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Intraoperative mechanical ventilation strategies for one-lung ventilation

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One-lung ventilation (OLV) has two major challenges: oxygenation and lung protection. The former is mainly because the ventilation of one lung is stopped while the perfusion continues; the latter is mainly because the whole ventilation is applied to only one lung. Recommendations for maintaining the oxygenation and methods of lung protection can contradict each other (such as high vs. low inspiratory oxygen fraction (FiO_2), high vs. low tidal volume (TV), etc.). In light of the (very few) randomized clinical trials, this review focuses on a recent strategy for OLV, which includes a possible decrease in FiO_2, lower TVs, positive end-expiratory pressure (PEEP) to the dependent lung, continuous positive airway pressure (CPAP) to the non-dependent lung and recruitment manoeuvres. Other applications such as anaesthetic choice and fluid management can affect the success of ventilatory strategy; new developments have changed the classical approach in this respect.

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One-lung ventilation (OLV) is a unique ventilation method whereby one lung is excluded from ventilation while the perfusion to the non-ventilated lung is continued.

The historical classification of 'absolute' and 'relative' indications is now considered rather confusing and inappropriate: a 'relative' indication is not just a 'surgical comfort' but also a confirmation of the decrease in intra- and post-operative complications. In addition, any 'relative' indication may unpredictably become an 'absolute' indication during the operation. The current classification of indications of OLV includes indications for 'lung separation' and 'lung isolation' [1].

Historically, the guidelines for OLV are primarily aimed at preventing and treating hypoxaemia, which was considered to be the most important, if not the only, problem during OLV. Hypoxaemia is still an important challenge to OLV for several reasons. However, a growing number of studies have shown that lung injury (acute lung injury (ALI)) associated with/induced by OLV is also an important problem [2]. Therefore, an 'optimal' ventilation strategy should overcome these two challenges: maintaining adequate gas exchange and protecting the lung.

Unfortunately, the number of 'randomized clinical trials' (RCT) examining intraoperative mechanical ventilation strategies for OLV is still not sufficient to provide adequate evidence. In a recent meta-analysis on the incidence of mortality and morbidity related to post-operative ALI in patients who have undergone abdominal or thoracic surgery, only four studies with exclusively thoracic operations could be included [3]. This review attempts to focus on mechanical ventilation strategies during OLV using both 'oxygenation' and 'lung protection'.

Hypoxaemia during OLV

During OLV, the ventilation of one lung is interrupted, while the perfusion persists. Hypoxaemia is caused not only by the increased intrapulmonary shunt (Q_s/Q_t) from the blood flow to the non-ventilated lung but also by the hypoventilation in the dependent lung as a result of derecruitment of the alveoli. Several mechanisms (above all, 'hypoxic pulmonary vasoconstriction (HPV)') cause a decrease of blood flow to the non-ventilated lung, resulting in a decreased Q_s/Q_t. For anaesthesia and intensive care, knowledge of the basic (patho)physiology of HPV is essential [4,5]. Yet, the inhibition of HPV is not the only cause of hypoxaemia during OLV [6]; any application causing a diversion of blood flow to the non-ventilated lung (e.g., high airway pressures in the ventilated lung) can lead, even without any impact of HPV, to hypoxaemia.

Matching of the ventilation and perfusion (V–Q) play a crucial role, with changes after anaesthesia induction (and also during OLV) leading to a V–Q mismatch [7]. It has been shown that the lateral decubitus position was associated with better oxygenation compared with the supine position [8], and that the relative position of the ventilated versus the non-ventilated lung markedly affects arterial oxygenation during OLV [9]. Although many OLV procedures are performed successfully in the lateral decubitus position, the number of OLV procedures performed in the supine position is increasing (double-lung transplantation, minimally invasive coronary artery surgery, etc.).

Although several studies and practical experience support the classical knowledge that gravity is most important determinant of the distribution of both ventilation and perfusion, some studies have shown that anatomical differences can also play a role. An 'onion-like' layering of perfusion with reduced flow at the periphery of the lung and higher flow toward the hilum was demonstrated [10].

