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REVIEW

Intraoperative mechanical ventilation: state of the art

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ABSTRACT

Mechanical ventilation is a cornerstone of the intraoperative management of the surgical patient and is still mandatory in several surgical procedures. In the last decades, research focused on preventing postoperative pulmonary complications (PPCs), both improving risk stratification through the use of predictive scores and protecting the lung adopting so-called protective ventilation strategies. The aim of this review was to give an up-to-date overview of the currently suggested intraoperative ventilation strategies, along with their pathophysiologic rationale, with a focus on challenging conditions, such as obesity, one-lung ventilation and cardiopulmonary bypass. While anesthesia and mechanical ventilation are becoming increasingly safe practices, the contribution to surgical mortality attributable to postoperative lung injury is not negligible: for these reasons, the prevention of PPCs, including the use of protective mechanical ventilation is mandatory. Mechanical ventilation should be optimized providing an adequate respiratory support while minimizing unwanted negative effects. Due to the high number of surgical procedures performed daily, the impact on patients' health and healthcare costs can be relevant, even when new strategies result in an apparently small improvement of outcome. A protective intraoperative ventilation should include a low tidal volume of 6-8 mL/kg of predicted body weight, plateau pressures ideally below 16 cmH_2O, the lowest possible driving pressure, moderate-low PEEP levels except in obese patients, laparoscopy and long surgical procedures that might benefit of a slightly higher PEEP. The work of the anesthesiologist should start with a careful preoperative visit to assess the risk, and a close postoperative monitoring.

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Mechanical ventilation (MV) is a cornerstone of the intraoperative management of the surgical patient and, despite the increasing use of locoregional anesthesia techniques, is still mandatory in several surgical procedures. Moreover, several surgical and patient-related conditions pose specific challenges in the management of ventilatory settings, such as obesity, laparoscopy, Trendelemburg position and high-risk procedures such as cardiothoracic surgery. Recently, the improvements in scientific knowledge, the innovations in biomedical technology and the advancements in surgical techniques have led to a relevant decrease in perioperative mortality, that however remains elevated, around 4%.[1] Despite these encouraging results, the surgical population is increasingly elderly and with several comorbidities: mortality and postoperative complications are still clinically relevant.[1,2] In particular, postoperative pulmonary complications (PPCs) have a negative impact on patients' outcome, increasing surgery-associated mortality and hospital length of stay; this also applies to mild PPCs such as postoperative desaturation.[3,4] Mechanical ventilation can be

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harmful even in healthy lung, triggering pathophysiological mechanisms leading to ventilator-induced lung injury (VILI):[5] in the last decades research focused on preventing PPCs, both improving risk stratification through the use of predictive scores and protecting the lung adopting so-called protective ventilation strategies.[6-8] This concept has been borrowed from the Intensive Care Unit (ICU) setting, and it is aimed at preserving the lungs, while ensuring an adequate gas exchange. Recent randomized controlled trials (RCT) evaluated the role of a reduction of tidal volume (Vt), increase of positive end-expiratory pressure (PEEP) and the routine use of recruitment manoeuvers (RMs) alone or combined as a bundle of interventions.[9] The aim of this narrative review was to give an up-to-date overview of the intraoperative ventilation strategies, along with their pathophysiologic rationale, with a focus on challenging conditions, such as obesity, one-lung ventilation and cardiopulmonary bypass.

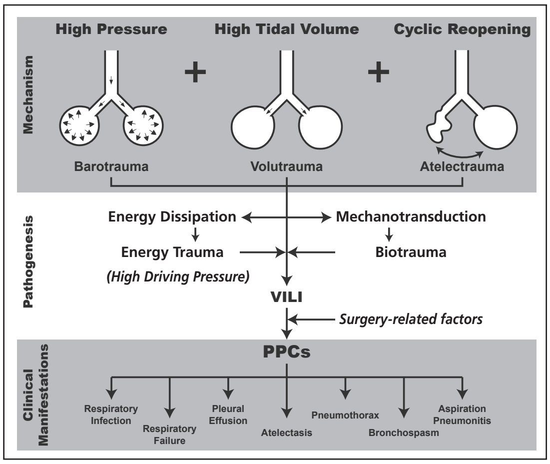

Figure 1.—Mechanisms underlying ventilator-induced lung injury (VILI), contributing, along with surgery- and patient-related factors, to the development of postoperative pulmonary complications (PPCs).

