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REVIEW

Protective mechanical ventilation during general anaesthesia

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S U M M A R Y

Pulmonary postoperative complications (PPCs) occur in 5% of patients undergoing surgery and anaesthesia, and could be associated with an increase in morbidity and mortality. Different mechanical ventilation techniques for general anaesthesia, the use of positive end-expiratory pressure (PEEP), protective tidal volume (VT) and recruitment manoeuvres (RMs), have been proposed in order to reduce the incidence of PPC.

The aim of this review is:

1. To analyse the effects of general anaesthesia on respiratory function.
2. To evaluate the different general anaesthetic protective mechanical ventilation strategies proposed for use during open and laparoscopic surgery.
3. To provide a brief focus on ventilation strategies during anaesthesia for particular diseases such as obesity, chronic obstructive pulmonary disease and asthma.

1. Introduction

Pulmonary postoperative complications (PPCs) occur in 5% of patients undergoing surgery and anaesthesia, and could be associated with an increase in morbidity and mortality.[1,2] The risk factors for PPCs depend on the type of surgery, anaesthesia and patient's conditions.[3] In particular, general anaesthesia may affect the respiratory system in many ways, resulting in an impairment of oxygenation, gas-exchange, and altered distribution of alveolar ventilation (V_A) and perfusion (Q). Different mechanical ventilation techniques for use during general anaesthesia, the use of positive end-expiratory pressure (PEEP), protective tidal volume (VT) and recruitment manoeuvres (RMs), have been proposed in order to reduce the incidence of PPC.

The aim of this review is:

1. To analyse the effects of general anaesthesia on respiratory function
2. To evaluate the different protective mechanical ventilation techniques proposed for use during open and laparoscopic surgery.
3. To provide a brief focus on ventilation strategies during anaesthesia for particular diseases such as obesity, chronic obstructive pulmonary disease and asthma.

2. General anaesthetic effects on the respiratory system

General anaesthesia may affect the respiratory system in many different ways resulting in alteration of breathing control, respiratory muscles activity, residual functional capacity, atelectasis and distribution of alveolar ventilation and perfusion.

Different areas of the nervous system, responsible for physiological and pathological breathing patterns as well as inspiratory muscle activity, may be affected by anaesthetic drugs.[4–6] Sedatives and opioids used for hypnosis, sedation and analgesia, may have detrimental effects on central and peripheral centres of respiratory control, resulting in a reduction in alveolar ventilation, irregular respiratory rate, hypoxaemia and hypercapnia.[6,7] Volatile halogenated anaesthetics reduce the response of respiratory centres to hypoxia and potentiate the effect of neuromuscular blocking agents on respiratory muscle.[8] Intravenous anaesthetic agents are also responsible for the depression of inspiratory muscle activity, while diaphragmatic activity is preserved.

A reduction in functional residual capacity has been reported after induction of anaesthesia and kept stable during and after surgery.[9] Nevertheless, atelectasis occurs in 90% of anaesthetised patients, and is predominantly located in dependent lungs.[3]

Fig. 1 shows the mechanisms suggested for the reduction of residual functional capacity during general anaesthesia.

Fig. 2 shows the possible mechanisms for the formation of atelectasis during general anaesthesia.