Table 1
Historical recommendation for OLV (to avoid hypoxaemia) (modified from Ref. [35]).

- FiO$_2$: 1.0
- High TV (e.g., 10 mL/kg)
- PaCO$_2$ = 40 mmHg (if necessary, increase respiratory rate)
- If severe hypoxaemia occurs, CPAP to non-dependent lung
- PEEP, only if severe hypoxaemia occurs, should be ≤ CPAP
- Use intravenous anaesthetics to prevent HPV

Fortunately, the same author also reported that the distribution of ventilation follows the distribution of perfusion in a similar manner [11]. The classical approach during OLV is based on the prevention and treatment of acute hypoxaemia (Table 1). Although the incidence of hypoxaemia has declined from 20 to 25% in the 1970s to about 10% presently, it must still be considered a pertinent issue of OLV [2]. Indeed, one of the most common reasons of hypoxaemia (e.g., 38%) during OLV is dislocation of OLV devices [12]. Intraoperative displacement is very common; therefore, it is crucial to perform fibre-optic bronchoscopy (FOB) if desaturation occurs [13].

Lung injury as a result of OLV

Thoracic surgery is unique in that the target organ of both the surgeon and the mechanical ventilation is the same: the lung. One can assume that the post-operative lung injury would be more likely caused by surgical trauma; however, it has been shown that the radiological density increase was significantly greater in the non-operative lung than in the operative lung after lobectomy [14].

In fact, OLV-associated ALI has been known for a longer time, albeit in different names such as 'postpneumonectomy pulmonary oedema' (PPE) [15]. As a matter of fact, OLV and acute respiratory distress syndrome (ARDS) have certain similarities: OLV can be assumed as a 'variation' of ventilation in ARDS, not least because both deal with smaller volumes of lung ('baby lung' in ARDS, and the 'one lung' in OLV) [16].

It has been shown that ALI can also occur in 'healthy lungs' and even after the 'short' period (compared with ventilation in an intensive care unit (ICU)) of ventilation [17]. In a recent meta-analysis, it has been demonstrated that thoracic surgery was associated with an incidence of post-operative ALI of 4.3%. This rate was similar to that for abdominal surgery (3.4%), but the attributable mortality of post-operative lung injury was higher in patients who underwent thoracic surgery than those who underwent abdominal surgery (26.5% vs. 12.2%) [3] (Fig. 1A).

OLV is also associated with an increased pulmonary immune response [18]; furthermore, the alveolar damage during OLV can be greater than that during two-lung ventilation [19].

Ventilatory settings during OLV: (Table 2 and Fig. 1B)

Inspiratory oxygen fraction

The 'classical' recommendation is to use an inspiratory oxygen fraction (FiO_2) of 1.0 during OLV. This approach should provide not only a higher margin of safety but also vasodilatation of the vessels in the ventilated lung, which augments the blood flow redistribution due to HPV in the non-ventilated lung.

However, even a short period of preoxygenation with an FiO_2 of 1.0 can cause atelectasis, and recruitment manoeuvres (RMs) are not as effective at high FiO_2 [20]. Displacement of nitrogen would lead to a collapse of the alveoli, meaning that high FiO_2 aiming to improve oxygenation can paradoxically worsen it.

It is appropriate to keep the FiO_2 at the lowest possible level; it is more reasonable to start with a level of <1.0 and increase if necessary, rather than start with 1.0 and decrease.

