce pulmonary dynamic compliance. In thoracic surgery, PEEPi can be exaggerated by lateral position, previous respiratory diseases, double lumen endotracheal intubation, and one lung ventilation. It may be necessary to add appropriate exogenous PEEP to offset PEEPi as well as avoid alveoli hyperdilatation. When exogenous PEEP is set to zero, expiration pauses and the measured end-expiratory pressure value is PEEPi. PEEP should be set to 80% of PEEPi, which plays a certain role in reducing airway resistance and improving man–machine synchronization.

4.1.4 | Oxygenation index

There is a positive correlation between oxygenation index and lung compliance. The principle of the method is to determine optimal PEEP corresponding to the highest oxygenation index from blood gas analysis. However, it requires multiple arterial blood samples for blood gas analysis, which is expensive and cannot be monitored in real time, so it is not suitable for individualized PEEP titration during operation. Moreover, the PEEP value titrated by oxygenation index is comparatively high because it only focuses on the improvement of oxygenation but does not take ventilator-induced lung injury into account.

4.1.5 | Driving pressure

Driving pressure, reflecting the change of alveolar pressure before and after inhalation, is defined as the ratio of tidal volume to respiratory compliance, which can be calculated by plateau airway pressure minus PEEP. Park et al. defined the PEEP value causing the minimum driving pressure as the optimal PEEP and found it permits reducing PPCs. The mechanism may be that lower driving pressure is pertinent to a higher survival rate and lower incidence of periodic strain. While in a large multicenter randomized trial, PEEP guided by driving pressure did not reduce the incidence of PPCs though improving intraoperative lung compliance and arterial partial pressure of oxygen during pneumonectomy compared with 5 cmH₂O PEEP. Wang F et al. believed that PEEP guided by driving pressure could effectively alleviate postoperative inflammatory response because the results showed the level of postoperative inflammatory factors of IL-6 and HMGB1 were decreased, which may be related to its reducing the number of collapsed alveoli and maintaining the expansion of distal collapsed airway. The evidence supporting the driving pressure method to titrate individualized PEEP is limited. More clinical trials need to be carried out in the future.

4.1.6 | Dead space fraction

Dead space fraction refers to the ratio of dead space volume to tidal volume, reflecting collapse and re-expansion of alveolar. As gas exchange is insufficient and the lungs are susceptible to VILI during OLV, monitoring dead space in real time plays an important role in adjusting ventilator settings. Given that the ideal PEEP minimizes dead space fraction to bring ventilation and blood flow into the best state, dead space fraction is an attractive physiological target for PEEP titration.

4.1.7 | Transpulmonary pressure

Transpulmonary pressure is the pressure gradient from the airway to the pleural space, driving the contraction and expansion of alveoli. The minimum transpulmonary pressure, which can keep positive throughout the respiratory cycle to expand the collapsed alveoli, can be used as one of the selection criteria for PEEP titration. Esophageal manometry is one of the approaches to measuring transpulmonary pressure. Rauseo M et al. found that individualized PEEP titrated by esophageal manometry could significantly reduce the occurrence of intraoperative hypoxemia as well as improve pulmonary compliance and hemodynamics. However, it is difficult to judge the best monitoring position by esophageal manometry due to a certain pressure gradient in the pleural cavity from the non-ventilated lung to the ventilated lung in lateral position during thoracic surgery and heterogeneity in the lung tissue. The PEEP step method (PSM) determining the lung mechanics and chest wall mechanics of patients through the calculated change of end-expiratory lung volume is another approach to measuring transpulmonary pressure and the measurement is highly consistent with esophageal manometry. Although PSM is noninvasive, convenient, and can obtain the pressure in the whole chest cavity, it requires specialized monitoring equipment to record and cannot measure transpulmonary pressure continuously, which limit its adoption in clinical practice.

4.1.8 | Functional residual capacity

FRC is the volume of gas remaining in the lungs after calm exhalation, which can better reflect the alveolar recruitment and collapse compared with lung
compliance. It can be used as a supplement to select the optimal PEEP. The FRC value was recorded at each PEEP level, and the last pressure level of PEEP corresponding to the lowest FRC was the optimal PEEP. Compared with oxygenation index and dynamic compliance method, the optimal PEEP guided by FRC benefits lung compliance, oxygenation index and hemodynamics while reducing oxidative stress response in patients undergoing radical lung cancer surgery. FRC method is not invasive, but it may lead to DO₂ decreased, which should be comprehensively considered in clinical.

4.2 Imaging method

More precise indicators were called for to provide quantitative evaluation indicators for individualized PEEP such as computed tomography, electrical impedance tomography, and ultrasound.

4.2.1 Computed tomography

Computed tomography (CT) can calculate the air content of lung tissue through the density, intuitively displaying the re-expansion of collapsed alveoli. It may be useful to adjust PEEP to the desired levels. However, it is unlikely that the CT approach to tailoring PEEP to individual patients is suitable in operation for its radiative and cumbersome and other techniques, which could be used at the bedside to reach similar information would replace it.

4.2.2 Electrical impedance tomography

Electrical impedance tomography (EIT) is a bedside imaging method that visualizes local ventilation and lung perfusion distribution. Changes in CRS as well as alveolar overdistension and collapse can be assessed by EIT dynamically and noninvasively. Compared with 5 cmH₂O PEEP, the individualized PEEP determined by EIT was effective in reducing the driving pressure and improving the survival rate and respiratory mechanics without affecting the hemodynamic stability. In recent years, EIT has not yet been widely disseminated in thoracic surgery though it is popular in clinical trials as a method to select the optimal PEEP value. The reasons include but are not limited to its high price and only monitoring a single dimension of the thoracic cavity, which makes it difficult to reflect the overall ventilation of the lung. Moreover, electrodes placed in the 4th to 5th intercostal spaces at the parasternal line would affect the scope of surgical disinfection and maneuvers.