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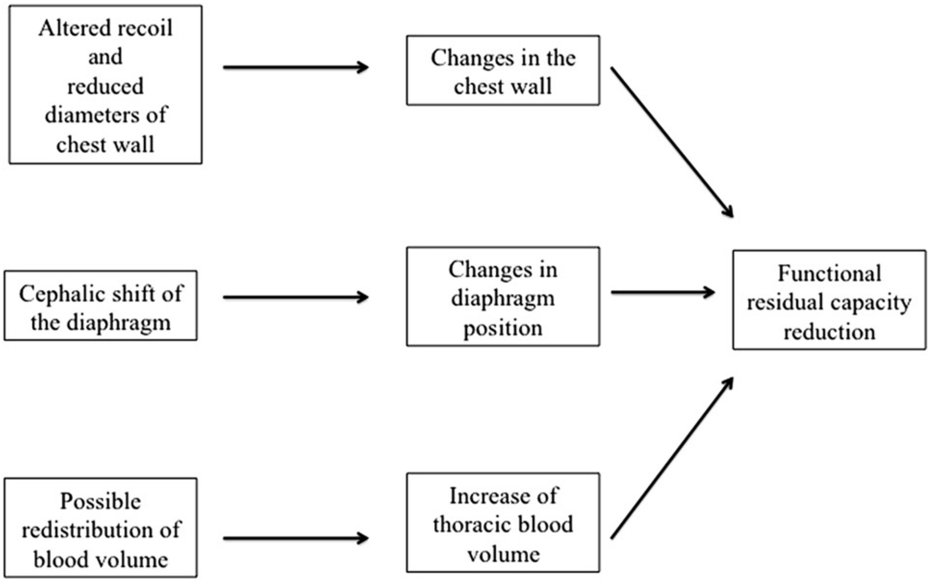

Fig. 1. Possible mechanisms that may reduce the functional residual capacity during and after surgery. Altered recoil and reduced diameters of chest wall alter the chest wall physiology. Cephalic shift of the diaphragm changes the diaphragm position. Possible redistribution of blood volume may increase thoracic blood volume.

3. Protective mechanical ventilation

3.1. *Tidal volume*

Protective mechanical ventilation with low tidal volume (VT) strategy is well known in patients with acute respiratory distress syndrome (ARDS) but not for patients with healthy lungs during general anaesthesia.[10] According to Benedixen et al., at the beginning of mechanical ventilation, healthy patients were ventilated with high VT (15 ml/kg) in order to avoid intraoperative and postoperative atelectasis.[11] Recently, several studies have investigated the hypothesis that low VT may protect the healthy lungs from the deleterious effects and possible injuries induced by high VT. The beneficial effects of low VT have also been evaluated in different kinds of surgery as well as cardiac and abdominal surgical procedures. Koner et al., in a prospective randomized clinical trial evaluated the effects of protective mechanical ventilation with or without PEEP on pulmonary function and systemic cytokine in patients undergoing cardiopulmonary bypass.[12] Forty-four patients were divided into 3 groups: 1) protective VT (6 ml/kg) and PEEP (5 cmH_2O); 2) conventional VT (10 ml/kg) and PEEP (5 cmH_2O); and 3) conventional VT (10 ml/kg) without PEEP. The results found no significant difference between the distribution of systemic cytokines, while plateau airway pressure and shunt fraction were lower

