Atelectasis in one lung ventilation: the good, the bad, and the ugly: a narrative review

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Background and Objective: One-lung ventilation (OLV) requires the ability to manage different clinical presentations of atelectasis. Good atelectasis is the one induced in the non-ventilated lung before the surgical incision to maximize exposition. Bad atelectasis needs to be avoided in the ventilated lung while minimizing volutrauma and barotrauma during surgery. Then, ugly atelectasis leading to post-operative pulmonary complications (PPCs) needs to be prevented in both lungs when delivering the patient to the post-operative ward. This review aims to highlight key points and advances in literature linked to a successful ventilatory management of OLV in thoracic surgery. Clinicians involved in the operative course of the thoracic patient should be aware of the implications related to this complex ventilatory method.

Methods: An extensive review of the literature through PubMed and anesthesiology textbooks was conducted using the keywords: thoracic anesthesia, OLV, atelectasis, and postoperative pulmonary complications. Publications before December 31st 2021, in French and in English, were considered.

Key Content and Findings: The technique of OLV has evolved tremendously within the last four decades. Recent findings about lung deflation, protective ventilation and strategies to manage atelectasis are discussed in this review,

Conclusions: Using complementary ventilatory strategies, the anesthesiologist can play a major role by facilitating the surgical act and decreasing PPCs following the use of OLV in thoracic surgery. This review should provide perspective on the evolution and advances in OLV to the clinicians involved with the thoracic surgery patient, while discussing potential interventions to optimize patient care.

Keywords: Atelectasis; one-lung ventilation (OLV); lung collapse; protective ventilation; video-assisted thoracic surgery (VATS); postoperative pulmonary complications (PPCs)

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Introduction

Rationale/background

The ways of conducting one-lung ventilation (OLV) in thoracic surgery have changed tremendously in the last four decades. Use of deleterious large tidal volumes (TVs) up to 14 mL/kg and fear of the potential hemodynamic impact of positive end-expiratory pressure (PEEP) were commonly seen in the thoracic anesthesia of the 80's (1-3). Among important changes, optimization of lung deflation techniques, implementation of protective ventilation strategies and recognition of factors precipitating lung injury revolutionized the practice of thoracic anesthesia. Consequently, physicians should be aware of the recent advances in literature to ensure the highest standards of care for the thoracic surgery patient. They should also be

Table 1 Summary of the research strategy

Item	Specification
Date of search	December 31st, 2021
Databases and other sources searched	PubMed
Search terms used	Thoracic anesthesia
	One lung ventilation
	Atelectasis
	Post-operative pulmonary complications
Timeframe	Before December 31st, 2021
Inclusion and exclusion criteria	Observational studies, literature reviews, randomized clinical trials, systematic reviews and meta-analyses were included
	Publications in English and French were considered
Selection process	The selection process was conducted by both authors and consensus was obtained by discussion in regard to which studies should be included

informed of certain research gaps concerning techniques like PEEP titration and use of alveolar recruitment maneuvers (ARM).

Objectives

This review aims to address the recent evidence in the management of atelectasis during OLV, as it remains one of the most common complications following induction of anesthesia (4). It is of particular interest as it can become the first step in a cascade of postoperative pulmonary complications (PPCs) (5). In this case, PPCs are defined as a composite of postoperative respiratory diagnoses [atelectasis, pneumonia, and acute respiratory distress syndrome (ARDS)] that share common pathophysiological mechanisms including pulmonary collapse and airway contamination (6). Ventilation strategies that have an impact on atelectasis during the three main periods of OLV are reviewed in this article:

(I) Good atelectasis is the one induced in the non-ventilated (or operative) lung following lung isolation to achieve lung collapse. It is needed for thoracic surgery and is essential for the realization of video-assisted thoracic surgery (VATS) and robotic-assisted thoracic surgery (RATS). The objective of lung isolation should be to obtain a complete lung collapse of rapid onset. Here, a recently published technique is described to ensure this objective.

(II) During OLV, the ventilated lung (non-operative) presents a restrictive pattern of ventilation resulting from compression by both the mediastinum in lateral decubitus and the abdominal content via the inferior hemidiaphragm (7). This compression, paired with other mechanisms can precipitate atelectasis. Causes, consequences, and management of this bad atelectasis such as protective ventilation are explored in this article.

