Lung-Protective Mechanical Ventilation during General Anaesthesia: Tidal Volume, PEEP and an Individualized Approach

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Abstract. *Mechanical ventilation is an essential component of general anaesthesia, yet inappropriate ventilator settings may contribute to alveolar overdistension, atelectasis and postoperative pulmonary complications (PPCs), which are associated with prolonged hospital stay and increased mortality. The aim of this narrative review was to synthesise current evidence on intraoperative lung-protective ventilation and to translate it into a practical, individualised approach. Randomised controlled trials, individual-patient-data meta-analyses, systematic reviews and risk-prediction studies were examined. The evidence supports selecting tidal volume according to predicted rather than actual body weight, with 6–8 mL/kg predicted body weight as a reasonable starting range, and monitoring plateau and driving pressures. A combined protective strategy of low tidal volume with moderate PEEP and recruitment reduced pulmonary and extrapulmonary complications compared with high tidal volume without PEEP in abdominal surgery, whereas high PEEP with routine recruitment manoeuvres did not reduce PPCs in either non-obese or obese patients and increased intraoperative hypotension and vasopressor use. Higher driving pressure has been associated with PPCs, but it is not a stand-alone therapeutic target. Ventilation should therefore be tailored to respiratory mechanics, oxygenation, haemodynamics, body habitus and type of surgery, and integrated into a broader perioperative bundle that includes risk assessment, analgesia, early mobilisation and respiratory physiotherapy.*

Keywords: *general anaesthesia; mechanical ventilation; lung-protective ventilation; tidal volume; PEEP; driving pressure; atelectasis; postoperative pulmonary complications*

1. Introduction

General anaesthesia profoundly alters respiratory mechanics. Loss of muscle tone, neuromuscular blockade, supine or steep Trendelenburg positioning and surgical retraction displace the diaphragm cephalad and reduce functional residual capacity. Atelectasis develops within minutes of induction in most patients, particularly in those with obesity and during abdominal and laparoscopic surgery, and impairs gas exchange and lung compliance. Mechanical ventilation maintains oxygenation and carbon dioxide removal, but excessive stretch and repetitive opening and closing of alveoli can themselves injure the lung (Futier et al., 2013).

Postoperative pulmonary complications (PPCs), including respiratory failure, pneumonia, atelectasis requiring intervention, bronchospasm and pleural effusion, are among the most frequent complications after surgery. They are associated with longer hospital stay, higher costs and increased mortality, and their risk can be estimated preoperatively with tools such as the ARISCAT score (Canet et al., 2010). A systematic review of perioperative

interventions has shown that several components of anaesthetic care, including ventilation strategy, may influence the incidence of PPCs (Odor et al., 2020).

The concept of lung-protective ventilation originated in the intensive care of patients with acute respiratory distress syndrome, where low tidal volumes improved survival. Its transfer to the operating room, where most patients have healthy lungs and ventilation lasts hours rather than days, raised important questions: which tidal volume is appropriate, how much positive end-expiratory pressure (PEEP) should be applied, and whether recruitment manoeuvres are beneficial or harmful.

The objectives of this review were therefore (i) to summarise the mechanisms of ventilator-induced lung injury during anaesthesia; (ii) to evaluate evidence on tidal volume selection; (iii) to examine the role of PEEP and recruitment manoeuvres; (iv) to discuss plateau and driving pressure as monitoring variables; and (v) to propose a practical, individualised approach to intraoperative ventilation.

2. Materials and Methods

This article was prepared as a narrative literature review. Relevant publications were identified in PubMed/MEDLINE, Scopus and Google Scholar using combinations of the terms "protective ventilation", "general anaesthesia", "tidal volume", "positive end-expiratory pressure", "recruitment manoeuvre", "driving pressure" and "postoperative pulmonary complications".

Priority was given to multicentre randomised controlled trials of intraoperative ventilation strategies, individual-patient-data meta-analyses, systematic reviews and validated risk-prediction studies. Publications in English, predominantly from 2010 to 2025, were considered. Studies limited to one-lung ventilation, cardiopulmonary bypass, paediatric patients or intensive care ventilation were not the focus of this review, although physiological concepts from these settings were referred to where relevant.

Findings were synthesised thematically into mechanisms of injury, tidal volume, PEEP and recruitment, respiratory mechanics monitoring and individualisation. Because the review was not designed as a systematic review or meta-analysis, no PRISMA selection flow, risk-of-bias scoring or pooled statistical analysis is presented, and the conclusions should be interpreted in this context.

3. Results

3.1. Mechanisms of ventilator-induced lung injury

Ventilator-induced lung injury comprises several interrelated mechanisms. Volutrauma results from excessive regional lung stretch, barotrauma from high transpulmonary pressure, atelectrauma from cyclic opening and closing of unstable alveoli, and biotrauma from the release of inflammatory mediators that may have local and systemic effects. During anaesthesia, the coexistence of collapsed dependent regions and overdistended non-dependent regions means that a tidal volume which appears moderate may be concentrated in a reduced aerated lung volume.