4.2.3 Lung ultrasonic score

Lung ultrasonic score (LUS) allowing non-invasive monitoring of lung recruitment in real time has been proposed as a practical bedside imaging method alternative to CT method in the assessment of appropriate PEEP during OLV. The higher the LUS is, the more serious the atelectotrauma will be. The PEEP value when the LUS suddenly increases by more than 30% and then plus 2 cmH₂O is defined as the best PEEP value. The individualized PEEP on the basis of LUS method could reduce the risk of hyperinflation of the ventilated lung with intraoperative oxygenation and pulmonary compliance improved. Ultrasound is a technique widely used in clinic whose advantage is its availability at the bedside and high-cost performance. Nevertheless, the method has certain limitations in operation due to the ultrasonic probe placed on the chest wall with the lack of spatial resolution and the limited penetration of ultrasound.

Individualized PEEP has been advocated to be applied in clinical though lacking solid evidence from evidence-based medicine. A large number of studies above have shown the benefits of individualized PEEP to clinical outcomes. Conversely, Mascotto G et al. reported that it has no significant influence on the improvement of intraoperative and postoperative oxygenation.

More recently, we mainly implement the low tidal volume ventilation mode involved in LPVS during thoracic surgery to ameliorate the respiratory and circulatory system. In addition to the low tidal volume ventilation mode, we gradually applied PEEP suitable for the individual characteristics of patients in clinical work. The beneficial effects of PEEP are pertinent to the prevention of atelectasis and avoiding the cyclical opening and collapse of alveoli. No guidelines exist on the best PEEP setting during OLV, which should be tailored to the patient in order to achieve beneficial consequences while limiting adverse reactions as much as possible. However, the concept of maximizing oxygenation and lung compliance and reducing the amount of dead space is commonly recognized. Therefore, further investigations are warranted to determine optimal PEEP to be implemented in routine clinical practice.

5 CONCLUSION

On the whole, PEEP has been widely accepted and applied in clinical as a part of LPVS. Different levels of
PEEP have been used in thoracic surgery to improve oxygenation and reduce intrapulmonary shunt and postoperative pulmonary complications, but it is still necessary to explore a simple and economical method to determine the optimal PEEP value. Reaching an agreement on the determination represents a high priority of clinical trials and experiments.

ACKNOWLEDGEMENTS
The authors thank Mr. Lianbing Gu and Ms. Jing Tan for assistance in the modification of the review.

CONFLICT OF INTEREST
No potential conflict of interest was reported by all authors.

ETHICS STATEMENT
Ethics statement is not applicable.

AUTHOR CONTRIBUTION
Jiang Yueyi: Conceptualization (lead), writing–original draft (lead), formal analysis (lead), and writing–review and editing (equal). Tan Jing: Methodology (lead), writing–original draft (supporting), conceptualization (supporting), and writing–review and editing (equal). Gu Lianbing: Conceptualization (supporting), supervision (lead), and writing–review and editing (equal).

DATA AVAILABILITY STATEMENT
Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

ORCID
Jiang Yueyi https://orcid.org/0000-0002-8994-8695

REFERENCES
1. Nespoli H, Rupp T, Bachasson D, et al. Positive expiratory pressure improves oxygenation in healthy subjects exposed to hypoxia. PLoS ONE. 2013;8(12):e85219. doi:10.1371/journal.pone.0085219
2. Hedenstierna G, Tenling A. The lung during and after thoracic anaesthesia. Curr Opin Anaesthesiol. 2005;18(1):23–28.
3. Tusman G, Böhm SH, Melkun F, et al. Alveolar recruitment strategy increases arterial oxygenation during one-lung ventilation. Ann Thorac Surg. 2002;73(4):1204-1209.
4. Tusman G, Böhm SH, Sipmann FS, Maisch S. Lung recruitment improves the efficiency of ventilation and gas exchange during one-lung ventilation anesthesia. Anesth Analg. 2004;98(6):1604-1609.
5. Cinnella G, Grasso S, Natale C, et al. Physiological effects of a lung-recruiting strategy applied during one-lung ventilation. Acta Anaesthesiol Scand. 2008;52(6):766-775.
6. Yinxing Z, Xiaoxia P, Jingyu Z. Effects of positive end-expiratory pressure on the oxygenation and shunt fraction during ventilation with solitary lung. Med J Chin People’s Lib Army. 2013;38(12):989-991.
7. Neustein S. Association of high tidal volume with postpneumonectomy failure. Anesthesiology. 2007;106(4):875-876.
8. Kacmarek RM, Villar J. Lung-protective ventilation in the operating room: individualized positive end-expiratory pressure is needed! Anesthesiology. 2018;129(6):1057-1059.
9. Hartland BL, Newell TJ, Damico N. Alveolar recruitment maneuvers under general anesthesia: a systematic review of the literature. Respir Care. 2015;60(4):609-620.
10. Marret E, Cinotti R, Berard L, et al. Protective ventilation during anaesthesia reduces major postoperative complications after lung cancer surgery: a double-blind randomised controlled trial. Eur J Anaesthesiol. 2018;35(10):727-735.
11. Yang M, Ahn HJ, Kim K, et al. Does a protective ventilation strategy reduce the risk of pulmonary complications after lung cancer surgery?: a randomized controlled trial. Chest. 2011;139(3):530-537.
12. Levin MA, McCormick PJ, Lin HM, Hosseinian L, Fischer GW. Low intraoperative tidal volume ventilation with minimal PEEP is associated with increased mortality. Br J Anaesth. 2014;113(1):97-108.
13. Michelet P, Roch A, Brousse D, et al. Effects of PEEP on oxygenation and respiratory mechanics during one-lung ventilation. Br J Anaesth. 2005;95(2):267-273.
14. Blank RS, Colquhoun DA, Durieux ME, et al. Management of one-lung ventilation: impact of tidal volume on complications after thoracic surgery. Anesthesiology. 2016;124(6):1286-1295.
15. Liu Z, Liu X, Huang Y, Zhao J. Intraoperative mechanical ventilation strategies in patients undergoing one-lung ventilation: a meta-analysis. SpringerPlus. 2016;5(1):1251. doi:10.1186/s40064-016-2867-0
16. Ferrando C, Soro M, Unzueta C, et al. Individualised perioperative open-lung approach versus standard protective ventilation in abdominal surgery (iPROVE): a randomised controlled trial. Lancet Respir Med. 2018;6(3):193-203.
17. Serpa Neto A, Hemmes SN, Barbosa LS, et al. Protective versus conventional ventilation for surgery: a systematic review and individual patient data Meta-analysis. Anesthesiology. 2015;123(1):66-78.
18. Pang Y, Feng Y, Li Y. Influence of different positive end-expiratory pressure on oxygenation and pulmonary shunt fraction during one-lung ventilation. J Jilin Univ (Med Ed). 2012;38(5):977-980.
19. Li W, Li Y, Wang M. Effects of different levels of positive end-expiratory pressure on blood gas analysis and hemodynamics in patients with one-lung ventilation after thoracoscopic bullectomy. Modern Instr. 2016;22(3):55-56,54.
20. Fujiwara M, Abe K, Mashimo T. The effect of positive end-expiratory pressure and continuous positive airway pressure on the oxygenation and shunt fraction during one-lung ventilation with propofol anesthesia. J Clin Anesth. 2001;13(7):473-477.
21. Xiaoming Y, Jun L, Hui J. The effect of different PEEP and CPAP on the oxygenation and shunt fraction during one-lung ventilation in VATS. Guide China Med. 2005;3(8):876-878.
22. De Monte V, Grasso S, De Marzo C, Crovace A, Staffieri F. Effects of reduction of inspired oxygen fraction or application of positive end-expiratory pressure after an alveolar recruitment maneuver on respiratory mechanics, gas exchange, and
lungs aeration in dogs during anesthesia and neuromuscular blockade. Am J Vet Res. 2013;74(1):25-33.