Pathophysiology of ventilation injury

Both experimental [10] and clinical [11] studies show that mechanical ventilation has the potential to aggravate [12] or even initiate [13] lung injury. The main determinants of VILI comprise high pressures, high tidal volumes, and cyclic opening and closing of respiratory units. These features harm the epithelial and endothelial compartments of the alveolo-capillary membrane and the extracellular matrix (ECM) [14] inducing mechanotransduction, namely the translation of physical stimuli in biochemical signals and inflammatory mediators.[15] Figure 1 illustrates these mechanisms and the PPCs as defined by a recent joint statement of the ESA and ESICM.[16]

The ECM plays an important role in the development of ventilation injury. ECM is composed of proteoglycans, insoluble fibrous collagen, elastin and hyaluronic acid. High Vt [14] induce ECM damage, interstitial oedema and the activation of matrix metalloproteinases, which further contribute to damage the ECM. The fragmentation of the ECM itself contributes to trigger the inflammatory process,[17, 18] and fluid overload can contribute to worsen the damage.[19] These findings suggest that, in the early stages, MV initiates a process making healthy lung tissue more susceptible to further injury.

Moreover, endothelial dysfunction causes increased vessel leak due to cytoskeleton rearrangements, activating the rho-kinase pathway, and this has been proposed as a target for pharmacological preventive strategies using statins [20] or adrenomedullin.[21] Both low [22] and high [23] lung volumes can increase the permeability of the epithelial compartment, causing the upregulation of inflammatory pathways. Rac1 regulates epithelial structure and function inducing cytoskeletal remodeling and contributing to platelet activation, therefore Rac1 inhibitors could have a role in reducing stretch-induced increased permeability.[24] Evidence concerning pharmacological measures to prevent VILI is limited to experimental studies, therefore optimization of MV using protective strategies is so far the cornerstone of prevention of VILI and PPCs.

Mechanical ventilation in the surgical patient

Each year, over 230 million surgical procedures are performed both in elective and emergency settings.[25] While anesthesia and MV are becoming increasingly safe practices, the contribution to surgical mortality attributable to postoperative lung injury is estimated around 19%:[3] for these reasons, prevention of PPCs is mandatory. MV should be titrated within a therapeutic window, providing an adequate respiratory support minimizing its negative effects, and tailored case-by-case.[6] Due to the high number of surgical procedures performed, the impact on patients' health and healthcare costs is not negligible, even when new strategies result in an apparently small improvement of outcome.[26, 27] Good clinical practice should start at the preoperative visit, followed by a thoughtful intraoperative management and an accurate postoperative follow-up and monitoring.[28] The goal of the patient management in the entire perioperative period should be an improvement of the overall clinical outcome, not limited to a mere improvement of a single physiological parameter such as intraoperative oxygenation or atelectasis reversal.

Ventilation modes

In the last decades anesthesia machines become increasingly sophisticated, offering not only classical volume- or pressure-controlled ventilation modes (VCV and PCV) but also assisted/controlled and purely assisted ventilation modes, such as pressure support ventilation (PSV), as well as dual-controlled modes.[29] Several studies compared VCV versus PCV ventilation (Table I),[30-38] without showing clinically relevant differences. Dual-controlled

TABLE I.—*Randomized controlled trials comparing VCV and PCV during general anesthesia.*

Study	N.	Population	Procedures	Findings
Oğurlu *et al.*[30]	60	Women ASA I-II	Laparoscopic gynecologic surgery	No differences in: operating, pneumoperitoneum and anaesthesia duration, hemodynamics, minute ventilation, gas exchange, operating conditions as reported by the surgeon. With PCV: lower peak and plateau pressure, lower resistance, higher dynamic compliance.
Jeon *et al.*[31]	60	Women ASA I-II	Laparoscopic gynecologic surgery	No differences in: pneumoperitoneum duration, hemodynamics, gas exchange.
Kim *et al.*[32]	34	Children ASA I-II	Laparoscopic appendectomy	No differences in: hemodynamics, gas exchange. With PCV: higher mean airway pressure, higher dynamic compliance.
Tyagi *et al.*[33]	42	ASA I-II BMI<30 hg/m^2	Laparoscopic cholecystectomy	No overall differences in: gas exchange, hemodynamics. At 5 minutes after intubation: no differences in peak and mean airway pressure, higher dynamic compliance with PCV. From 10 to 30 minutes after the start of surgery: with PCV, lower peak pressure and higher mean airway pressure. No differences in dynamic compliance.
Gupta *et al.*[34]	102	ASA I-II BMI 30-40 kg/ m^2	Laparoscopic cholecystectomy	No differences in: operating, pneumoperitoneum and anaesthesia duration, hemodynamics, intra-abdominal pressure.
Jo *et al.*[35]	40	ASA I-II	Lumbar spine surgery	No differences in: operating and anaesthesia duration, hemodynamics, gas exchange, minute ventilation, mean airwair pressure.
Aydin *et al.*[36]	70	ASA I-II	Laparoscopic cholecystectomy	No differences in: operating, pneumoperitoneum, anaesthesia and emergence duration, hemodynamics, dynamic compliance, oxygenation index.
Lian *et al.*[37]	26	Women ASA I-II	Laparoscopic gynecologic surgery	No differences in: operating, pneumoperitoneum and anaesthesia duration, hemodynamics, gas exchange, dynamic compliance, percent changes of alveolar dead space/tidal volume ratio.
Liao *et al.*[38]	52	Women ASA I-II	Laparoscopic gynecologic surgery	No differences in: pneumoperitoneum duration, hemodynamics, ventilatory parameters, gas exchange, post-operative course.