(III) After completion of the surgery, two-lung ventilation should be carefully re-instituted. Management of ventilation at the end of OLV is covered as it remains crucial to prevent the occurrence of any postoperative ugly atelectasis which may be responsible for PPCs.

We present this article in accordance with the Narrative Review reporting checklist (available at https://ccts.amegroups.com/article/view/10.21037/ccts-21-26/rc).

Methods

Research selection

An extended review of the relevant literature through PubMed and anesthesiology textbooks was conducted using the keywords: thoracic anesthesia, OLV, atelectasis, and PPCs (*Table 1*). The following study designs were included in this review: observational studies, literature reviews, randomized clinical trials, systematic reviews and meta-analyses. Scientific publications before December 31st 2022, in English or French, were considered for this review. Publications were included based on the impact they had on the management of OLV.

Atelectasis: the good one

OLV represents an integral part of thoracic anesthesia especially for VATS and RATS. It is also a rare occasion in medicine where inducing atelectasis actually benefits the patient. Lung isolation with either a double-lumen endotracheal tube (DLT) or a bronchial blocker (BB) enables operative lung collapse or good atelectasis to facilitate surgical exposure of intra-thoracic structures. Ventilation of the surgical lung is interrupted by clamping the corresponding DLT lumen or by inflating the endobronchial balloon of the BB. A widespread practice amongst anesthesiologists during OLV is to open either the internal lumen of the BB or the bronchoscopy port of the DLT leading to the surgical lung to ambient air before pleural opening. The belief is that it will facilitate lung collapse by venting the lung and allowing subsequent egress of residual gas.

Over the years, many investigators published results on the efficacy of BB and DLT in the management of the OLV. A systematic review in 2014, showed that neither of the devices were superior in terms of time to achieve lung collapse (8). Most studies included in the review were of high heterogeneity and often comprised few patients. We would like to share the experience of our research program on lung collapse during OLV to address this lack in literature. Unlike other studies, our research group has obtained faster lung collapse using BB than DLT, especially when the internal channel of the BB was occluded (9,10). Based on those findings, we (11) demonstrated that a negative pressure develops in the non-ventilated surgical lung after OLV initiation and before pleural opening with both devices. This results in the entrainment of ambient air into the lung via the internal lumen of the BB or the non-ventilated lumen of the DLT if left open.

Recently, we published more results showing that the time to lung collapse could be improved if the surgical lung was excluded from communicating with ambient air before the pleura was opened (12). This study was designed with two groups and comprised only DLT. During OLV, in the control group, the DLT port leading to the surgical lung was left open before pleural opening, while it remained closed in the experimental group. Results showed that median time to lung collapse occurred faster in the closed group when compared to the open group {24 [20–37] *vs.* 54 [48–68] min, respectively; median difference, 30 min; 95% confidence interval (CI): 14 to 46; P=0.001}.

Therefore, rather than facilitating lung collapse in the control group, opening the bronchoscopy port of the surgical lung during closed-chest OLV allowed for ambient air entrainment. This resulted in re-nitrogenation of the lung and led to a higher residual gas volume with lower residual oxygen concentration in the lung at pleural opening. Such phenomenon lowers intra-alveolar oxygen concentration which decreases oxygen absorption by the pulmonary blood vessels and consequently reduces the speed of lung collapse. However, in the experimental group, preventing the surgical lung from communicating with ambient air before pleural opening resulted in lower residual gas volumes and a higher residual oxygen concentration inducing a faster lung collapse.

After lung resection, the remnant collapsed surgical lung should be re-expanded. It can be done with a second ventilatory circuit or with the anesthesia circuit (*Figure 1*) (13). Using the anesthesia circuit, the distal part of the DLT leading to the ventilated lung must be temporarily clamped to enable manual ventilation for the re-expansion of the surgical lung. This preferentially redirects the aerial flow to the collapsed surgical lung, while making sure not to fully re-expand it to avoid any forms of lung volutrauma or barotrauma (14). Manual OLV should be slow, progressive, and directed only on the surgical lung. Doing this prevents a severe diminution of venous return to the left heart since the ventilated lung is not exposed to an undesired high intra-alveolar pressure. Ideally, the inspiratory fraction of oxygen (FiO_2) should be less than 0.50 thus helping recovery of the alveolar frame for the next few hours. Following manual ventilation, two lungs mechanical ventilation may be resumed with PEEP and minimally tolerated FiO_2. TV should be adjusted following the amount of resected lung (e.g., a simple lobectomy equals approximately a 10–15% diminution of the TV).