PEEP counteracts end-expiratory collapse but is not without cost. Excessive PEEP increases intrathoracic pressure, reduces venous return and cardiac output, may increase pulmonary vascular resistance and can overdistend already open alveoli. The assumption that higher PEEP is always better is therefore not supported by evidence, and its effect depends on the balance between recruitment and overdistension in each patient.

3.2. Tidal volume selection

Tidal volume should be calculated from predicted body weight (PBW), which is determined by height and sex (men: $50 + 0.91 \times [\text{height in cm} - 152.4]$; women: $45.5 + 0.91 \times [\text{height in cm} - 152.4]$), rather than from actual body weight, because lung size is related to height and not to adiposity. Using actual weight in obese patients leads to inappropriately large tidal volumes.

In the IMPROVE trial, 400 patients at intermediate to high risk undergoing major abdominal surgery were randomised to a protective strategy (6–8 mL/kg PBW, PEEP 6–8 cmH_2O and recruitment manoeuvres every 30 minutes) or to non-protective ventilation (10–12 mL/kg PBW without PEEP or recruitment). Major pulmonary and extrapulmonary complications within seven days occurred in 10.5 % of the protective group and 27.5 % of the non-protective group (Futier et al., 2013). An individual-patient-data meta-analysis subsequently found that protective ventilation was associated with fewer PPCs, and that the benefit was linked mainly to lower tidal volume (Serpa Neto et al., 2015).

However, when moderate PEEP was applied in both groups, the PROTECTIVE trial of patients undergoing major surgery found no significant difference in PPCs between 6 mL/kg and 10 mL/kg PBW (Karalapillai et al., 2020). These results suggest that very high tidal volumes without PEEP should be avoided, but that further lowering tidal volume below conventional moderate values provides limited additional benefit. Very low tidal volumes can cause hypercapnia, increased work of breathing and dyssynchrony, so 6–8 mL/kg PBW remains a reasonable starting range, adjusted to pressures and gas exchange (Table 1).

Table 1. Key randomised trials and meta-analyses of intraoperative ventilation strategies.

Study	Population	Comparison	Principal finding
Futier et al., 2013 (IMPROVE)	400 patients, major abdominal surgery	6–8 mL/kg PBW + PEEP 6–8 + RM vs 10–12 mL/kg, no PEEP	Major complications 10.5 % vs 27.5 % in favour of protective strategy
PROVE Network, 2014 (PROVHILO)	900 non-obese patients, open abdominal surgery	PEEP 12 cmH_2O + RM vs PEEP ≤ 2 cmH_2O (both 8 mL/kg)	No reduction in PPCs (40 % vs 39 %); more hypotension and vasopressor use with high PEEP
Serpa Neto et al., 2015	Individual-patient-data meta-analysis	Protective vs conventional ventilation	Fewer PPCs with protective ventilation, associated mainly with lower tidal volume
Neto et al., 2016	Individual-patient-data meta-analysis	Driving pressure, PEEP and tidal volume	Higher driving pressure, but not PEEP level, associated with PPCs
PROBESE Group, 2019	2 013 patients with BMI ≥ 35 kg/m^2	PEEP 12 cmH_2O + RM vs PEEP 4 cmH_2O	No reduction in PPCs (21.3 % vs 23.6 %); more hypotension with high PEEP
Karalapillai et al., 2020 (PROTECTIVE)	1 236 patients, major surgery	6 vs 10 mL/kg PBW, both with PEEP 5 cmH_2O	No significant difference in PPCs

3.3. PEEP and recruitment manoeuvres

PEEP helps maintain alveolar patency at end expiration, but the optimal level depends on body habitus, compliance, type of surgery, positioning and haemodynamic tolerance. In the PROVHILO trial, 900 non-obese patients undergoing open abdominal surgery were ventilated with 8 mL/kg PBW and randomised to PEEP 12 cmH_2O with recruitment manoeuvres or to PEEP ≤ 2 cmH_2O without recruitment. PPCs occurred in 40 % and 39 % respectively, while hypotension and vasopressor use were more frequent with the high-PEEP strategy (PROVE Network Investigators, 2014).

Obese patients were expected to benefit most from higher PEEP because of their greater tendency to atelectasis. Nevertheless, the PROBESE trial in 2 013 patients with a body mass index of at least 35 kg/m^2 found that PEEP 12 cmH_2O with recruitment manoeuvres did not reduce PPCs compared with PEEP 4 cmH_2O (21.3 % vs 23.6 %) and was associated with more intraoperative hypotension (PROBESE Collaborative Group, 2019). Recruitment manoeuvres should therefore be reserved for selected situations, such as documented atelectasis with hypoxaemia, and performed with attention to haemodynamic risk.

3.4. Plateau pressure and driving pressure

Plateau pressure, measured during an end-inspiratory pause, approximates alveolar pressure. Driving pressure is the difference between plateau pressure and PEEP, equivalent to tidal volume divided by respiratory system compliance, and reflects the stress applied to the ventilated lung relative to its functional size. In an individual-patient-data meta-analysis of surgical trials, higher driving pressure was associated with PPCs, whereas the level of PEEP itself was not; increases in PEEP that resulted in higher driving pressure were associated with more

complications (Neto et al., 2016).