23. Maisch S, Reissmann H, Fuellekrug B, et al. Compliance and dead space fraction indicate an optimal level of positive end-expiratory pressure after reconditioning in anesthetized patients. Anesth Analg. 2008;106(1):175-181. PMID: table of contents.

24. Ladha K, Vidal Melo MF, McLean DJ, et al. Intraoperative protective mechanical ventilation and risk of postoperative respiratory complications: hospital based registry study. BMJ (Clin Res Ed). 2015;351:h3646. doi:10.1136/bmj.h3646

25. Serpa Neto A, Cardoso SO, Manetta JA, et al. Association between use of lung-protective ventilation with lower tidal volumes and clinical outcomes among patients without acute respiratory distress syndrome: a meta-analysis. JAMA. 2012;308(16):1651-1659.

26. de Jong MAC, Ladha KS, Vidal Melo MF, et al. Differential effects of intraoperative positive end-expiratory pressure (PEEP) on respiratory outcome in major abdominal surgery versus craniotomy. Ann Surg. 2016;264(2):362-369.

27. Shaefi S, Eikermann M. Analysing tidal volumes early after a positive end-expiratory pressure increase: a new way to determine optimal PEEP in the operating theatre? Br J Anaesth. 2018;120(4):623-626.

28. Pereira SM, Tucci MR, Morais CCA, et al. Individual positive end-expiratory pressure settings optimize intraoperative mechanical ventilation and reduce postoperative atelectasis. Anesthesiology. 2018;129(6):1070-1081.

29. He H, Yuan S, Yi C, Long Y, Zhang R, Zhao Z. Titration of extra-PEEP against intrinsic-PEEP in severe asthma by electrical impedance tomography: a case report and literature review. Medicine. 2020;99(26):e20891. doi:10.1097/MD.0000000000020891

30. Abe K, Mashimo T, Yoshiya I. Arterial oxygenation and shunt fraction during one-lung ventilation: a comparison of isoflurane and sevoflurane. Anesth Analg. 1998;86(6):1266-1270.

31. Li D, Meng L. Effects of positive end-expiratory pressure on oxygenation and airway pressure during one-lung ventilation with low tidal volume. J China Med Univ. 2008;37(6):815-816,821.

32. Ye J, Ma N. Clinical observation of low tidal volume with low positive end-expiratory pressure in one-lung ventilation patients undergoing thoracic surgery. J Clin Anesth. 2013;29(3):238-240.

33. Peel JK, Funk DJ, Slinger P, Srinathan S, Kidane B. Positive end-expiratory pressure and recruitment maneuvers during one-lung ventilation: A systematic review and meta-analysis. J Thorac Cardiovasc Surg. 2020;160(4):1112-1122.

34. Lohser J, Slinger P. Lung injury after one-lung ventilation: an review of the pathophysiologic mechanisms affecting the ventilated and the collapsed lung. Anesth Analg. 2015;121(2):302-318.

35. Kiss T, Wittenstein J, Becker C, et al. Protective ventilation with high versus low positive end-expiratory pressure during one-lung ventilation for thoracic surgery (PROTHOR): study protocol for a randomized controlled trial. Trials. 2019;20(1):213. doi:10.1186/s13063-019-3208-8

36. Steinberg JM, Schiller HI, Halter JM, et al. Alveolar instability causes early ventilator-induced lung injury independent of neutrophils. Am J Respir Crit Care Med. 2004;169(1):57-63.

37. Hong CM, Xu DZ, Lu Q, et al. Low tidal volume and high positive end-expiratory pressure mechanical ventilation results in increased inflammation and ventilator-associated lung injury in normal lungs. Anesth Analg. 2010;110(6):1652-1660.