The conclusion of this research program could change the paradigm of how lung collapse is optimized during OLV. The results allow the authors to recommend routine closure of the bronchoscopy port leading to the surgical lung during closed-chest OLV. Conscientious application of this technique is warranted to obtain the expected results.

Atelectasis: the bad one

More than 90% of patients develop a certain degree of

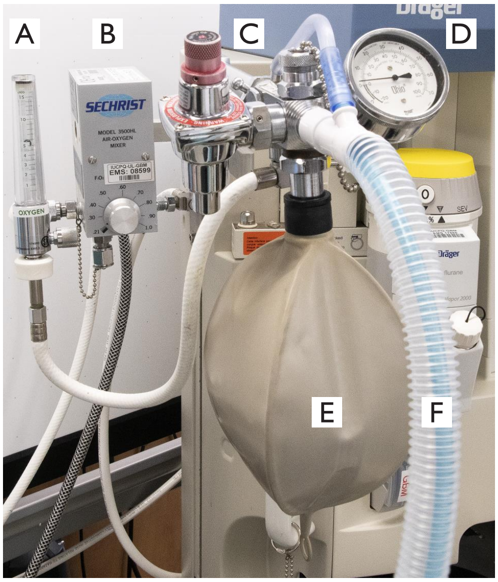


Figure 1 Second ventilatory circuit. After lung resection, the remnant collapsed surgical lung should be re-expanded. It can be done with the anesthesia circuit or with a second ventilatory circuit. The second ventilatory circuit can be a coaxial circuit (F) with a 2 liters bag (E) and must be equipped with a manometer (D) with pressure relief valve (C) to protect the lung from barotraumas. An oxygen blender (B) can be used alongside the flowmeter (A) to regulate the fraction of inspired oxygen administered to the non-ventilated lung. Permissions were obtained and figure was adapted from: Bussières J, Cournoyer C, Couture EJ. Use of a second ventilatory circuit when using a double-lumen endotracheal tube. *Can J Anaesth* 2020;67:1114-5.

atelectasis following induction of general anesthesia (15). Since peri-operative atelectasis can trigger the installation of PPCs, it should be understood and prevented accordingly (5,16). One of the major mechanisms that promote the formation of atelectasis in the anesthetized patient is extrinsic lung compression. The sole change of position from upright to supine can decrease functional residual capacity (FRC) by about 0.7 L because of the cephalad displacement of abdominal content exerting pressure on the diaphragm (17). Induction of anesthesia leads to relaxation of the diaphragm and intercostal muscles, further reducing FRC by up to 0.8 L, leaving only half the initial volumes of an average non-obese awake patient (18). This reduction in FRC induces closure of the small airways when it falls under the closing capacity.

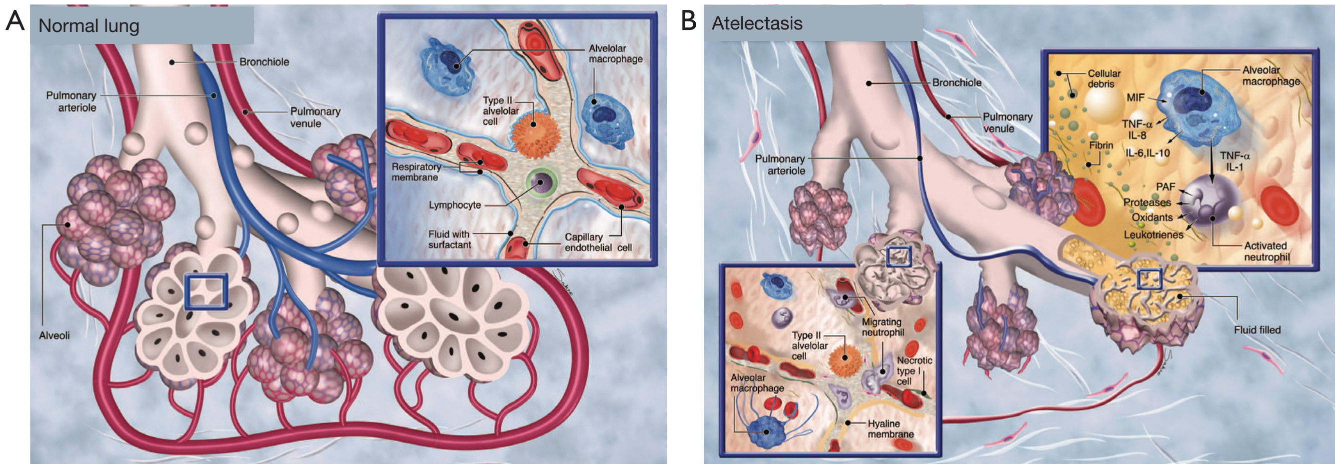
Resorption of alveolar gas is a second mechanism that can induce atelectasis (15). In the situation where small airways are occluded, pockets of gas distal to the occlusion will be slowly absorbed by the still perfused but non-ventilated alveoli, creating atelectasis. This may also happen in the case of intermittently closed airways where the ventilation/perfusion ratio is reduced. It must be kept in mind that the time it takes to absorb the remaining gas behind the occluded airway depends on the gas composition (19). A higher FiO_2 will accelerate the resorption of gas in these alveoli since oxygen has a faster uptake than nitrogen (20).