'Protective ventilation' and its components

'Protective ventilation' was defined and determined in patients with ARDS [21]. For intraoperative management, this procedure has three components: low tidal volumes (TV), RMs and positive end-expiratory pressure (PEEP). This approach has also been shown to be appropriate in 'healthy' lungs [22]. However, during OLV, the classical guidelines controvert to all of the components of protective ventilation in some degree.
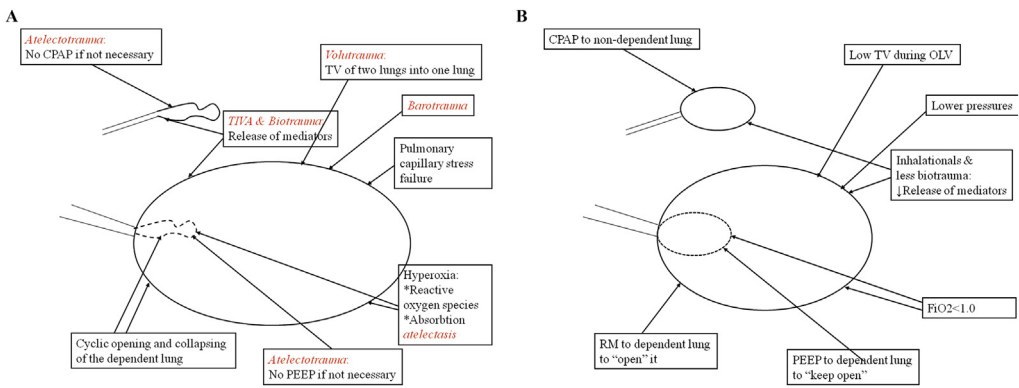
Fig. 1. A: The traditional setting for OLV can lead to lung injury via its four classical pathways: Baro-, volu-, atelecto- and biotrauma. It is to be noted that, during expiration (dashed line), the dependent lung can collapse entirely; during inspiration, it is over-expanded due to the high tidal volume (TV), which is normally applied to two lungs. The non-dependent lung is also fully collapsed. B: Current suggestion for OLV can prevent lung injury: During expiration (dashed line), PEEP can prevent a total collapse; during inspiration, lower TV can achieve a more appropriate ventilation. CPAP to non-dependent lung is beneficial for both oxygenation and lung protection.

Low TVs

In 1963, Bendixen HH et al. found a relation between the degree of ventilation and the magnitude of fall in arterial oxygen tension [23]: Large TVs appeared to protect against falls in oxygen tension, whereas shallow TVs led to atelectasis and increased shunting, with impaired oxygenation.

Pioneers of thoracic anaesthesia have followed Bendixen's recommendation: According to the traditional approach of OLV, the dependent lung should be ventilated with the same TV as for two-lung ventilation (10–12 mL/kg) [24]. This approach is not relevant anymore. First, 'conventional' high TVs have been shown to be hazardous even for two-lung ventilation: In a meta-analysis, post-operative pulmonary complications showed lower incidence in patients ventilated with lower TVs [25]. Considering that high TVs are hazardous even for two lungs, applying this amount to only one lung should be associated with extended complications [26]. In an animal study, applying the same TV to one lung compared with two lungs has resulted in significantly greater lung injury, as shown in the

Table 2
Current recommendations for OLV (to avoid both hypoxaemia and lung injury) (see text for abbreviations).

Setting	Rationale	Problems
$FiO_2 < 1.0$	FiO_2 of 1.0 can facilitate atelectasis, so high FiO_2 can induce atelectotrauma and paradoxically hypoxaemia [20]	Is there any 'cut-off' point (e.g., SpO_2) to set the FiO_2?
Low TV (e.g., 6 mL/kg) (or low pressures)	High TV (or high pressures) can lead to volotrauma (or barotrauma) [18,27].	What is the ideal TV for one lung?
Routine use of PEEP	PEEP is beneficial for oxygenation [36] and also for lung protection [41]	Is there a general 'best PEEP'? How can it be determined?
Recruitment manoeuvres	RM improves oxygenation [43], and achieves a better distribution of aeration [44]	Should it be used routinely? How should it be applied?
Routine use of CPAP to non-dependent lung	CPAP is beneficial for both oxygenation [45] and lung protection [47]	The increasing frequency of VATS, where CPAP is contraindicated
Permissive hypercapnia	High pCO_2 can be beneficial in avoiding ALI [34]	Is there any cut-off point for pCO_2 to avoid haemodynamic instability?
Inhalational anaesthetics + TEA	They do not inhibit HPV relevantly [58,66]; inhalational anaesthetics avoid ALI [59,60]	What are the effects of TEA on ALI?

histological 'diffuse alveolar damage' score [19]. One cohort [27] and one retrospective [28] study have similar results, wherein high intraoperative TV was associated with an increased rate of post-operative respiratory failure.