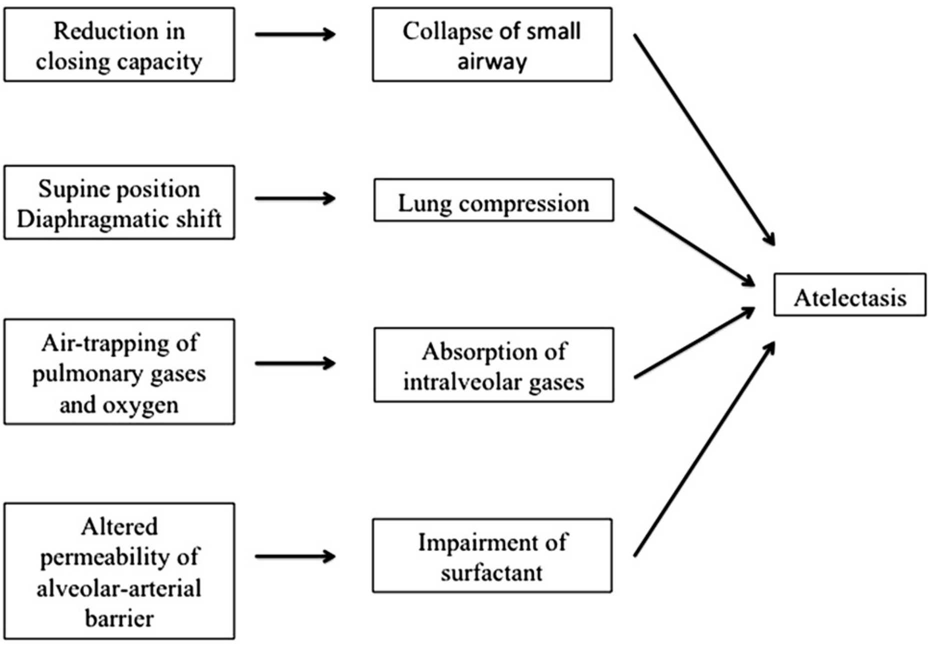

Fig. 2. Possible mechanisms that may produce atelectasis during and after surgery. Reduction of closing capacity produces a collapse of the small airway. Supine position and diaphragmatic shift compresses the lungs. Air-trapping of pulmonary gases and oxygen reduce the absorption of intra-alveolar gases. Altered permeability of alveolar–arterial barrier produces an impairment of surfactant.

in the protective ventilation group than in the conventional ventilation groups.[12] Reis Miranda et al. evaluated the effect of open-lung concept to avoid atelectasis in cardiac surgery.[13] Patients were divided into a group receiving conventional ventilation (VT = 9 ml/kg and PEEP = 5 cmH_2O) and an open-lung group (VT = 4–6 ml/kg and PEEP = 10 cmH_2O). The results showed that IL-8 decreased and oxygenation improved in the open-lung group.[13] More recently, Sundar et al. in a randomized clinical trial evaluated the effect of lower (6 ml/kg) versus higher (10 ml/kg) VT in 149 patients undergoing elective cardiac surgery.[14] In this study PEEP was set at the best value. The lower VT ventilation did not reduce the time to extubation after cardiac surgery, but after 6–8 h a higher proportion of lower VT than higher VT strategy was extubated.[14] Michelet et al. evaluated the effect of one lung protective ventilation in patients undergoing oesophagectomy.[15] One lung protective ventilation was set to 5 ml/kg VT and 5 cmH_2O PEEP, while conventional one lung ventilation was set to 9 ml/kg VT without PEEP. Patients treated with protective ventilation had a lower level of systemic cytokines at the end of one lung ventilation than patients in the conventional arm. Protective ventilation also improved the oxygen partial pressure and reduced the postoperative duration of mechanical ventilation.[15] Walthuis et al. evaluated the effect of protective mechanical ventilation on pulmonary inflammation in elective abdominal surgery with duration $\geq$5 h.[16] Patients were randomly assigned to mechanical ventilation with higher tidal volumes of 12 ml/kg and no PEEP or lower VT of 6 ml/kg and PEEP of 10 cmH_2O. Protective mechanical ventilation was associated with a reduction in the pulmonary IL-8, while IL-6, IL-1, IL-2 and TNFα were not affected by mechanical ventilation.[16]

Different patterns of protective mechanical ventilation seem to be associated with a reduction in systemic and pulmonary inflammatory response after surgery and an improvement in some respiratory parameters in oxygenation as well as extubation.

Further research may assess which is the optimal level of VT during general anaesthesia and its effectiveness in preventing lung injury as well as after surgical interventions.