A third mechanism involving the loss of surfactant has been proposed since mechanical ventilation with high TVs in animals can induce abnormalities in the alveolar surfactant (21). However, this mechanism may not be as contributory as compression and resorption atelectasis in OLV. Altogether, these mechanisms help to explain how atelectasis is generated during general anesthesia, creating an inflammatory reaction of the alveolus. The physiopathology of this inflammatory reaction is summarized in *Figure 2*.

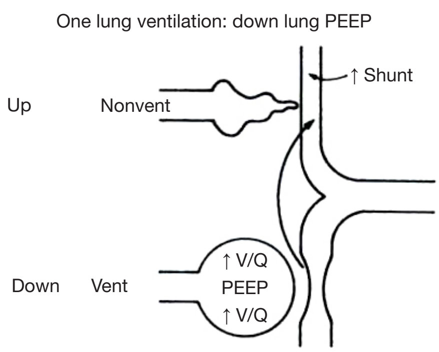
Clinical interventions to prevent atelectasis have been proposed for over 50 years in anesthesiology. In 1963, Bendixen *et al.* suggested that large TV and increased resistance to expiration could be means to counteract atelectasis (22). It was not until 1969 that the first clinical use of PEEP (continuous positive-pressure breathing at that time) was described in the literature (23). In 1982, the use of large TV volumes during OLV was still supported as impressive TVs of 14 mL/kg in actual body weight without any PEEP were recommended (1). Physicians feared that PEEP in OLV would have a harmful effect by diverting pulmonary flow into the non-ventilated lung thereby increasing the shunt (*Figure 3*) (2,3,24). This outdated belief was perpetuated in thoracic anesthesia textbooks until 2003, at which point the concept of protective ventilation started to gain recognition (25).

Protective ventilation

Mechanical ventilation by means of positive pressure has been found to cause lung injuries in general anesthesia patients. A combination of multiple mechanisms can explain the incidence of these injuries such as high TV causing volutrauma; high airway pressure causing barotrauma; cyclic alveolar closing and opening (atelectrauma) and a high FiO_2 causing systemic inflammation (biotrauma) (26-30). Lung injuries have been found in up to 33% of patients undergoing major surgery under general anesthesia with increases in the risk of in-hospital stay, 7-day and 30-day



Figures 2 Biologic events associated with atelectasis. In normal lungs (A), ventilation is associated with low alveolar and capillary stress. In context of atelectasis (B), alveolar collapse leads to accumulation of inflammatory mediators which causes epithelial injury. Concomitant compression of blood capillaries may be also be traumatic because of flow-induced disruption of the microvascular endothelium. Permissions were obtained from: Duggan M, Kavanagh BP. Pulmonary atelectasis: a pathogenic perioperative entity. *Anesthesiology* 2005;102:838-54. MIF, migration inhibitory factor; TNF, tumor necrosis factor; IL, interleukin; PAF, platelet-activating factor.