38. Gama de Abreu M, Heintz M, Heller A, Széchényi R, Albrecht DM, Koch T. One-lung ventilation with high tidal volumes and zero positive end-expiratory pressure is injurious in the isolated rabbit lung model. Anesth Analg. 2003;96(1):220-228.

39. Naik AS, Kallapur SG, Bachurski CJ, et al. Effects of ventilation with different positive end-expiratory pressures on cytokine expression in the preterm lamb lung. Am J Respir Crit Care Med. 2001;164(3):494-498.

40. Ren Y, Peng ZL, Xue QS, Yu BW. The effect of timing of application of positive end-expiratory pressure on oxygenation during one-lung ventilation. Anaesth Intensive Care. 2008;36(4):544-548.

41. Brassard CL, Lohser J, Donati F, Bussières JS. Step-by-step clinical management of one-lung ventilation: continuing professional development. Can J Anaesth. 2014;61(12):1103-1121.

42. Batchelor TJP, Rasbourn NJ, Abdelnour-Berchtold E, et al. Guidelines for enhanced recovery after lung surgery: recommendations of the enhanced recovery after surgery (ERAS®) society and the European Society of Thoracic Surgeons (ESTS). Eur J Cardiothorac Surg. 2019;55(1):91-115.

43. Şentürk M, Slinger P, Cohen E. Intraoperative mechanical ventilation strategies for one-lung ventilation. Best Pract Res Clin Anaesthesiol. 2015;29(3):357-369.

44. Wang L, Wang Y. Effect of lung protective ventilation on melatonin and prognosis in patients with esophageal cancer. Acta Univ Med Anhui. 2021;56(8):1311-1315.

45. Kozian A, Schilling T, Schütze H, Senturk M, Hachenberg T, Hedenstierna G. Ventilatory protective strategies during thoracic surgery: effects of alveolar recruitment maneuver and low-tidal volume ventilation on lung density distribution. Anesthesiology. 2011;114(5):1025-1035.

46. Slinger PD, Kruger M, McRae K, Winton T. Relation of the static compliance curve and positive end-expiratory pressure to oxygenation during one-lung ventilation. Anesthesiology. 2001;95(3):1096-1102.

47. Hofman N, Canales C, Leduc M, Mahajan A. Positive end-expiratory pressure during one-lung ventilation: selecting ideal patients and ventilator settings with the aim of improving arterial oxygenation. Ann Card Anaesth. 2011;14(3):183-187.

48. Emr B, Gatto LA, Roy S, et al. Airway pressure release ventilation prevents ventilator-induced lung injury in normal lungs. JAMA Surg. 2013;148(11):1005-1012.

49. Pardos PC, Garutti I, Piñeiro P, Olmedilla L, de la Gala F. Effects of ventilatory mode during one-lung ventilation on intraoperative and postoperative arterial oxygenation in thoracic surgery. J Cardiothorac Vasc Anesth. 2009;23(6):770-774.

50. Kitabjian L, Bordi S, Elisha S, et al. Anesthesia case management for video-assisted thoracoscopic surgery. AANA J. 2013;81(1):65-72.

51. El Tahan MR, El Ghoneimy Y, Regal M, Deria A, Al Ahmadey M, El Emam H. Effects of nondependent lung ventilation with continuous positive-pressure ventilation and high-frequency positive-pressure ventilation on right-ventricular function during 1-lung ventilation. Semin Cardiothorac Vasc Anesth. 2010;14(4):291-300.
52. You X, Chen Q, Bao Z. Effect of one lung ventilation with PEEP on blood gas and hemodynamics in thorascopic surgery. *J Clin Anesth*. 2003;19(6):340-342.

53. Zeng Q, Meng Y, Zhu S. Effect of Ventilation with High Levels of PEEP and Lower-Tidal Volume on the Hemodynamics in Patients with Normal Respiratory Function. *J Clin Anesth*. 2009;25(2):109-112.

54. Yu R, Liang Q, Liu L. Study on the correlation between cerebral oxygen saturation and PEEP level of thorascopic elderly patients with lung cancer. *Chin J Gen Pract*. 2021;19(2):189-192. PMID: 259.

55. Guo W, Chen M. Effects of lung protective ventilation on cerebral oxygen metabolism and postoperative cognitive function in elderly patients requiring one-lung ventilation. *Chin J Anesthesiol*. 2017;37(4):396-399.

56. Fiorelli S, Defraia V, Cipolla F, et al. Short-term one-lung ventilation does not influence local inflammatory cytokine response after lung resection. *J Thorac Dis*. 2018;10(3):1864-1874.

57. Zhao Y, Chen J. Effects of protective lung ventilation on postoperative delirium and recovery in patients with lung cancer undergoing thorascopic surgery. *China J Modern Med*. 2020;30(5):71-75.

58. Shen Y, Zhong M, Wu W, et al. The impact of tidal volume on pulmonary complications following minimally invasive esophagectomy: a randomized and controlled study. *J Thorac Cardiovasc Surg*. 2013;146(5):1267-1273. PMID: discussion 1273-1264.

59. Hu J, Chai X, Wang D. Perioperative Use of Lung Protective Ventilation Strategy on Immune Function in Patients Undergoing Thorascopic Radical Resection of Lung cancer. *J Clin Anesth*. 2019;35(1):8-11.

60. Grichnik KP, Shaw A. Update on one-lung ventilation: the use of continuous positive airway pressure ventilation and positive end-expiratory pressure ventilation–clinical application. *Curr Opin Anaesthesiol*. 2009;22(1):23-30.

61. Sun Y, Zheng Y. Effect of different positive end-expiratory pressures on inferior vena cava and variation of cardiac output after volume expansion measured by transthoracic echocardiography in patients under mechanically respiratory support. *Chinese J Emerg Med*. 2015;24(8):872-877.

62. Végh T, Juhász M, Szatmári S, et al. Effects of different tidal volumes for one-lung ventilation on oxygenation with open chest condition and surgical manipulation: a randomised cross-over trial. *Minerva Anestesiol*. 2013;79(1):24-32.