In an RCT, OLV with a TV of 10 mL/kg induced an inflammatory response with higher concentrations of inflammatory mediators compared with 5 mL/kg [18].

With respect to oxygenation, some studies have found no relevant difference in oxygenation between low and high TV [29], whilst some studies have found a significant difference in favour of a higher TV [30]. However, one of the most important reasons for both hypoxaemia and ALI is the decline of functional residual capacity (FRC) below the closing capacity (CC) and a high TV cannot be the solution of this main problem (Fig. 2).

Currently, the advantages of low TV appear to be unquestionable. Yet, there are some important questions on the ventilator setting to be answered:

i. How 'low' is 'low enough'? A TV of 6–8 mL/kg is considered 'protective' for two-lung ventilation. When applied to only one lung, this would indicate a doubly high value, which may not be protective anymore. However, halving the TV again to 3–4 mL/kg would descend below dead-space ventilation. Empirically, a TV of 5–6 mL/kg seems rational, but this needs to be proven.

ii. In patients with decreased lung compliance, very high driving pressures can be required to obtain even the low TV's. In these patients, the so-called 'ultraprotective ventilation' (application of extracorporeal lung assist (ECLA) systems) can be necessary to avoid applying high ventilation pressures. Iglesias et al., have shown in two studies (an animal study [31] and a clinical study [32]) that ECLA systems help decrease the TV to very low amounts to avoid high pressures during ALI in the post-operative period; the resulting survival rate was much higher than usual (100% in the animal study, and 86% (six of seven patients) in the clinical setting). For the intraoperative ventilation, in 10 patients, apnoeic oxygenation could be applied successfully with the aid of ECLA [33].

iii. Should the RR be adjusted to maintain normocapnia? Although normocapnia was reported as the conventional aim, hypercapnia was shown to be well tolerated in the majority of patients, and it is beneficial in preventing ALI [34]. Moreover, increasing the RR would shorten both the
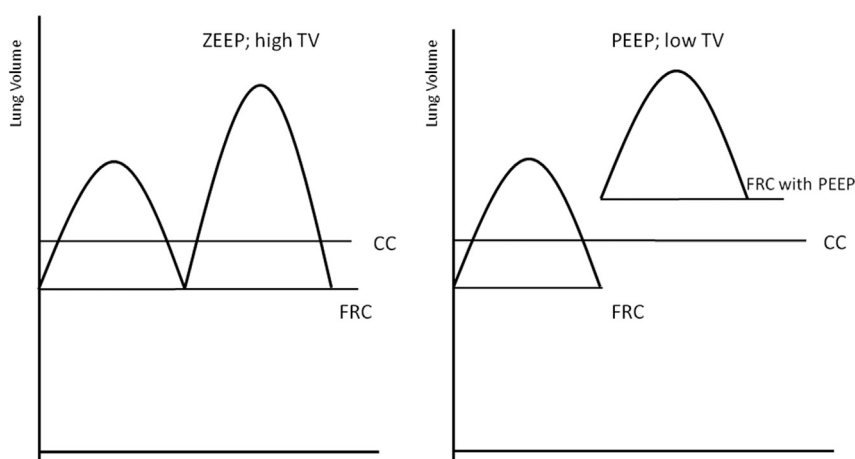

Fig. 2. Relationship of FRC (functional residual capacity) and CC (closing capacity) in different ventilatory settings. Right: FRC falls below CC during mechanical ventilation; a larger tidal volume (TV) can obtain better gas exchange (note the larger area above the CC line); however, a cyclic recruitment cannot be avoided. Left: Applying PEEP while keeping the TV low: PEEP obtains an FRC above the CC. Cyclic recruitment is avoided, and the ventilation (now the area above the 'new' FRC) is still better than the one without PEEP.

inspiratory and expiratory times, leading to higher ventilation pressures and increased intrinsic PEEP, respectively.