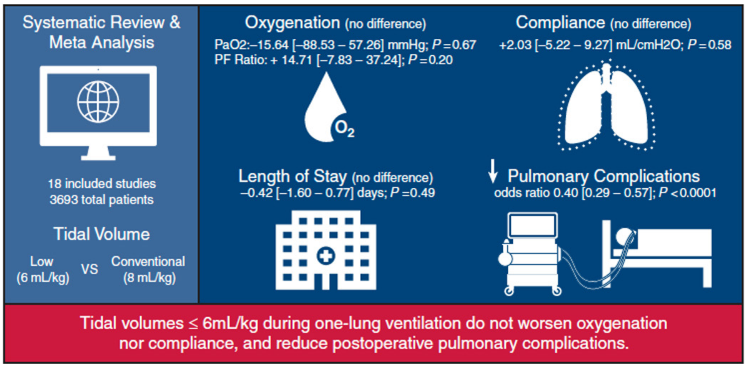


Figures 3 "Out dated belief" of the effect of PEEP on the dependent lung during OLV. The figure illustrates the belief that PEEP in OLV would have a harmful effect by diverting pulmonary flow into the non-ventilated lung thereby increasing the shunt during OLV. However, the clinical relevance of such an increase of shunt flow through the non-ventilated lung is not as important as previously believed. Permissions were obtained and adapted from: Triantafillou AN, Benumof JL, Lecamwasam HS. Chapter 4: Physiology of the Lateral Decubitus Position, the Open Chest, and One Lung Ventilation. In: Thoracic Anesthesia. Kaplan JS, Slinger PD. editors. 3rd edition. Philadelphia: Churchill Livingstone, 2003:87 (Fig 4-17). PEEP, positive end-expiratory pressure; OLV, one-lung ventilation; V/Q, ventilation/perfusion.

mortality (31-34).

Thoracic surgery patients necessitating OLV are at high risk of lung injury, as all these mechanisms can affect simultaneously a single ventilated lung. In fact, this single lung is tasked with the patient's whole respiratory load during the major part of the surgery while being exposed to a high FiO_2 and the deleterious effects of mechanical ventilation. Moreover, direct injury from surgical manipulations followed by a necessary re-expansion of the non-ventilated lung results in a systemic inflammatory cascade (28,29). The lateral decubitus position required for most thoracic surgeries also induces a reduction in chest wall compliance as the ventilated lung experiences the weight of both the mediastinum and abdomen. This positioning can further contribute to atelectrauma by reducing FRC (7,26). Therefore, patients undergoing thoracic surgery represent quite a unique population with physiologic and clinical peculiarities that complexify the application of conventional lung-protective ventilation techniques (35).

The concept of protective ventilation was first described for ARDS patients in 1998 and is still part of the actual intensive care guidelines (36,37). This strategy of ventilation gave interesting results in ventilating severely pathological ARDS lungs in the intensive care units. Patients with ARDS present with stiff non-compliant lungs and impaired gas exchanges due to filling of the alveolus with inflammatory liquid (38). Even if patients requiring OLV have relatively healthy lungs, a parallel can be drawn between the two clinical situations. Both cases could be compared to a "baby



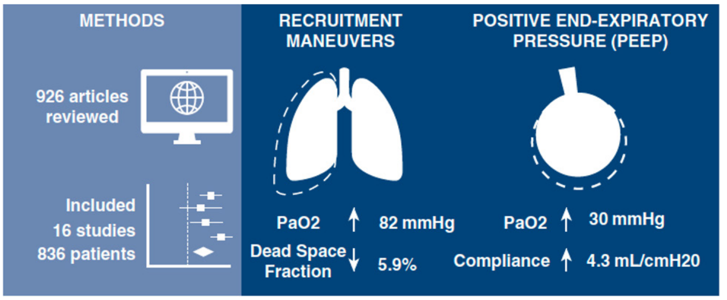
Figures 4 Effects of tidal volume during one-lung ventilation. Despite concerns of intraoperative hypoventilation, the evidence suggests no worsening of oxygenation or compliance with low tidal volumes of 6 mL/kg. A low tidal volume ventilation strategy during one-lung ventilation was associated with a significant reduction in postoperative pulmonary complications. Permissions were obtained from: Peel JK, Funk DJ, Slinger P, et al. Tidal volume during 1-lung ventilation: A systematic review and meta-analysis. *J Thorac Cardiovasc Surg* 2022;163:1573-1585.e1. PaO_2, partial pressure of oxygen; PF, arterial oxygen tension to fractional intake of oxygen ratio.