VCV: volume controlled ventilation; PCV: pressure controlled ventilation; ASA: American Society of Anesthesiologists physical status class; BMI: Body Mass Index.

ventilation modes are available under different brand names: VCV with autoflow, PCV with volume guaranteed or pressure-regulated VCV. All these ventilation modes deliver a decelerating inspiratory flow, adjusting the inspiratory pressure breath by breath to maintain the Vt close to a target value. These modes are rapidly gaining popularity because they can guarantee minute ventilation, like in VCV, even when the respiratory system compliance changes during the surgical intervention, e.g. as occurs when pneumoperitoneum is induced, while avoiding elevated peak pressures thanks to the decelerating flow, as occurs during PCV. Whether this has positive consequences on the clinical outcome remains to be determined. PSV, that can be used in patients undergoing minor surgery or in patients deeply sedated after loco-regional anesthesia or while emerging from general anesthesia, delivers a higher pressure when an inspiratory effort is detected.

In conclusion, no data is available showing clear benefits of one ventilation mode over the others, therefore the choice should be based on the clinician's experience, considering that conventional PCV provides poor control on the minute ventilation.

Protective mechanical ventilation

The demonstration that VILI can also occur in healthy lungs [12, 39] gave a strong drive to research towards the development of lung-protective mechanical ventilation techniques in the operating room, deriving concepts from the advances achieved in the ICU, where the reduction of Vt in acute respiratory distress syndrome (ARDS) patients lead to a decreased mortality.[40] The definition of "intraoperative protective ventilation" is not yet unanimous: while consensus exists concerning the use of low tidal volumes,[9] the role of high PEEP levels and RMs is more controversial, as discussed in the following paragraphs.

Role of tidal volume

Low Vt should be applied in all patients undergoing mechanical ventilation for surgery. Lung dimensions are not affected by the patient's nutritional status: the Vt should always be titrated based on the predicted body weight (PBW), rather than on the actual body weight.[6, 9] This is of crucial relevance in obese patients, where the high discrepancy between predicted and actual weight could lead to a harmful over-estimation of the required Vt. PBW can be calculated easily with on-line tools and simplified formulas, and is a function of the patient's height and sex. The linear relationship between lung weight and patient's height has also been confirmed in a recent computed tomography study on healthy subjects.[41] Several RCTs performed in differ-

TABLE II.—*Randomized controlled trials comparing conventional versus protective ventilation during general anesthesia.*

Study	N.	Surgical Procedures	Tidal volume (intervention *vs.* control, mL/kg PBW)	PEEP (intervention *vs.* control, cmH_2O)	Findings
Futier *et al.*[45]	400	Abdominal	6-8 *vs.* 10-12	6-8 *vs.* 0	Reduction of PPCs with protective ventilation
Severgnini *et al.*[46]	55	Abdominal	7 *vs.* 9	10 *vs.* 0	Improved pulmonary function with protective ventilation
Shen *et al.*[44]	101	Thoracic	5 *vs.* 8	5 *vs.* 0	Reduction of PPCs with protective ventilation
Sundar *et al.*[43]	149	Cardiac	6 *vs.* 10	Titrated on the ARDSnetwork table	Reduction of re-intubation rate with protective ventilation
Ge *et al.*[47]	60	Spinal	6 *vs.* 10-12	10 *vs.* 0	Reduction of PPCs with protective ventilation
PROVHILO[48]	894	Abdominal	8 *vs.* 8	12 *vs.* 0-2	No difference between higher vs lower PEEP in PPCs, but higher incidence of intraoperative hypotension