PEEP to the dependent lung

According to the traditional approach, PEEP should be applied if the patient is hypoxaemic and continuous positive airway pressure (CPAP) fails to improve the oxygenation during OLV [35]. In such cases, the PEEP level should not exceed the CPAP to prevent the diversion of blood flow to the non-dependent lung. Studies have shown that PEEP increased [36], decreased [37] or did not change [38] PaO_2. In some cases, application of PEEP during OLV increases FRC, improves the *V/Q* relationship in the dependent lung and prevents alveolar collapse at end expiration (Fig. 3). In some other cases, PEEP leads to a compression of the perialveolar vessels, which would cause a diversion of perfusion to the non-ventilated lung, and consequently to an increased Q_s/Q_t and decreased PaO_2.

A study by Slinger et al. offers a solution to the dilemma of the different effects of PEEP on oxygenation: PEEP was beneficial if it caused the total end-expiratory pressure (EEP = intrinsic + external PEEP) to reach closer to the lower inflection point (LIP) of the static compliance curve [39]. Conversely, in patients in whom the application of external PEEP 'diverts' the EEP away from LIP (e.g., some patients have an LIP at 0 cm H_2O), PEEP was associated with a decrease in oxygenation (Fig. 3).

In a recent RCT, the authors first applied an RM after the beginning of OLV; afterwards, the lung in the control group was ventilated with a 5-cm H_2O PEEP, whereas an 'individualized' PEEP level according to the compliance was determined by a PEEP decrement trial in the study group. The individualized PEEP group was associated with an improvement in oxygenation [40].

The effects of PEEP on the 'protection' of the lung have been examined to a lesser extent. A comparison of − only − different PEEP levels on lung protection during OLV has not been performed. In general, a combination of different components of protective ventilation has been examined. As a specific example, in an animal study, the mean pulmonary artery pressure and lung weight gain values,
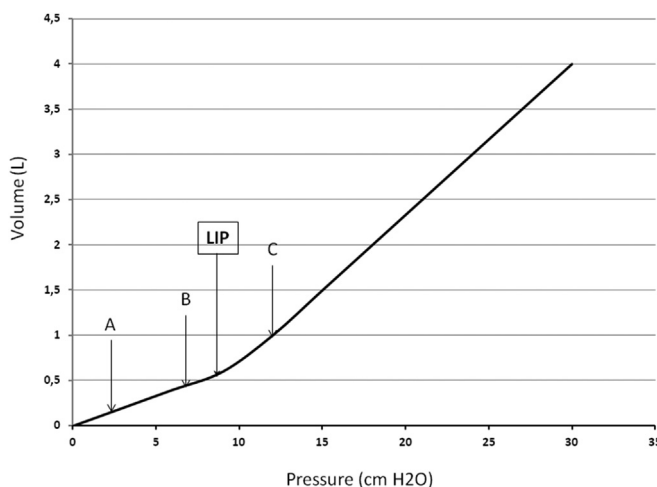

Fig. 3. Relationship of PEEP and LIP (lower inflection point). It is to be noted that LIP can differ in each individual, sometimes attaining a value of zero. A, B or C are possible points for total (intrinsic + external) end-expiratory pressure. The level of external PEEP should be adjusted to approach LIP. For example, if the external PEEP brings the total PEEP from A to B, oxygenation improves, but if the external PEEP brings the total PEEP from B to C, oxygenation is impaired. If the LIP is 0, the best oxygenation is obtained by A (modified from Slinger et al. [39]).

as well as the concentration of thromboxane B(2), were found to be lower in the protective (low TV + PEEP) OLV group than in OLV with TV of 10 mL/kg and two-lung ventilation [41].