63. Ahn HJ, Kim JA, Yang M, Shim WS, Park KJ, Lee JJ. Comparison between conventional and protective one-lung ventilation for ventilator-assisted thoracic surgery. *Anaesth Intensive Care*. 2012;40(5):780-788.

64. Spadaro S, Grasso S, Karbing DS, et al. Physiologic evaluation of ventilation perfusion mismatch and respiratory mechanics at different positive end-expiratory pressure in patients undergoing protective one-lung ventilation. *Anesthesiology*. 2018;128(3):531-538.

65. Cywilik J, Buda N. Lung Ultrasoundography in the Monitoring of Intraoperative Recruitment Maneuvers. *Diagnostics (Basel, Switzerland)*. 2021;11(2):276. doi: 10.3390/diagnostics11020276

66. Huang D, Wang Y. Effect of Small Tidal Volume Combined with PEEP on Extracascular Lung Water during One-Lung Ventilation in Patients Undergoing Thoracic Surgery. *Chin J Anesthesiol*. 2010;30(7):811-813.

67. Kuzkov VV, Suborov EV, Kirov MY, et al. Extravascular lung water after pneumonectomy and one-lung ventilation in sheep. *Crit Care Med*. 2007;35(6):1550-1559.

68. Liu N, Gu Q. The influence of positive end-expiratory pressure on stroke volume variation for the accuracy of evaluating volume. *Chin Crit Care Med*. 2012;24(7):419-422.

69. Mosing M, Iff I, Moens Y. Endoscopic removal of a bronchial carcinoma in a dog using one-lung ventilation. *Vet Surg*: VS. 2008;37(3):222-225.

70. Riquelme M, Monnet E, Kudnig ST, et al. Cardiopulmonary effects of positive end-expiratory pressure during one-lung ventilation in anesthetized dogs with a closed thoracic cavity. *Am J Vet Res*. 2005;66(6):978-983.

71. Kudnig ST, Monnet E, Riquelme M, Gaynor JS, Corliss D, Salman MD. Effect of positive end-expiratory pressure on oxygen delivery during 1-lung ventilation for thoracoscopy in normal dogs. *Vet Surg*:VS. 2006;35(6):534-542.

72. Sun Z, Wang N. The effects of different values of PEEP on heart index, stroke volume variation and oxygen transport index in patients monitored by FloTrac/Vigileo system. *Tianjin Med J*. 2017;45(3):294-296.

73. Gao L, Yu D. Comparison of the efficacies of different ventilatory pattern during one-lung ventilation. *Chin J Anesthesiol*. 2000;20(11):658-660.

74. Xu D, Ma S. Anesthetic Management of Combined Thorascoscopic and Laparascopic Esophagectomy. *Chin J Minim Invasive Surg*. 2015;4:293-297.

75. Martin JB, Garbee D, Bonanno L. Effectiveness of positive end-expiratory pressure, decreased fraction of inspired oxygen and vital capacity recruitment maneuver in the prevention of pulmonary atelectasis in patients undergoing general anesthesia: a systematic review. *JBI Database System Rev Implement Rep*. 2015;13(8):211-249.

76. Hallioglu M, Bilgili B, Ozdemir M, Umuroglu T, Bakan N. Low tidal volume positive end-expiratory pressure versus high tidal volume zero-positive end-expiratory pressure and postoperative pulmonary functions in robot-assisted laparascopic radical prostatectomy. *Med Princ Pract*. 2017;26(6):573-578.

77. Ouyang T. A study on the appropriate PEEP value of protective lung ventilation during one lung ventilation. 2018.

78. Tang Y, Li H. Effect of lung protective ventilation on perioperative pulmonary function in elderly patients received pulmonary lobectomy of lung cancer. *China Med Herald*. 2017;14(20):120-124.

79. Kim YS, Seo KH, Jeon YS, et al. Effects of Positive End-Expiratory Pressure on Intraocular Pressure during One-Lung Ventilation in the Lateral Decubitus Position-A Prospective Randomized Trial. *Medicina (Kaunas)*. 2022;58(7):940. doi: 10.3390/medicina58070940

80. Chen Z, Sun L, Liu W. Effects of different lung protective ventilation strategies on intraoperative ventilation and postoperative pulmonary complications after pneumonectomy. *Int J Pathol Clin Med*. 2022;42(1):159-165.