lung" as the total lung surface participating in gas exchanges is greatly reduced and may be submitted to an excessive mechanical stress from ventilation (39). In fact, the protective ventilation strategy of ARDS was quicky adopted in anesthesia to minimize the pulmonary effect of ventilation on healthy lungs in the operating room. Protective ventilation was first tested and adopted during abdominal surgery at the beginning of 2000 (40). It took a few more years to accept this practice in thoracic surgery. Changes occurred mainly after the publication by Michelet *et al.* presenting favorable results after esophagectomy (41). Low TV of 5 mL/kg with a PEEP of 5 cmH_2O was shown to improve lung function and decreased both the proinflammatory systemic response and time to extubation when compared to a TV of 9 mL/kg without PEEP (41). Those results triggered a change of practice towards the use of protective ventilation in the operating room, notably in OLV.

Protective ventilation in OLV includes two main modalities: low TV, the use of PEEP and according to certain recommendations, ARM (42). A majority of published studies recommend TV during OLV to be from 4 to 6 mL/kg of ideal body weight, based on the ARDS net formula (43) or the body mass index (BMI) (44). The objective in using low TV is to prevent PPCs by minimizing volutrauma, barotrauma, and biotrauma (45). Application of PEEP during OLV helps to restore functional FRC, therefore avoiding closure of the small airways. This also stabilizes the alveolus by avoiding cyclic opening and closure, which decreases shear stress and prevents alveolar collapse leading to atelectrauma (15).

PEEP needs to be titrated, as too little is ineffective, and too much increases the shunt through the non-ventilated lung. Ideally, the level of PEEP should be selected by challenging either the dynamic compliance (32) or the driving pressure (plateau pressure minus PEEP) of the lung (46). For instance, the dynamic compliance of the lung is defined as the change in TV divided by the change in airway pressure. Dynamic compliance can be measured during mechanical ventilation and mainly depends on the compliance of the chest wall, lung tissue and airway resistance. A decremental or incremental titration of PEEP helps determining the highest dynamic compliance after lung recruitment, improving oxygenation and lung mechanics (47). Also, titration of PEEP to produce the lowest driving pressure showed reduction in postoperative pneumonia or ARDS in a recent study on OLV (P=0.028, odds ratio 0.42; 95% CI: 0.19 to 0.92) (46). Beyond these benefits, the effect of an individualized PEEP on patient outcomes remains mostly unknown and warrants further clinical studies. Additionally, ARM aim to reverse intraoperative atelectasis using brief and controlled increases in airway pressure with the expansion of the lung (48,49).

Major randomized controlled trials comparing conventional and protective ventilation during OLV have been published in the last two decades. Two recent and well-designed systematic reviews and meta-analyses evaluated ventilatory strategies during OLV (26,50). The conclusions of this extensive work are summarized in *Figures 4,5*. The first publication (50) evaluated low *vs.* conventional TV during OLV (5.6±0.8 *vs.* 8.1±3.1 mL/kg). Despite concerns



Figures 5 Effect of positive end-expiratory pressure and recruitment maneuvers during one-lung ventilation. Recruitment maneuvers and positive end-expiratory pressure were associated with significant improvements in PaO_2 during OLV. However, future studies with patient-important clinical outcomes are needed to elucidate whether recruitment maneuvers and PEEP during OLV are truly lung-protective. Permissions were obtained from: Peel JK, Funk DJ, Slinger P, et al. Positive end-expiratory pressure and recruitment maneuvers during one-lung ventilation: A systematic review and meta-analysis. *J Thorac Cardiovasc Surg* 2020;160:1112-1122.e3. PaO_2, partial pressure of oxygen; OLV, one-lung ventilation.

of intraoperative hypoventilation, the evidence suggested no worsening of oxygenation or pulmonary compliance low TV. Patients in the low TV group showed a significant reduction in PPC [pooled odds ratio, 0.40 (0.29–0.57); P<0.0001]. This evidence supports lung protective ventilation strategies and the necessity of individualizing TV based on ideal weight for each patient undergoing OLV.