The effects of different PEEP levels during OLV on lung protection require further investigation.

Recruitment manoeuvres

PEEP can only 'keep' the alveoli open and cannot affect the collapsed ones. To 'reopen' the atelectasis, a sustained inflation above the 'upper inflexion point' is necessary, which can be achieved by several methods of RM. The efficacy of RM in opening the atelectasis and improvement of oxygenation was first shown in ARDS. Afterwards, in several studies, RM was shown to achieve a significant improvement of oxygenation during OLV [42,43]. These studies have shown that RM was effective not only in the improvement of oxygenation but also in a decrease of dead space and in an increase of the efficiency of the ventilation.

With respect to ALI, the 'one-lung recruitment manoeuvre' was associated not only with an improvement of oxygenation but also with a more appropriate distribution of aeration and decreased mechanical stress [44]. In this animal study, the distribution of aeration was examined via computed tomography (CT) scan; RMs have improved aeration and respiratory mechanics during OLV.

Combined use of the component of protective ventilation

In an RCT performed in patients undergoing open abdominal surgery (not thoracic!), the effects of the combination of RM, low TV, and PEEP were examined. During five post-operative days, intraoperative protective ventilation was associated with an improvement in oxygenation (higher SpO_2), fewer alterations in the chest X-ray and a lower 'modified Clinical Pulmonary Infection Score' [22]. A similar study examining both oxygenation and lung protection in thoracotomy has not been conducted. All possible combinations of the three components of protective ventilation have to be examined based on their effects on oxygenation, lung protection and also global outcome (Table 2).

CPAP to the non-dependent lung

Several studies have clearly shown that CPAP applied to the non-dependent lung increased PaO_2 [37,45]. With the exceptions of video-assisted thoracoscopic surgery (VATS) (where the total collapse is often absolutely necessary) and airway surgery, in open thoracotomy, a CPAP of 5 cm of H_2O does not interfere with surgical exposure. This approach would also allow a wider margin of protection of the ventilated lung and lower FiO_2 levels [45,46]. It should be noted that CPAP must be applied after delivering a VT to the non-dependent lung; otherwise, the application to collapsed alveoli would not achieve adequate expansion.

CPAP also prevents the non-dependent lung from completely collapsing. In a recent RCT, it has been shown that CPAP to the non-dependent lung was associated with a lower local immune response during OLV in oesophagectomies [47]. This new finding suggests that CPAP is beneficial for both oxygenation and lung protection. Its effects on outcome have yet to be investigated.

High-frequency jet ventilation

Application of high-frequency jet ventilation (HFJV) to the non-dependent lung has been shown to improve oxygenation [48]. In this respect, HFJV has comparable effects with CPAP [49]. Some additional advantages were noted with HFJV achieving some degree of CO_2 elimination. In most patients, however, CO_2 elimination is not a major problem during OLV. Because of its simplicity and familiarity, many anaesthesiologists prefer applying CPAP rather than HFJV. The routine use of HFJV is therefore limited to patients in whom a bronchus has been surgically opened and CPAP cannot be maintained [50].

Ventilatory modes

A relationship between high pressures ($P_{peak} > 35$ cm H_2O) has been reported during operation and development of ALI [51]. In a previous study, 'pressure-controlled ventilation' (PCV) during OLV compared with 'volume controlled ventilation' (VCV) could obtain the same VT with lower airway pressures, lesser Q_s/Q_t and better oxygenation, probably due to the 'decelerating' flow pattern [52]. However, these findings could not be confirmed in the studies that followed [53]. The only difference between these modes is probably the lower peak (not the plateau) airway pressures, which contributes less (if any) to ALI. In a recent study, PCV was found to offer more improved right ventricular function than did VCV during OLV [54].