PBW: predicted body weight; PEEP: positive end-expiratory pressure; PPCs: postoperative pulmonary complications.

ent settings, including cardiac,[42, 43] thoracic [44] and abdominal [45, 46] surgery have shown that a reduction of tidal volume to 6-8 mL/kg PBW improve the postoperative outcome,[9] including a reduction of the incidence of PPCs and healthcare costs as illustrated in Table II.[43-48] A recent individual data meta-analysis on more than 2000 patients included in 15 RCTs observed a dose-response relationship between tidal volume and the development of PPCs:[49] the lower the Vt, the lower the incidence of PPCs. Extremely low tidal volumes are difficult to implement in clinical practice: there is consensus that 6-8 mL/kg PBW represent a reasonable compromise between lung protection and adequate gas exchange in surgical patient, and that respiratory rate should be titrated to achieve an end-tidal carbon dioxide tension between 35 and 45 mmHg.[9]

Role of PEEP

The use of PEEP during general anesthesia has been for long time advocated based on physiological arguments.[50] Several studies have shown that a level of at least 10 cm H_2O PEEP, especially when is preceded by a recruitment maneuver, is required to keep the lung open during MV.[51] Studies have shown that a PEEP around 10 cm H_2O is required to reduce intraoperative atelectasis,[52] improve compliance [53] and maintain the physiologic end-expiratory lung volume during general anesthesia in both non-obese and obese patients.[54] Most of the RCTs on protective ventilation comprised a bundle of intervention in which the use of higher PEEP levels with or without periodic recruitment maneuvers was combined with a reduction of Vt, making difficult to discriminate between the benefits attributable to each factor.[9, 55]

In a large RCT, the use of a fixed higher PEEP level compared to low PEEP failed to show clinical benefits in terms of reduction of the incidence of PPCs, and was associated with higher hemodynamic impairment.[48] In an individual patient meta-analysis, higher PEEP was not associated with a reduction of incidence of PPCs,[49] while in a large retrospective study low-moderate PEEP levels were associated with the lowest incidence of PPCs.[56] Moreover, it was shown that a PEEP increase can even be detrimental, if it is associated with a worsening of lung compliance, despite the benefit on gas exchange.[57] Nonetheless, higher PEEP levels could be necessary in specific sub-populations of patients, and trials are ongoing trying to clarify whether individualized PEEP titration [58] can improve outcome.

In conclusion, based on the current evidence, the routine use of higher PEEP levels cannot be recommended as a standard measure for all patients,[59] and low-moderate levels should be preferred.

Role of recruitment maneuvers

Recruitment maneuvers are procedures aimed at restoring lung aeration through the increase of transpulmonary pressure, and are often suggested in conjunction with higher PEEP levels:[60] in this perspective, RMs are used to obtain recruitment and PEEP to maintain it. Nonetheless, the pressure needed to open poorly aerated regions of the lung, can be sufficient to cause overdistension of normally aerated regions. These maneuvers can be considered a rescue maneuver to overcome an intraoperative oxygenation impairment, or can be routinely performed as a preventive measure.

There are different methods to perform RMs intraoperatively, including manual squeezing of the anesthesia balloon or stepwise changes in PEEP, Vt and/or inspiratory pressure. A commonly used method is the "bag squeezing" manoeuver, which consists in the delivery of a higher airway pressure, with the ventilator switched in manual mode and the adjustable pressure limiting valve set to 30-40 cm H_2O. This technique has several pitfalls, in particular the inaccuracy of the manual squeezing in maintaining a fixed pressure, the abrupt change in pressure, and the loss of pressure immediately after the maneuver: in most ventilators when switching back to the automated mechanical ventilation mode, a transient loss of pressure in the respiratory circuit occurs.[9, 29]

A ventilator-based cycling maneuver is performed progressively increasing PEEP level until a plateau pressure of 30-40 cm H_2O is reached, then slowly decreasing it until the final desired PEEP level, either returning to the basal value or titrating PEEP the best compliance of the respiratory system. Similarly, stepwise Vt changes are performed gradually increasing tidal volume in VCV or inspiratory pressure in PCV to achieve a plateau pressure of 30-40 cm H_2O, and then decreased to the best PEEP.[29] Moreover, it is known from studies in the critically ill patients that obese patients might require higher pressures, possibly up to 60 cm H_2O.[61]

Undoubtedly useful as a rescue measure, the routine preventive use of RMs has been often proposed but limited evidence supports its use. If the clinician opts for the use RMs, despite the lack of evidence in this field, there is a strong pathophysiological rationale suggesting that ventilator-based maneuvers should be preferred to the conventional bag-squeezing.