These observations suggest that PEEP is beneficial when it improves compliance, thereby reducing driving pressure, and harmful when it causes overdistension. Driving pressure is, however, a physiological indicator derived from observational data and not a validated target in its own right. It should be interpreted together with tidal volume, compliance, PEEP, positioning and the effect of pneumoperitoneum, in which chest wall stiffness raises plateau pressure without necessarily increasing lung stress.

3.5. Individualisation and monitoring

Ventilation should be adapted to age, obesity, chronic lung disease, baseline oxygenation, laparoscopy, steep positioning and the expected duration of surgery. Preoperative risk can be stratified using the ARISCAT score, which includes age, preoperative oxygen saturation, respiratory infection in the previous month, anaemia, upper abdominal or intrathoracic incision, duration of surgery more than two hours and emergency surgery (Canet et al., 2010). Monitoring includes tidal volume, respiratory rate, peak and plateau pressures, PEEP, driving pressure, compliance, SpO_2, end-tidal CO_2, arterial blood gases when indicated and haemodynamic variables. When oxygenation deteriorates, clinicians should assess tube position, secretions, atelectasis, bronchospasm, pneumothorax and haemodynamic causes rather than simply increasing the inspired oxygen fraction. A stepwise approach is summarised in Table 2.

Table 2. Practical approach to individualised intraoperative ventilation.

Step	Action	Key considerations
1. Before surgery	Assess PPC risk (e.g. ARISCAT); record height, sex and baseline SpO_2	Plan monitoring and postoperative respiratory care for high-risk patients
2. Set tidal volume	Calculate PBW; start at 6–8 mL/kg PBW	Use height, not actual weight; adjust respiratory rate for normocapnia
3. Set PEEP	Start with moderate PEEP (about 5 cmH_2O) and adjust	Increase if compliance and oxygenation improve without haemodynamic compromise
4. Check mechanics	Measure plateau pressure, driving pressure and compliance	Aim to avoid high driving pressure; consider effects of pneumoperitoneum and position
5. Recruitment	Only for selected cases with atelectasis or hypoxaemia	Ensure adequate volume status; monitor blood pressure
6. Oxygenation problems	Check tube, secretions, bronchospasm, pneumothorax, haemodynamics	Do not rely solely on increasing FiO_2
7. Emergence and after	Full reversal of neuromuscular block; analgesia; early mobilisation; physiotherapy	Continue respiratory surveillance in high-risk patients

4. Discussion

The evidence reviewed here supports a nuanced interpretation of intraoperative lung-protective ventilation. The clearest benefit comes from avoiding large tidal volumes without PEEP, which were common in historical practice. The IMPROVE trial demonstrated that a combined protective strategy reduced complications substantially (Futier et al., 2013), and meta-analytic data link this benefit mainly to lower tidal volume (Serpa Neto et al., 2015). Once moderate tidal volumes and moderate PEEP are used, however, further reductions in tidal volume appear to provide little additional benefit (Karalapillai et al., 2020).

In contrast, the hypothesis that high PEEP with routine recruitment improves outcomes has not been confirmed. Both PROVHILO and PROBESE showed no reduction in PPCs and increased haemodynamic instability (PROVE Network Investigators, 2014; PROBESE Collaborative Group, 2019). These trials tested fixed PEEP levels; it remains possible that PEEP titrated to individual mechanics, for example to the best compliance, lowest driving pressure or with electrical impedance tomography, could be beneficial, but this has not yet been established in large outcome trials.

Driving pressure provides a useful physiological link between these findings, because it integrates tidal volume and the functional size of the lung (Neto et al., 2016). In practice, observing how driving pressure and compliance change after an adjustment of PEEP helps the clinician judge whether the lung is being recruited or overdistended. Nevertheless, the clinical context, including

pneumoperitoneum, positioning and haemodynamics, must always be considered.

Finally, ventilation is only one component of pulmonary protection. Risk assessment, avoidance of residual neuromuscular blockade, effective analgesia, early mobilisation, respiratory physiotherapy and appropriate use of oxygen are all part of a comprehensive perioperative strategy (Odor et al., 2020).

This review has limitations. It is a narrative synthesis and the selection of studies may be subject to bias. The trials differ in population, surgical procedure, definition of PPCs and control-group ventilation, which limits direct comparison. Future studies should evaluate individualised PEEP titration strategies, the effect of ventilation in laparoscopic and robotic surgery, and patient-centred long-term outcomes.

5. Conclusion

Lung-protective ventilation during general anaesthesia is not a single universal set of ventilator settings but a strategy adapted to physiological and clinical variables. Tidal volume should be based on predicted body weight, typically 6–8 mL/kg, combined with moderate PEEP and monitoring of plateau and driving pressures. Routine high PEEP and recruitment manoeuvres are not recommended for every patient because they do not reduce pulmonary complications and may cause hypotension. The optimal approach balances gas exchange, respiratory mechanics and haemodynamic safety and is integrated with risk assessment and postoperative respiratory care.

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