Recently, it has been reported that the driving pressure (defined as TV/respiratory system compliance) is the ventilation variable that best stratified the risk of ALI in patients with ARDS [55]. Decreases in driving pressure due to changes in ventilator settings were strongly associated with increased survival the most. With respect to OLV, it should be noted that ventilating only one lung would imply that the same driving pressure would obtain less (if not half of) TV; this phenomenon is not different in PCV or VCV. Whether there would be a difference in the distribution of aeration (as a result of the different flow patterns) remains to be examined.

'Physiological' breathing is irregular in all its components (TV, frequency, sighs, etc.). In an experimental ALI study, a so-called 'noisy' pressure support ventilation was found to be associated with an improvement in oxygenation and also a redistribution of pulmonary blood flow [56]. Whether and how this approach can be related to OLV must be investigated further.

Effects of non-ventilatory strategies

It has been shown that some non-ventilatory strategies can directly affect the success of mechanical ventilation during OLV. In this section, some of these strategies have been reviewed in terms of their effects on both oxygenation and lung protection.

Anaesthetics

Numerous historical studies show that inhalational anaesthetics inhibit HPV, whilst intravenous (IV) ones (i.e., propofol) do not; therefore, total intravenous anaesthesia (TIVA) was conventionally recommended for OLV, which was found to be associated with an increased PaO$_2$ and a decreased Q_s/Q_t [57]. Presently, inhalational agents in 'equi-anaesthetic' doses are known to not aggravate hypoxaemia when compared with IV propofol; at least the difference in PaO$_2$ is not clinically relevant, probably because of the interaction of other haemodynamic effects of anaesthetics (both inhalational and IV) [58]. From the point of view of ALI, IV anaesthesia is associated with an increased inflammatory response during OLV, as shown by the increased release of different mediators in the broncho-alveolar lavage fluid of the dependent [59] and non-dependent lung [60]. It was also associated with lower post-operative complications.

Based on a meta-analysis – and in contrast to the classical approach – the use of inhalation anaesthesia is preferred for its protective effects that attenuate inflammatory responses [61]. New RCTs should focus on 'patient outcome', rather than less relevant intraoperative physiological variables.

Thoracic epidural anaesthesia

Thoracic epidural anaesthesia (TEA) is the gold standard for controlling acute and chronic post-operative pain after thoracotomies [62]. With regard to its effects on oxygenation during OLV, former studies have shown that TEA decreased [63], increased [64] or did not change [65] PaO$_2$. Current knowledge confirms that, in routinely used doses (e.g., bupivacaine 0.1% + 0.1 mg/mL morphine; 10 mL

of bolus + 7 mL/h infusion) [66], TEA does not affect oxygenation. With respect to ALI, the effects of TEA are less examined.

Fluid management

The specific features of lungs ('lungs do not have a third space') have led to a general agreement on 'restrictive' fluid management. However, there are controversial results on a 'direct' relationship between fluid load and PPE. Moreover, it should be noted that there is still no RCT comparing different fluid managements in thoracic anaesthesia: the evidence of the preventive effect of fluid restriction is weaker than its reputation. Current evidence is only sufficient to argue that, as quoted by Slinger, '(with IV fluids), we can make the lung injury worse, but we don't cause it' [67].

The optimal fluid management during OLV can be titrated in the newer, objective monitoring strategies such as 'pulse pressure variation' [68]. After the development of objective monitorization, a 'goal-directed' management (rather than subjective 'liberal' or 'restrictive') appears to be possible.