Role of driving pressure and energy load

Driving pressure (P_{driv}) is the difference between plateau pressure and PEEP (Pplat-PEEP). The precise measurement of plateau pressure implies a prolonged inspiratory hold, which is not feasible in most operating room ventilators. However, an acceptable approximation can be obtained measuring the airway pressure during semi-static conditions of zero or minimal flow, setting a brief end-inspiratory pause in VCV. The P_{driv}, as measured with the ventilator, reflects the compliance of the respiratory system, which is itself related to the end-expiratory volume of healthy lungs. Recently, higher P_{driv} were associated with mortality in ARDS;[62] while in a large retrospective study,[56] intraoperative P_{driv} above 13 cm H_2O was associated with a two-fold increase in the incidence of PPCs. An individual data meta-analysis on more than 2000 surgical patients observed a dose-response effect between P_{driv} and the development of PPCs.[57] Moreover, in the same analysis, the patients in which PEEP increase resulted in an increased P_{driv} had a worse postoperative outcome.

A promising field of research is trying to interpret VILI as the result of energy transfer from the ventilator to the respiratory system.[63] This concept was conceived for the injured lung, but also provides a rationale for protective ventilation in healthy lungs, as even in this setting energy is transferred to the lungs through mechanical power, triggering inflammation. The energy delivered per minute is proportional to $P_{driv}{}^2 \cdot C_{rs} \cdot RR$, where C_{rs} is the compliance of the respiratory system and RR the respiratory rate: P_{driv} is squared, explaining the importance of keeping P_{driv} along with its counterpart, Vt, as low as possible, even at the price of increasing the respiratory rate, which is instead a linear term. Nonetheless, this concept needs further studies to be translated to the routine clinical practice.

Keeping P_{driv} below a desired threshold is not always easy, as a patient might be objectively difficult to ventilate, for its basal conditions or for the modifications occurring during the surgical procedure: the goal should be keeping the P_{driv} as low as possible, and if the clinician opts for a PEEP increase, this should not lead to an increase of P_{driv}.

Role of fraction of inspired oxygen

The use of low FiO_2 is often advocated.[9] At high inspired oxygen levels, the substitution of nitrogen with oxygen inside the alveoli can worsen the formation of atelectasis through a resorption mechanism.[64] However, there is consensus that during the induction phase the benefits of a high FiO_2 up to 100% overwhelms this risk as it increases the safety time-window for intubation.[65] Nonetheless, recent studies based on imaging have challenged the paradigm that high intraoperative FiO_2 worsens postoperative atelectasis.[66] Patients that have a higher risk of developing peripheral oxygen desaturation, like pregnant women or obese patients whose functional residual capacity decreases rapidly during the induction of anesthesia, can also benefit from positive-pressure ventilation at induction.[65] This technique recruits collapsed alveoli, potentially allowing safer use of higher FiO_2 at induction.

After ensuring a safe airway, intraoperative ventilation should be carried on with the lowest possible FiO_2 ensuring adequate oxygenation, in particular in conditions where high FiO_2 are contraindicated, like COPD, acute myocardial infarction and hypertension,[67, 68] where increased vascular resistance due to hyperoxia could potentially be harmful, or when cerebral blood flow reduction is a concern, as is the case in the elderly.[69]

The clinician should keep in mind that SpO_2 can be maintained at lower levels than those often seen in the operating room: several guidelines recommend $SpO_2 \geq 92\%$ as an acceptable target in most patients. In case of desaturation, FiO_2 can be increased stepwise, and RMs and PEEP increase can be considered.[9]

Mechanical ventilation in specific settings

While most of the recommendations based on evidence are valid in the vast majority of patients, such as the use of lower tidal volumes, the anesthesiologist is often facing issues related to specific sub-groups of patients or surgical procedures: intraoperative mechanical ventilation has to be tailored on a case-by-case basis.[6] Three peculiar conditions represent a challenge for the clinician: obesity, one lung ventilation and ventilation during cardiopulmonary bypass.