81. Leong LM, Chatterjee S, Gao F. The effect of positive end expiratory pressure on the respiratory profile during one-lung ventilation for thoracotomy. *Anaesthesia*. 2007;62(1):23-26.
82. Tusman G, Böhm SH, Suarez-Sipmann F. Dead space during one-lung ventilation. *Curr Opin Anaesthesiol*. 2015;28(1):10-17.
83. Trela-Stachurska K, Nestorowicz A, Kotlińska-Hasiec E, Sawulski S, Dąbrowski W. Effects of unilateral PEEP on biomechanics of both lungs during independent lung ventilation in patients anaesthetised for thoracic surgery. *Anaesthesia Intensive Ther*. 2015;47(1):1-6.
84. Lin W, Lu X. Effects of the lung protective Ventilatory strategy on Proinflammatory cytokine release during one-lung ventilation. *Cancer Plus*. 2008;27(8):870-873.
85. Kim HJ, Seo JH, Park KU, Kim YT, Park IK, Bahk JH. Effect of combining a recruitment maneuver with protective ventilation on inflammatory responses in video-assisted thoracoscopic lobectomy: a randomized controlled trial. *Surg Endosc*. 2019;33(5):1403-1411.
86. Wrigge H, Uhlig U, Zinserling J, et al. The effects of different ventilatory settings on pulmonary and systemic inflammatory responses during major surgery. *Anesth Analg*. 2004;98(3):775-781. PMID: table of contents.
87. Wang H, Gu Z. Effects of one-lung ventilation combined with positive pressure terminal respiration on blood gas and circulation. *Mod Med Health*. 2005;21(9):913-914.
88. Gonçalves-Ferri WA, Jauregui A, Martins-Celini FP, et al. Analysis of different levels of positive end-expiratory pressure during lung retrieval for transplantation: an experimental study. *Braz J Med Biol Res*. 2019;52(7):e8585. doi:10.1590/1414-431X20198585
89. Roosens CD, Ama R, Leather HA, et al. Hemodynamic effects of different lung-protective ventilation strategies in closed-chest pigs with normal lungs. *Crit Care Med*. 2006;34(12):2990-2996.
90. Nieszkowska A, Lu Q, Vieira S, Elman M, Fetita C, Rouby JJ. Incidence and regional distribution of lung overinflation during mechanical ventilation with positive end-expiratory pressure. *Crit Care Med*. 2004;32(7):1496-1503.
91. Sahetya SK, Goligher EC, Brower RG. Fifty years of research in ARDS. Setting positive end-expiratory pressure in acute respiratory distress syndrome. *Am J Respir Crit Care Med*. 2017;195(11):1429-1438.
92. Hol L, Nijbroek S, Schultz MJ. Perioperative lung protection: clinical implications. *Anesth Analg*. 2020;131(6):1721-1729.
93. Guo J, Xu J. Effect of positive end expiratory pressure level selection in prone ventilation on lung recruitment and inflammatory factors in patients with severe acute respiratory distress syndrome. *Chin Crit Care Med*. 2020;32(7):702-706.
94. Kim SH, Jung KT, An TH. Effects of tidal volume and PEEP on arterial blood gases and pulmonary mechanics during one-lung ventilation. *J Anesth*. 2012;26(4):568-573.
95. Barbosa FT, Castro AA, de Sousa-Rodrigues CF. Positive end-expiratory pressure (PEEP) during anaesthesia for prevention of mortality and postoperative pulmonary complications. *Cochrane Database Syst Rev*. 2014;6(CD007922. doi:10.1002/14651858.CD007922.pub3
96. Jo YY, Lee JY, Lee MG, Kwak HJ. Effects of high positive end-expiratory pressure on haemodynamics and cerebral oxygenation during pneumoperitoneum in the Trendelenburg position. *Anaesthesia*. 2013;68(9):938-943.
97. Hemmes SN, Gama de Abreu M, Pelosi P, Schultz MJ. High versus low positive end-expiratory pressure during general anaesthesia for open abdominal surgery (PROVHILLO trial): a multicentre randomised controlled trial. *Lancet (London, England)*. 2014;384(9942):495-503.
98. Bluth T, Serpa Neto A, Schultz MJ, et al. Effect of intraoperative high positive end-expiratory pressure (PEEP) with recruitment maneuvers vs low PEEP on postoperative pulmonary complications in obese patients: a randomized clinical trial. *JAMA*. 2019;321(23):2292-2305.
99. Lachmann RA, van Kaam AH, Haitsma JJ, Lachmann B. High positive end-expiratory pressure levels promote bacterial translocation in experimental pneumonia. *Intensive Care Med*. 2007;33(10):1800-1804.
100. Krebs J, Pelosi P, Tsagogiorgas C, Alb M, Lucee T. Effects of positive end-expiratory pressure on respiratory pressure and hemodynamics in patients with acute respiratory failure with and without intra-abdominal hypertension: a pilot study. *Crit Care*. 2009;13(5):R160. doi:10.1186/cc8118
101. Yan S, Zhuang Y, Ge K. Impact of positive end-expiratory pressure on respiratory mechanics and hemodynamics in concomitant acute lung injury and intra-abdominal hypertension. *Chin J Respir Crit Care Med*. 2014;13(4):360-363.
102. Dai Z, He F. Effects of different ventilation modes on intrapulmonary shunt and oxygenation during one lung ventilation. *J Nongken Med*. 2009;31(6):545-548.
103. Nieman GF, Satalin J, Andrews P, Aiash H, Habashi NM, Gatto LA. Personalizing mechanical ventilation according to physiologic parameters to stabilize alveoli and minimize ventilator induced lung injury (VILI). *Intensive Care Med Exp*. 2017;5(1):8. doi:10.1186/s40635-017-0121-x
104. Sahetya SK, Brower RG. Lung recruitment and titrated PEEP in moderate to severe ARDS: is the door closing on the open lung? *JAMA*. 2017;318(14):1327-1329.
105. Zampieri FG, Costa EL, Iwashyna TJ, et al. Heterogeneous effects of alveolar recruitment in acute respiratory distress syndrome: a machine learning reanalysis of the alveolar recruitment for acute respiratory distress syndrome trial. *Br J Anaesth*. 2019;123(1):88-95.
106. Constantin JM, Jabaoudon M, Lefrant JY, et al. Personalised mechanical ventilation tailored to lung morphology versus low positive end-expiratory pressure for patients with acute respiratory distress syndrome in France (the LIVE study): a multicentre, single-blind, randomised controlled trial. *Lancet Respir Med*. 2019;7(10):870-880.
107. Battaglini D, Ball L, Wittenstein J, Cohen E, Gama DEAM, Pelosi P. PEEP in thoracic anesthesia: pros and cons. *Minerva Anestesiol*. 2021;87(2):223-229.
108. Rauseo M, Mirabella L, Grasso S, et al. Peep titration based on the open lung approach during one lung ventilation in thoracic surgery: a physiological study. *BMC Anesthesiol*. 2018; 18(1):156. doi:10.1186/s12871-018-0624-3
109. Park M, Ahn HJ, Kim JA, et al. Driving pressure during thoracic surgery: a randomized clinical trial. *Anesthesiology*. 2019;130(3):385-393.
110. Li P, Kang X, Miao M, Zhang J. Individualized positive end-expiratory pressure (PEEP) during one-lung ventilation for prevention of postoperative pulmonary complications in patients undergoing thoracic surgery: a meta-analysis. *Medicine*. 2021;100(28):e26638. doi:10.1097/MD.00000000000026638
111. Reinius H, Borges JB, Engström J, et al. Optimal PEEP during one-lung ventilation with capnotherm: An experimental study. *Acta Anaesthesiol Scand*. 2019;63(2):222-231.