Glycocalyx

The relationship between hydrostatic and oncotic pressure to determine fluid flux across a semipermeable membrane, such as the lung capillary endothelium, was described in a classic equation developed in 1896 by Starling [69]. However, the Starling formula does not explain several subsequent clinical observations, such as the intact organism's relative resistance to developing oedema and the inability of therapy with hyperoncotic agents to draw fluid from the pulmonary interstitium into the vascular compartment [70]. This discrepancy is now attributed to the glycocalyx, a microcilial layer that lines the endothelium and acts as a molecular sieve [71]. This layer tends to increase the oncotic pressure on the inner surface of the endothelium and decrease leucocyte and platelet adhesion to the endothelium. The glycocalyx deteriorates during ischaemia–reperfusion injury and in the presence of a wide variety of inflammatory mediators such as cytokines, which probably contributes to the increased vascular permeability seen in these situations. In addition, the glycocalyx deteriorates in the presence of atrial natriuretic peptides, which may explain the increase in plasma protein filtration observed with colloid boluses. Protecting the glycocalyx may be among the anaesthesiologist's most important duties in the perioperative period. Volatile anaesthetics may have a protective effect on the glycocalyx [72].

Pharmacological manipulation to support oxygenation

A more appropriate match of ventilation and perfusion by dilating the vessels in ventilated areas and constricting the vessels in the non-ventilated regions can theoretically be achieved by the pharmacological manipulation of the pulmonary blood flow. The drawback of this approach appears simultaneously: How can the effects on the target area be limited?

Inhaled NO was suggested to be an optimal solution to this drawback, because it has a direct effect on well-ventilated lung regions, achieving selective vasodilation in the surrounding region. However, the results have been controversial and mostly disappointing: inhaled NO can improve oxygenation only with smaller doses (4 ppm) [73]. According to another study, NO appears to be effective only in patients with pulmonary hypertension and hypoxaemia during OLV [74].

Generally, it should be borne in mind that 'treating the hypoxaemia' can interfere with 'tissue hypoxia' in some circumstances [75]. For now, the use of 'pharmacological manipulations' should be limited to situations when other strategies fail to improve oxygenation [76].

Practice points

- The mechanical ventilation strategy during OLV should be adjusted to overcome two different challenges: oxygenation and lung protection
- The disposition of the double-lumen tube/blocker is one of the most frequent reasons of hypoxaemia during OLV.
- High FiO_2 (1.0) should be avoided unless necessary.
- Protective ventilation' has three intraoperative components: low TV, RM and PEEP. The combined use of these three components can help prevent both hypoxaemia and ALI
- CPAP to the non-dependent lung is beneficial for both challenges.
- Fluid management should be adjusted according to new monitorization facilities.

Research agenda

- Effects of intraoperative ventilation strategies on post-operative pulmonary outcomes.
- Acceptable use of low TV and PEEP, questions such as How low is the TV?' and How high is the PEEP?' to be answered.
- Comparison of inhalational versus intravenous anaesthetics regarding their effects on post-operative outcome
- Effects of different fluid management strategies (amount and type) on respiratory functions and lung protection
- Glycocalyx being a promising area of future research: Effects of different ventilatory regimens on glycocalyx, as well as effects of changes in glycocalyx on mortality and morbidity.

Summary

OLV has two major challenges: hypoxaemia during OLV and ALI after the operation. Protection methods against hypoxaemia were defined years ago, when the ALI was not considered a complication of healthy lung ventilation, and protection methods against ALI have been defined primarily in patients with ARDS. Combining these two methods for OLV can be tricky, because several components can contradict each other. Fortunately, the combined application of all components of protective ventilation (low TV, RM and PEEP) can also help improve oxygenation. The application of CPAP to the non-dependent lung, if possible, is a rational option for decreasing FiO_2 safely. The ventilatory mode to be used is probably not very important; rather, it is more important to keep the 'driving pressure' as low as possible. To this end, ECLA can be suggested in some cases. Contrary to previous knowledge, inhalational anaesthetics are preferred over IV anaesthetics because of their lung-protective effects, with no relevant difference in oxygenation. Thoracic epidurals can be used in the majority of cases intraoperatively as well. Fluid management also has a significant effect on ventilation. After introducing techniques to monitor fluid status, it is more rational to apply 'optimal' fluids instead of inappropriately defined 'restricted' and 'liberal' regimens.

Conflict of interest

None.

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