Obese patients

Obese patients represent a challenge for clinicians due to the presence of several comorbidities and alterations of the respiratory system. The Body Mass Index (BMI) is an important determinant of respiratory function before and during anesthesia. Obesity results in reduced lung volume with increased atelectasis and small airway collapse, decreased lung and chest wall compliance and increased airway resistance, as well as moderate to severe hypoxemia.[70] These alterations are more marked in obese patients with obstructive sleep apneas.[71] Obese patients undergoing general anesthesia and surgery risk to develop atelectasis, expiratory flow limitation, auto-PEEP, increased work of breathing, and decreased oxygenation.

Several strategies can be adopted in the perioperative period to reduce complications. In the induction phase, intubation should be always considered potentially at risk, and devices for difficult intubation must be available; preinduction non-invasive positive pressure support with ≥10 cmH_2O PEEP should be considered at least as an option.[72] The use of higher PEEP levels compared to the non-obese patients, typically 10-15 cmH_2O, is often advocated as it improves oxygenation and reduces intra-operative atelectasis but, to avoid lung overdistension, before any PEEP increase a RM should be performed.[73] PEEP can be titrated to the best respiratory system compliance in obese patients, but this could lead to even higher PEEP levels, with potentially relevant hemodynamic effects. If RMs are performed, obese patients might require higher pressures to revert lung collapse, often above 40 cm H_2O. During invasive mechanical ventilation, Vt should be set in the range of 6 to 8 mL/kg of predicted body weight, independent of BMI,[74] and either VCV or PCV can be used safely. The respiratory rate should be titrated to maintain normocapnia. Table III shows the results of the most recent trials.[34, 75-82]

A meta-analysis of studies comparing different ventilation strategies for obese patients undergoing general anesthesia, VCV with higher PEEP plus a single recruitment maneuver was associated with improved oxygenation and intraoperative pulmonary compliance and a reduced incidence of intraoperative atelectasis.[83] However, whether these strategies result in an improved postoperative clinical outcome is not clear, and ongoing trials are trying to clarify the best ventilatory settings. In the postoperative period, beach chair position, intensive physiotherapy, non-invasive respiratory support and short-term stay in intermediate critical care units, careful fluid management and optimal pain control may be useful to reduce PPCs.

The obesity task force of the SIAARTI has recently published a consensus statement,

TABLE III.—*Randomized controlled trials comparing different ventilatory strategies in obese patients.*

Trial	N.	BMI and Surgery	Ventilation strategies
Cadi *et al.*[75]	36	BMI>35 kg/m² Laparoscopic bariatric (gastric banding) surgery	VCV with lower PEEP *vs.* PCV with lower PEEP
De Baerdemaeker *et al.*[76]	24	ASA I or II BMI>35 kg/m² Laparoscopic bariatric (gastric banding) surgery	VCV with lower PEEP *vs.* PCV with lower PEEP
Hans *et al.*[77]	40	ASA I or II BMI>35 kg/m² Laparoscopic and open Roux-en-Y bariatric (gastric bypass) surgery	VCV *vs.* PCV
De Souza *et al.*[78]	47	BMI>40 kg/m² Open Roux-en-Y bariatric (gastric bypass) surgery	VCV with lower PEEP *vs.* VCV with lower PEEP and single-progressive RMs *vs.* VCV with lower PEEP and single sudden RMs
Sprung *et al.*[79]	17	BMI>40 kg/m² Open bariatric surgery	VCV with lower PEEP *vs.* VCV with higher PEEP and single-progressive RMs
Talab *et al.*[80]	66	30<BMI<50 kg/m² Laparoscopic bariatric surgery	VCV with lower PEEP and single RMs *vs.* VCV with higher PEEP and single RMs *vs.* VCV and single RMs
Zoremba *et al.*[81]	68	ASA II or III, Moderately obese (BMI 25-35 kg/m²) Minor surgery	PCV with lower PEEP *vs.* PSV with lower PEEP
Gupta *et al.*[34]	102	ASA I or II BMI 30-40 kg/m² Laparoscopic bariatric surgery	VCV *vs.* PCV
Chalhoub *et al.*[82]	52	ASA III BMI>40 kg/m²	VCV with RMs *vs.* VCV without RMs

VCV: volume controlled ventilation; PCV: pressure controlled ventilation; PSV: pressure support ventilation; RM: recruitment maneuver; ASA: American Society of Anesthesiologists physical status class; BMI: Body Mass Index; PBW: predicted body weight; PEEP: positive end-expiratory pressure; PPCs: postoperative pulmonary complications.

comprising several detailed recommendations for the perioperative care of obese patients.[84]