112. Chen Z, Li J. Use of dynamic compliance identify the positive end-expiratory pressure level in the video-assisted pulmonary lobectomy. *Int J Anaesthesiol Resuscitat*. 2016;37(3):197-201.

113. Gernoth C, Wagner G, Pelosi P, Luecke T. Respiratory and haemodynamic changes during decremental open lung positive end-expiratory pressure titration in patients with acute respiratory distress syndrome. *Crit Care*. 2009;13(2):R59. doi:10.1186/cc7786

114. Ferrando C, Mugarra A, Gutierrez A, et al. Setting individualized positive end-expiratory pressure level with a positive end-expiratory pressure decrement trial after a recruitment maneuver improves oxygenation and lung mechanics during one-lung ventilation. *Anesth Analg*. 2014;118(3):657-665.

115. Xu D, Wei W, Chen L, Li S, Lian M. Effects of different positive end-expiratory pressure titrating strategies on oxygenation and respiratory mechanics during one-lung ventilation: a randomized controlled trial. *Ann Palliat Med*. 2021;10(2):1133-1144.

116. Suarez-Sipmann F, Böhm SH, Tusman G, et al. Use of dynamic compliance for open lung positive end-expiratory pressure titration in an experimental study. *Crit Care Med*. 2007;35(1):214-221.

117. Liu W, Zheng H. Effect of one lung protective ventilation regimen based on quasi-static pressure-volume curve in patients undergoing thoracic surgery. *Chin J Anaesthesiol*. 2011;31(8):950-954.

118. Si J, Su Y. Effect of low tidal volume combined with individualized positive end-expiratory pressure on one-lung ventilation in patients undergoing thoracic surgery. *Shandong Med J*. 2011;51(11):90-91.

119. LaFollette R, Hjornowski K, Norton J, DiRocco J, Carney D, Nieman G. Using pressure-volume curves to set proper PEEP in acute lung injury. *Nurs Crit Care*. 2007;12(5):231-241.

120. Marini JJ. Dynamic hyperinflation and auto-positive end-expiratory pressure: lessons learned over 30 years. *Am J Respir Crit Care Med*. 2011;184(7):756-762.

121. Zhu L. Effect of one-lung ventilation with pressure-controlled ventilation or volume-controlled ventilation on intrinsic PEEP in patients undergoing esophageus surgery. *Jinagsu Med J*. 2011;37(20):2412-2413.

122. Khan M, Frankel HL. Use and titration of positive end-expiratory pressure. *Curr Probl Surg*. 2013;50(10):446-451.

123. Zhang C, Xie J. Effect of individualized protective pulmonary ventilation strategy on pulmonary ventilation in elderly patients under general anesthesia. *Chin J Experiment Surg*. 2019;36(5):1475-1478.

124. Liu K. Optimize the Positive End-Expiratory Pressure During Perioperative Period of Thoracoscopic Surgery in Elderly Patients: Individualized Setting Using Electrical Impedence Tomography. *Shanghai Jiao Tong University*; 2020.

125. Amato MB, Meade MO, Slutsky AS, et al. Driving pressure and survival in the acute respiratory distress syndrome. *N Engl J Med*. 2015;372(8):747-755.

126. Neto AS, Hammes SN, Barbas CS, et al. Association between driving pressure and development of postoperative pulmonary complications in patients undergoing mechanical ventilation for general anaesthesia: a meta-analysis of individual patient data. *Lancet Respir Med*. 2016;4(4):272-280.

127. Park M, Yoon S, Nam JS, et al. Driving pressure-guided ventilation and postoperative pulmonary complications in thoracic surgery: a multicentre randomised clinical trial. *Br J Anaesth*. 2022. doi:10.1016/j.bja.2022.06.037

128. Wang F, Su R. Lung protective effect of driving pressure guided ventilation strategy in one-lung ventilation. *Gansu Med J*. 2022;41(2):120-122.

129. Ishikawa S, Lohser J. One-lung ventilation and arterial oxygenation. *Curr Opin Anaesthesiol*. 2011;24(1):24-31.

130. Tusman G, Suarez-Sipmann F, Böhm SH, et al. Monitoring dead space during recruitment and PEEP titration in an experimental model. *Intensive Care Med*. 2006;32(11):1863-1871.

131. Bian W, Chen W, Chao Y, et al. Application of dead space fraction to titrate optimal positive end-expiratory pressure in an ARDS swine model. *Exp Ther Med*. 2017;13(4):1572-1577.

132. Zhang M, Yan P. Effect of positive end expiratory pressure guided by esophageal pressure on hemodynamic and gas exchange in pig model with acute respiratory distress syndrome. *Chin J Clin Electron Edit*. 2016;10(5):663-668.

133. Persson P, Stenqvist O, Lundin S. Evaluation of lung and chest wall mechanics during anaesthesia using the PEEP-step method. *Br J Anaesth*. 2018;120(4):860-867.

134. Persson P, Lundin S, Stenqvist O. Transpulmonary and pleural pressure in a respiratory system model with an elastic recoiling lung and an expanding chest wall. *Intensive Care Med Exp*. 2016;4(1):26. doi:10.1186/s40635-016-0103-4

135. Stenqvist O, Lundin S. Lung elastance and transpulmonary pressure may be determined without using esophageal pressure measurements. *Am J Respir Crit Care Med*. 2014;190(1):120. doi:10.1164/rccm.201402-0313LE

136. Lundin S, Grivans C, Stenqvist O. Transpulmonary pressure and lung elastance can be estimated by a PEEP-step manoeuvre. *Acta Anaesthesiol Scand*. 2015;59(2):185-196.