The other systematic review and meta-analysis from the same group of authors (26) assessed the existing evidence regarding the use of PEEP and ARM during lung-protective ventilation in OLV. PEEP and ARM were associated with significant improvements in partial pressure of oxygen (PaO_2) during OLV, suggesting that recruitment maneuvers improve PaO_2. However, their optimal use needs to be further investigated as only physiological benefits have been reported with PEEP titration and ARM in OLV (26). A possible explanation for the lack of clinical benefits may be the context in which PEEP is studied. When titrated as a sole parameter of ventilation, benefits may only be physiological, but when titrated concomitantly with airway plateau pressures to obtain the lowest driving pressure, it could benefit clinical outcomes. As mentioned previously, driving pressure which takes PEEP into account, may become a valid predictor of PPCs in the upcoming literature (32).

Recently, interrogations about potential deleterious effects of ARM during OLV for thoracic surgery were raised. Data suggests a potentially harmful effect of recruitment: immediate physiologic parameters may be improved, but this transitory effect may come at the expense of delayed lung inflammation/injury (49). Two major multicentric European studies, Prothor, and iProve-OLV, which were launched a few years ago and are still ongoing, are examining the use of protective ventilation during OLV (51,52). Prothor aims to study the impact of a high PEEP with ARM *vs.* low PEEP without ARM, while iProve-OLV aims to study ARM with individualized PEEP *vs.* conventional protective ventilation. These studies should bring interesting data regarding the clinical value of ARM as a strategy of ventilation during OLV. In the meantime, the relevance of ARM should be adapted to each clinical situation. Finally, we propose an overview of the desaturation management during OLV that includes both PEEP and ARM as strategies to optimize oxygenation (53) (*Table 2*).

Atelectasis: "the ugly one"

PPCs are always dreaded in the postoperative course of lung surgery. They need to be prevented and treated aggressively as they are reported in as much as 7% to 49% of cases with an associated mortality ranging between 2% to 12% (54). Despite continuous improvements in the operating room and post-operative care, they continue to pose a serious threat to successful outcomes. The persistence of atelectasis from the perioperative to the postoperative setting can represent the starting point for a deleterious cascade of PPCs (16). In this third part, we will detail the occurrence of this ugly atelectasis when looking at surgical approaches to the thoracic cavity and oxygen concentration used during maintenance and emergence of anesthesia. Of note, ugly atelectasis may also originate from airway

Table 2 Management of desaturation during one lung ventilation

General maneuvers
FiO_2 of 100%
Assessment of the pulmonary isolation
Spirometry
Expiratory volumes
Seal of the bronchial cuff
Video-bronchoscopy
Isolation device positioning
Suctioning of secretions if necessary
Cardiac output
Vasopressors, inotropes
Lower anesthetic gas concentration
Maneuvers on the dependent ventilated lung
PEEP titration
Minute ventilation adjustment
Recruitment maneuvers
Maneuvers on the non-dependent surgical lung
Oxygenation
O_2 insufflation
CPAP 3–5–10 cmH_2O
Intermittent ventilation
Pulmonary artery clamping (only in extreme cases)

Reference adapted from: Cournoyer C, Bussieres J. Chapter 23: Respiratory System and Anesthesia. In: Beaulieu P. editor. Handbook of Anesthesia and Intensive Care. 6th edition. Montreal: Montréal University Press, 2020;456-75. FiO_2, fraction of inspired oxygen; PEEP, positive end-expiratory pressure; CPAP, continuous positive airway pressure.

obstruction (secretions) and altered respiratory mechanics often aggravated by a sub-optimal analgesia. Analgesic modalities will be discussed in a specific article of this series "Recent Advances in Perioperative Care in Thoracic Surgery and Anesthesia" (Clairoux A, Issa R, Bélanger MÈ, *et al.* Perioperative pain management for thoracic surgery: a narrative review of the literature. *Curr Chall Thorac Surg* 2023;5:36).

Surgical approaches

The development of new technologies, like VATS, to perform lung resection helped to reduce the incidence of PPCs. When compared to thoracotomy, VATS was associated with earlier mobilization, better preservation of pulmonary function, and shorter length-of-stay (55-57). A large propensity-matched study from the European Society of Thoracic Surgeons database consisting of 28,771 patients showed a significant reduction in total postoperative complications, major cardiopulmonary complications, atelectasis requiring bronchoscopy, and wound infection in favor of VATS (58). The clinical benefits of a minimally invasive approach are particularly evident in high-risk patients with poor predicted postoperative lung function (59). Another advantage of VATS against the open thoracotomy is also the minimal intensity and duration of postoperative pain (56).