Ventilation during cardiopulmonary bypass

Cardiopulmonary bypass (CBP) involves additional specific mechanisms contributing to inflammation and lung injury, due to the exclusion of lungs from ventilation and perfusion, and atelectasis from alveolar collapse. Inflammation can be triggered by hemodilution, non-pulsatile blood flow, hypothermia, heparinization, blood contact with extracorporeal circulation circuit surfaces, trapping of leukocytes in the pulmonary circulation, transfusion related lung injury,[85] myocardial ischemia,[85] reperfusion injury [86] and high FiO_2, although there is no clear evidence against the use of high FiO_2 during CBP.[87, 88] These factors contribute to the high observed incidence of PPCs after cardiac surgery.[89] The recommendations concerning the use of low Vt of 6-8 mL/kg PBW, moderate PEEP, lower FiO_2 and possibly recruitment maneuvers, derived from stud-

Details	Findings
V_T 8 ml/kg PBW PEEP 5 cmH_2O No RMs	No significant differences in ventilation variables, including plateau and mean airway pressures, hemodynamic variables intra-operatively and after operation, postoperative patient outcome. PCV: improves respiratory parameters and gas exchange
V_T 10 ml/kg PBW PEEP 5 cmH_2O No RMs	No significant differences in ventilation variables, including plateau and mean airway pressures, hemodynamic variables intra-operatively and after operation, postoperative patient outcome. No significant differences in oxygenation.
No RMs	No significant differences in ventilation variables, including plateau and mean airway pressures, hemodynamic variables, postoperative outcome. No significant differences in oxygenation.
Baseline PEEP 5 cmH_2O RMs	No significant differences in ventilation variables, hemodynamic variables, postoperative outcome.
Baseline PEEP 4 cmH_2O RMs	No significant differences in ventilation variables, anesthesia-related variables, hemodynamic variables. RMs: improve intraoperative oxygenation.
PEEP 0, 5, 10 cmH_2O RMs	No significant differences in ventilation variables, anesthesia-related variables, hemodynamic variables.
No RMs	PSV: improved intra-operative oxygenation and postoperative lung function.
No RMs	PCV: Improved PaO_2.
PEEP: 8 cmH_2O RMs: Ppeak 40 cmH_2O for 15s	RMs: Improved arterial oxygenation.

ies in abdominal surgery, might also be valid in this setting before and after CBP, as injurious ventilation can contribute to worsen lung injury. Early weaning and extubation, as well as the use of non-invasive mechanical ventilation are associated with better outcome.[90] In particular, the use of non-invasive respiratory assistance reduces the risk of re-intubation, ICU readmission and the length of hospitalization.[91]

During CBP, several options can be considered: the anesthesiologist can stop ventilation, apply a continuous positive airway pressure, or a minimal ventilation with low tidal volumes and low respiratory frequency. The first option is often preferred by the surgeon, because it offers a better operating field, but despite a lack of evidence, there is a pathophysiologic rationale suggesting that prolonged collapse of lungs could worsen postoperative respiratory function, potentially promoting PPCs.[92] In these patients hemodynamic instability is a major concern, therefore recruitment maneuvers should be brief and with a lower pressure compared to those used in abdominal surgery:[93] in many cases oxygenation can be improved with the application of pressures around 20 cmH_2O.[94] However, RMs are usually performed at the end of CPB to restore lung aeration, and a recent RCT highlighted the benefits of an aggressive recruitment strategy comprising higher pressure levels.[95] Prospective trials are warranted to define the best intraoperative ventilatory management of the patient undergoing CBP.

One-lung ventilation

One-lung ventilation (OLV) is used to isolate the lung during thoracic surgery to allow surgical procedures on the lung itself, the mediastinum or the chest wall. The collapse of one lung causes alveolar damage and inflammation similarly as during CPB; moreover, the ventilated lung must ensure gas exchange, and higher pressures and respiratory rates might be necessary.