137. Rylander C, Högman M, Perchiazzì G, Magnusson A, Hedenstierna G. Functional residual capacity and respiratory mechanics as indicators of aeration and collapse in experimental lung injury. *Anesthesiology*. 2004;98(3):782-789. PMID: table of contents.

138. Liu F, Li L, Hou J. Monitoring FRC to guide the value of optimal PEEP for lung revascularization in patients undergoing radical lung cancer surgery. *J Clin Exp Med*. 2022;21(11):1222-1226.

139. Albu G, Petak F, Zand T, Hallbäck M, Wallin M, Habre W. Lung volume assessments in normal and surfactant depleted lungs: agreement between bedside techniques and CT imaging. *BMC Anesthesiol*. 2014;14:64. doi:10.1186/1471-2253-14-64

140. Chiumello D, Marino A, Brioni M, et al. Visual anatomical lung CT scan assessment of lung recruitability. *Intensive Care Med*. 2013;39(1):66-73.

141. Costa EL, Borges JB, Melo A, et al. Bedside estimation of recruitable alveolar collapse and hyperdistension by electrical impedance tomography. *Intensive Care Med*. 2009;35(6):1132-1137.

142. Hinz J, Gehoff A, Moerer O, et al. Regional filling characteristics of the lungs in mechanically ventilated patients with acute lung injury. *Eur J Anaesthesiol*. 2007;24(5):414-424.
143. Liu K, Xu M. Effects of individualized ventilation on the respiratory mechanics and oxygenation in elderly patients during the recovery period after lobectomy. *Int J Anesthetic Resuscitat*. 2020;41(4):344-349.

144. Zhao Z, Wang W, Zhang Z, et al. Influence of tidal volume and positive end-expiratory pressure on ventilation distribution and oxygenation during one-lung ventilation. *Physiol Meas*. 2018;39(3):034003. doi:10.1088/1361-6579/aaaeb2

145. Kobylanski J, Murray A, Brace D, Goligher E, Fan E. Electrical impedance tomography in adult patients undergoing mechanical ventilation: a systematic review. *J Crit Care*. 2016;35:33-50. doi:10.21037/atm.2017.12.06

146. Brown BH. Electrical impedance tomography (EIT): a review. *J Med Eng Technol*. 2003;27(3):97-108.

147. Lobo B, Hermosa C, Abella A, Gordo F. Electrical impedance tomography. *Ann Translat Med*. 2018;6(2):26.

148. Putensen C, Wrigge H, Zinserling J. Electrical impedance tomography guided ventilation therapy. *Curr Opin Crit Care*. 2007;13(3):344-350.

149. Frerichs I, Dargaville PA, Dudykevych T, Rimensberger PC. Electrical impedance tomography: a method for monitoring regional lung aeration and tidal volume distribution? *Intensive Care Med*. 2003;29(12):2312-2316.

150. Zhao Z, Steinmann D, Frerichs I, Guttmann J, Möller K. PEEP titration guided by ventilation homogeneity: a feasibility study using electrical impedance tomography. *Crit Care*. 2010;14(1):R8. doi:10.1186/cc8860

151. Hsu HJ, Chang HT, Zhao Z, et al. Positive end-expiratory pressure titration with electrical impedance tomography and pressure-volume curve: a randomized trial in moderate to severe ARDS. *Physiol Meas*. 2021;42(1):014002. doi:10.1088/1361-6579/abad679

152. Liu K, Huang C, Xu M, et al. PEEP guided by electrical impedance tomography during one-lung ventilation in elderly patients undergoing thoracoscopic surgery. *Ann Translat Med*. 2019;7(23):757. doi:10.21037/atm.2019.11.95

153. Mauri T, Eronia N, Turrini C, et al. Bedside assessment of the effects of positive end-expiratory pressure on lung inflation and recruitment by the helium dilution technique and electrical impedance tomography. *Intensive Care Med*. 2016;42(10):1576-1587.

154. Xu J, Luo Y. Advances in the research of individualized positive end-expiratory pressure ventilation guided by electrical impedance tomography. *J Clin Anesth*. 2020;36(12):1229-1231.

155. Maciejewski D, Putowski Z, Czok M, Krzych LJ. Electrical impedance tomography as a tool for monitoring mechanical ventilation. An introduction to the technique. *Adv Med Sci*. 2021;66(2):388-395.

156. Monastesse A, Girard F, Massicotte N, Chartrand-Lefebvre C, Girard M. Lung ultrasonography for the assessment of perioperative atelectasis: a pilot feasibility study. *Anesth Analg*. 2017;124(2):494-504.

157. Gattinoni L, Collino F, Maiolo G, et al. Positive end-expiratory pressure: how to set it at the individual level. *Ann Translat Med*. 2017;5(14):288. doi:10.21037/atm.2017.06.64

158. Mascotto G, Bizzarri M, Messina M, et al. Prospective, randomized, controlled evaluation of the preventive effects of positive end-expiratory pressure on patient oxygenation during one-lung ventilation. *Eur J Anaesthesiol*. 2003;20(9):704-710.

159. Halter JM, Steinberg JM, Gatto LA, et al. Effect of positive end-expiratory pressure and tidal volume on lung injury induced by alveolar instability. *Crit Care*. 2007;11(1):R20. doi:10.1186/cc5695

160. Wen K. Lung ultrasound score to investigate thoracic surgery during single lung ventilation comparison of best PEEP with traditional lung protection ventilation. 2018.

**How to cite this article:** Yueyi J, Jing T, Lianbing G. A structured narrative review of clinical and experimental studies of the use of different positive end-expiratory pressure levels during thoracic surgery. *Clin Respir J*. 2022;16(11):717-731. doi:10.1111/crj.13545