3.2. *Positive end-expiratory pressure*

Positive end-expiratory pressure is fundamental in mechanical ventilation. The efficacy of the best PEEP or high PEEP level has been well established in ARDS patients. The rationale of using PEEP in protective intraoperative mechanical ventilation concerns avoiding atelectasis due to the open-lung approach. According to Reis Miranda et al., a high PEEP level with low VT is associated with a reduction in pulmonary inflammation after cardiopulmonary bypass.[13] Wetterrslev et al. investigated the efficacy of PEEP in preventing atelectasis and improving oxygenation in patients undergoing abdominal surgery.[17] Forty patients were randomly assigned to either a best PEEP-group or a zero PEEP (ZEEP) group. Perioperative oxygenation significantly improved in the PEEP-group while postoperative complications were lower in the PEEP-group but were not statistically significant.[17]

The concept that the application of PEEP was useful during surgery was also evaluated in laparoscopic surgical procedures. In this type of surgery, the prolonged insufflation of intraperitoneal gas may enhance the cephalic diaphragm shift and worsen the airway closing capacity, thus, resulting in an increase in lung injury and atelectasis. Meininger et al. evaluated the role of PEEP on arterial oxygenation and haemodynamics in laparoscopic surgery in non-obese patients.[18] PEEP was set to 10 cmH_2O or to a zero level (ZEEP). The PEEP-group had better oxygenation during intraperitoneal gas insufflation than the ZEEP-group but no significant haemodynamic differences were found between the groups.[18] Kim et al. evaluated the efficacy of PEEP in improving oxygenation and dynamic compliance during laparoscopic surgery in non-obese patients.[19] The oxygenation was significantly higher in the PEEP-group (5 cmH_2O) than the ZEEP-group during the pneumoperitoneum, but in both groups, respiratory system compliance decreased after 40 min.[19] Interestingly in obese-patients undergoing laparoscopic surgery, PEEP had different effects.

Whalen et al. investigated the effect of high PEEP level (12 cmH_2O) versus low PEEP level (4 cmH_2O) on arterial oxygenation in laparoscopic surgery in morbidly obese patients.[20] The high PEEP-group showed a better arterial oxygenation than the low PEEP-group during mechanical ventilation, but it disappeared after the extubation.[20] Thus in bariatric patients undergoing laparoscopic surgery, PEEP had a temporary effect on oxygenation during mechanical ventilation, while it is likely that an alveolar derecruitment could occur at extubation.

The use of PEEP in intraoperative mechanical ventilation was associated with a reduction in atelectasis during the postoperative period as reported by 3 studies using the high PEEP level (10 cmH_2O).[21–23] These studies involved healthy patients undergoing neurosurgical or eye surgery, as well as obese patients for laparoscopic and non-laparoscopic surgery. Interestingly, the incidence of atelectasis was lower in bariatric patients demonstrating possible beneficial effects in this category of patients.

Recently, a Cochrane systematic review and metaanalysis assessed the efficacy of using PEEP during anaesthesia on postoperative mortality and pulmonary complications.[24] This review finally included 8 randomized clinical trials involving 330 patients treated with intraoperative PEEP or ZEEP. The primary outcome was mortality and the secondary outcomes were respiratory failure, oxygen efficiency, mechanical ventilatory support, pneumonia, atelectasis and barotrauma. The results showed insufficient evidence to assess the role of intraoperative PEEP on mortality while two secondary outcomes were statistically significant. The PEEP-group had a higher PaO_2/FiO_2 ratio intraoperatively, and a lower incidence of postoperative atelectasis.[24]

The usefulness of PEEP to improve intraoperative and postoperative outcome is still a matter of debate and further research is necessary to evaluate the efficacy of PEEP during anaesthesia in healthy and non-healthy patients. It should also be noted that a worldwide multi-centre randomized controlled trial, known as PROVHILO has planned to recruit 900 patients, randomized into two PEEP arms (12 cmH_2O versus 2 cmH_2O) undergoing open abdominal surgery. This study may add new information about the rational of using protective ventilation with high PEEP during general anaesthesia to prevent pulmonary and extra-pulmonary postoperative complications.[25]