One of the most recent advances in lung surgery is the non-intubated (awake) VATS (NIVATS). A recent propensity score-matched analysis comparing NIVATS and intubated VATS showed a reduction in operative and anesthesia times with a faster and more stable recovery in the postoperative care unit. However, in an immediate postoperative setting, chest radiography showed higher rates of pulmonary atelectasis in the NIVATS group than in the standard VATS group (16.0% *vs.* 2.5%, $P<0.001$). A follow-up of the radiological evolution through time would have been interesting as the NIVATS group may have had a faster respiratory recovery (60). Further evaluation with multi-centric, prospective, and large-cohort clinical trials is required to evaluate the different effects of this new surgical and anesthetic technique.

Oxygen concentration

Supplemental oxygen is mandatory in the context of general anesthesia. A meticulous preoxygenation is done before induction to achieve an oxygen reserve in case of an unexpected difficult airway and to provide time for the complexity of DLT insertion and positioning. Following induction, an FiO_2 of 1.0 is used before the beginning of OLV to promote absorption atelectasis and increase the quality of lung deflation, facilitating surgical acts. The increase in FiO_2 also serves to counteract the consequences of the shunt caused by both atelectasis in the dependent lung and blood flow perfusing the non-dependent lung. Despite those advantages, the non-judicious use of supplemental oxygen may prove to be detrimental for the thoracic surgery patient, and the anesthesiologist should try to decrease progressively the FiO_2. The use of a higher FiO_2 during

OLV may indeed be associated with an increased incidence of PPCs by means of direct pulmonary toxicity (61). The now recognized toxicity of oxygen could therefore play a role in the postoperative course of a patients who undergo OLV (62).

Moreover, the use of a high FiO_2 during induction, maintenance of OLV, and emergence is a major cause of anesthesia-induced atelectasis, which is secondary to alveolar gas resorption (63,64). An interesting study, although not on OLV, showed that lung recruitment with a FiO_2 of 1.0 during two lung ventilation resulted in the rapid reappearance of atelectasis when compared to a FiO_2 of 0.4 because of absorption atelectasis (65). This demonstration could theoretically be applied as well in OLV. Using the lowest possible intra-operative FiO_2 raises the inspired concentration of nitrogen and may help to minimize the recurrence of atelectasis. Thus, ARMs must be followed by ventilation with moderate FiO_2 (19). In our experience, an FiO_2 of 0.40–0.50 during OLV should suffice if the ventilated lung is not atelectatic and if the patient medical condition allows it. Supplemental oxygenation remains an essential tool in the management of the anesthetized thoracic patient, but it must be kept in mind that even this daily essential can become harmful in excess.

Limitations

Although multiple authors have researched on the optimal management in OLV, there remains a need for solid randomized controlled trials examining key features like protective ventilation and recruitment maneuvers in OLV. Our review is therefore limited by our access to such studies and the need to gather information from smaller trials. Those large scale, multi-centric studies evaluating ventilatory strategies like Prothor and iProve-OLV will follow in the next years (51,52). In the future, studies should try to evaluate separately the modalities of protective ventilation to assess the impact of each of them. This could lead to an individualization of ventilatory parameters in OLV benefiting the thoracic surgery patient.

Conclusions

In summary, OLV represents a ventilatory challenge for both the thoracic surgery patient and anesthesiologist. In such conditions, small details may matter more than we think. Altogether FiO_2, TV, PEEP, and possibly the use of ARMs should be meticulously optimized for each patient. As of today, it remains hard to see if these individual components benefit the patient, however, studies tend to go in the same direction for each one of them. All things considered, the management of OLV during thoracic surgery has changed tremendously in the last 20 years. We hope this review gave you insights on how to optimize good atelectasis for an easier surgical resection, to preserve the ventilated lung from bad atelectasis leading to desaturation, and to minimize the installation of ugly atelectasis hereby preventing postoperative PPCs. The main objective of the anesthetic management should be to keep the lung open and to deliver the patient to the postoperative ward with the least amount of atelectasis (63).

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