A recent meta-analysis [96] has highlighted that a protective ventilation strategy with low tidal volume <6 mL/kg PBW with the application of a PEEP ≥5 cmH_2O could prevent PPCs following OLV, compared to conventional ventilation. In most of the small-sampled studies performed in OLV, tidal volume reduction was part of a bundle of interventions including PEEP. PEEP and RMs improve gas exchange and respiratory mechanics during OLV, but their impact on clinical outcome is unclear.[97, 98] No differences in outcome were observed when comparing PCV and VCV, but PCV is often preferred because it delivers lower peak pressures (Table IV).[44, 99-104] This advantage is in great part apparent, as the difference in pressures is explained by the decelerating inspiratory flow of PCV, mitigating the effects of airway resistance: the higher pressure measured by the ventilator during VCV does not necessarily reflect a higher pressure inside the alveoli, especially when a high respiratory rate is used. Moreover, only VCV and PCV-VG guarantee a constant Vt. Some surgical procedures, such as robot-assisted esophagectomy, require OLV during prone positioning: neither in this case a clear advantage of PCV could be

TABLE IV.—*Randomized trials comparing different ventilatory strategies during one-lung ventilation.*

Trial	N.	Ventilatory strategies	Tidal volume (mL/kg) and PEEP (cmH_2O)	Findings
Hu *et al.*[99]	30	PCV-VG VCV	VT=7; PEEP=0 VT=7; PEEP=0	No significant difference in: respiratory parameters, gas exchange and hemodynamic. With PCV-VG: lower IL-6 and TNF-α 1.
Qutub *et al.*[100]	39	PV PV CV	VT=4; PEEP=5 VT=6; PEEP=5 VT=8; PEEP=5	No significant differences in: incidence of PPCs, hospitalisation and 30-day mortality. VT of 4mL/kg: was associated with lower extravascular lung water content.
Jung *et al.*[101]	60	PV CV	VT=6; PEEP=8 VT=10; PEEP=0	RMs: improve the PaO_2/FiO_2 ratio and arterial oxygenation.
Shen *et al.*[44]	101	PV CV	VT=5; PEEP=5 VT=8; PEEP=0	No differences in: clinical characteristics, operation features, IL-1ß, IL-6, and IL-8 expressions in preoperative alveolar lavage fluid between the 2 groups. Protective ventilation: lower IL expression and pulmonary complications.
Maslow *et al.*[102]	32	PV CV	VT=5; PEEP=5 VT=10; PEEP=0	No differences in: operative characteristics, intraoperative hemodynamic, postoperative pain and sedation and in postoperative morbidity and hospital days. Conventional Ventilation: Higher Ppeak and Pplateau level.
Yang *et al.*[103]	100	PV CV	VT=6; PEEP=5 VT=10; PEEP=0	Protective Ventilation: Lower incidence of pulmonary dysfunction.
Boules *et al.*[104]	37	PCV-VG VCV	VT=6; PEEP=0 VT=6; PEEP=0	Lower Ppeak and Pplateau in PCV-VG. Higher PaO_2 in PCV-VG.

VCV: volume controlled ventilation; PCV: pressure controlled ventilation; PCV-VG: pressure controlled ventilation with volume guarantee; VT: tidal volume; PV: protective ventilation; CV: conventional ventilation; BMI: Body Mass Index; PBW: predicted body weight; PEEP: positive end-expiratory pressure; PPCs: postoperative pulmonary complications.

observed in terms of oxygenation, incidence of PPCs nor hemodynamic stability.[105] In another meta-analysis,[106] a slight improvement of the PaO_2/FiO_2 ratio was observed with the use of PCV compared to VCV, however this improvement was limited to the intraoperative period without a clear effect on clinical outcome.

The surgical incision of the chest wall and the exclusion of one lung modify profoundly the respiratory mechanics, therefore the findings of trials conducted in abdominal surgery can hardly be translated in this setting: also in this case, there is need for large RCTs to identify the best ventilatory strategy during OLV.

Conclusions

In the last decade, several trials improved our knowledge and challenged paradigms concerning intraoperative ventilation. A protective intraoperative ventilation should comprise a low tidal volume of 6-8 mL/kg of predicted body weight, plateau pressures ideally below 16 cmH_2O, the lowest possible driving pressure, moderate-low PEEP levels except in obese patients, laparoscopy and long surgical procedures that might benefit of a slightly higher PEEP. The work of the anesthesiologist should not be limited to the operating theatre, and should start with a careful preoperative visit to assess the risk, and a close postoperative monitoring.

Key messages

— Mechanical ventilation during general anesthesia is potentially harmful for the lungs, and ventilation settings are associated with postoperative pulmonary complications, directly affecting the clinical outcome.

— A protective ventilatory strategy, comprising low tidal volume and moderate-low PEEP levels to achieve the lowest possible driving pressure, should be part of the clinical practice

— Ventilation parameters should be adapted to specific surgical settings such as laparoscopy, obese patients, cardiac surgery, and one-lung ventilation.

— Patient care should start at the preoperative visit and continue in the postoperative period

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