3.3. *Recruitment manoeuvres*

Recruitment manoeuvres (RMs) in ARDS patients are useful to open atelectatic alveoli in order to increase end-expiratory lung-volume, improve gas-exchange and attenuate ventilator-induced lung injury.[26] The recruitment of collapsed alveoli is achieved by a transient increase in transpulmonary pressure.[27] Different types of RMs have been described for lung injured patients as sustained inflation manoeuvres, high pressure controlled ventilation, incremental PEEP, and intermittent sighs.[27] In anaesthesia the most common RM is the 'bag squeeze', a sustained manual inflation using the airway pressure valve of an anaesthetic ventilator. This type of RM has many possible limitations: 1) the airway pressure depends on the level of pressure applied to the bag and therefore it cannot be kept constant over time; 2) disconnecting a patient from the anaesthetic machine leads to a loss of airway pressure until the RM is started and a desired level of pressure achieved; 3) reconnecting the patient to the anaesthetic machine, the pressure delivered from a ventilator during inspiration can be greater than that exerted during a manual RM, thus resulting in possible barotrauma. Alternatively, RM with incremental PEEP can be applied during mechanical ventilation for different surgical procedures. Before using the incremental PEEP as RM, patients must be normovolaemic and ventilator parameters must be set as follows: inspired oxygen concentration (FiO_2) at 1, tidal volume at 8–12 ml/kg and inspiratory pause at 20%–50% of inspiration.[25] PEEP is progressively increased by 5 cmH_2O up to 20 cmH_2O every 3 or five breaths, then it is reduced by steps of 2–3 cmH_2O. Tidal volume is increased in steps of 4 ml/kg predicted body weight until a plateau pressure of 30–35 cmH_2O is achieved and then 3 breaths are administered with a plateau pressure of 30–35 cmH_2O.[25]

Several randomized clinical studies investigated the effects of different RMs performed during general anaesthesia. Manual RMs to achieve an airway pressure of 40–45 cmH_2O were investigated in 3 randomized clinical trials enrolling patients for cardiopulmonary bypass, laparoscopic cholecystectomy and general anaesthesia for magnetic resonance imaging.[29–31] Two studies reported an increase in intraoperative oxygenation, and only one study described a reduction in postoperative atelectasis.[29–31] Whalen et al. evaluated the effects of RM with incremental PEEP in laparoscopic bariatric surgery and described an intraoperative improvement in respiratory compliance and oxygenation.[20] Celebi et al. investigated the effect of RM with CPAP or RM with PEEP in cardiopulmonary bypass. This study reported an increase in oxygenation and compliance during anaesthesia and a postoperative reduction in atelectasis, pulmonary complications and length of hospital stay.[32] Three studies evaluated the effects of vital capacity manoeuvres with an airway pressure of 35–40 cmH_2O for 15 s, demonstrating an improvement in the intraoperative oxygenation.[33–35] Reinius et al. investigated the effect of RM performed by increasing airway pressure up to 55 cmH_2O and inspiratory hold in bariatric surgery.[23] RMs alone were able to improve oxygenation during anaesthesia, but RMs followed by PEEP also reduced the incidence of postoperative atelectasis.[23]

According to the previous clinical studies, RMs seem to improve intraoperative oxygenation as well as prevent postoperative atelectasis, but further research is necessary to evaluate their efficacy on perioperative pulmonary complications.

3.4. Protective mechanical ventilation in particular conditions

The incidence of obesity, chronic obstructive pulmonary disease (COPD) and asthma is increasing worldwide. Obese, COPD and asthma patients require customized intraoperative mechanical ventilation due to the specific pathophysiologic alterations induced by these diseases.

3.5. Obese patients

The main problem occurring in morbidly obese patients is the reduction in functional residual capacity by up to 50% from pre-anaesthesia levels, so any intervention during general anaesthesia should minimize this effect.[36] Optimization of intraoperative mechanical ventilation setting for obese patients may include:

1. Inspiratory oxygen fraction to achieve a peripheral oxygen saturation >92%,[37]
2. Tidal volume ≤ 13 ml/kg of ideal body weight,[38]
3. Lung recruitment manoeuvres with high airway pressure (up to 60 cmH_2O) to open collapsed alveoli,[39]
4. Adequate PEEP level before and after RM to prevent airway collapse and to keep alveoli opened.[37]

3.6. COPD and asthma patients

The main pathophysiological characteristic of COPD and asthma patients is the increase in airway resistance responsible for dynamic hyperinflation, altered gas-exchange and cardiovascular abnormalities.

Intraoperative mechanical ventilation for these patients should aim to minimize the level of airway resistance and avoid further worsening of hyperinflation, gas-exchange and cardiovascular

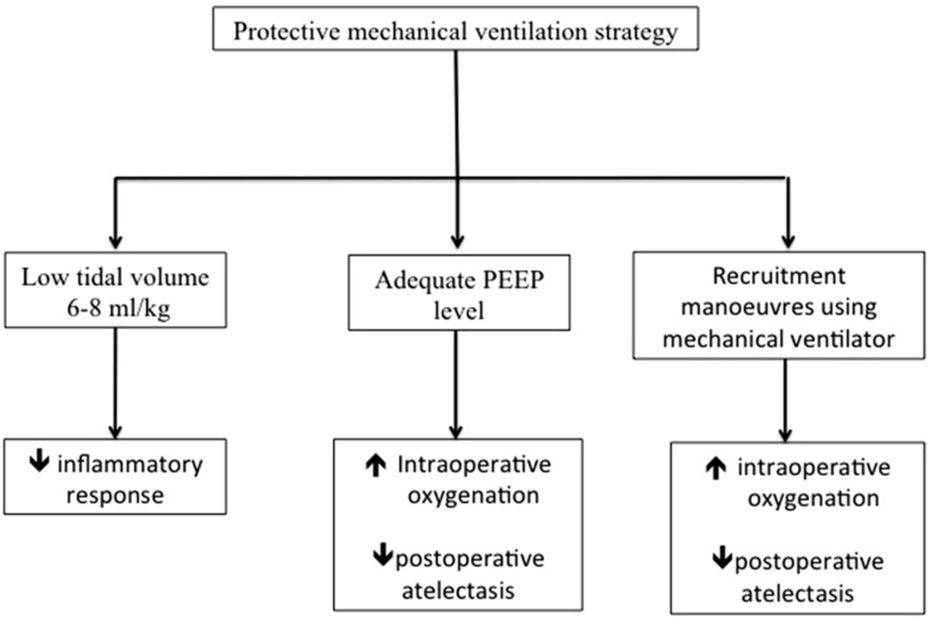

Fig. 3. Protective mechanical ventilation strategy. According to the literature, protective mechanical ventilation strategy may include: 1) low tidal volume to reduce inflammatory response, 2) adequate PEEP level to increase intraoperative oxygenation and to reduce the incidence of postoperative atelectasis, 3) recruitment manoeuvers using mechanical ventilator level to increase intraoperative oxygenation and to reduce the incidence of postoperative atelectasis.

function. The setting of mechanical ventilation during anaesthesia for COPD and asthma patients may include:

1. Reduction in minute volume (tidal volume and respiratory rate) targeted on individual physiologic homeostasis of CO_2 and pHa.
2. Increased expiratory time to allow an appropriate time for expiration.
3. Use of bronchodilators to minimize airway flow resistance.

Fig. 3 shows possible strategies for protective mechanical ventilation during general anaesthesia according to the results from available randomized clinical trials discussed in this review.

4. Conclusion

Protective mechanical ventilation during general anaesthesia may include: 1) low VT; 2) adequate PEEP level and 3) RMs by using mechanical ventilation.

Low VT may be associated with a reduction in pulmonary and systemic inflammatory response, the use of an adequate PEEP level may improve intraoperative oxygenation and RMs with mechanical ventilation may further improve intraoperative oxygenation and prevent postoperative atelectasis. Prospective controlled randomized clinical trials are required to demonstrate the efficacy of protective ventilation strategies during general anaesthesia to improve clinical outcome.

Conflict of interest

The authors have no conflict of interest.

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