Review / Derleme

Protective Ventilation in Anaesthesia

Anestezide Koruyucu Ventilasyon

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Abstract / Özet

General anaesthesia may affect the respiratory system in many different ways, resulting in intra-operative and post-operative pulmonary complications such as alteration of residual functional capacity and atelectasis. The aim of this review is: 1) to analyse different proposed strategies of protective mechanical ventilation during general anaesthesia for laparoscopic, open-abdominal and cardiac surgery and 2) to overview the different ventilatory modes commonly used during general anaesthesia in the operating room.

Key Words: Protective mechanical ventilation, residual functional capacity, atelectasis, protective tidal volume, positive end-expiratory pressure, recruitment manoeuvres

Genel anestezi, solunum sistemini bir çok farklı şekilde etkileyerek, rezidüel fonksiyonel kapasitenin değişmesi veya atelektazi gibi ameliyat sırası ve sonrası komplikasyonlara neden olabilir. Bu derlemenin amacı: 1) laparoskopik, açık karın ve kalp cerrahileri sırasında kullanımı önerilen koruyucu ventilasyon stratejilerini incelemek ve 2) ameliyathanede, genel anestezi sırasında sık kullanılan ventilasyon modları hakkında bilgi vermektir.

Anahtar Kelimeler: Koruyucu mekanik ventilasyon, rezidüel fonksiyonel kapasite, atelektazi, koruyucu soluk hacmi, soluk sonu pozitif basınç, rekruitment manevraları

Introduction

General anaesthesia may affect the respiratory system in many different ways, resulting in such intra-operative and post-operative pulmonary complications as alteration of residual functional capacity (FRC) and atelectasis. The proposed mechanisms responsible for the reduction in FRC are: 1) altered and/or reduced diameters of the chest wall; 2) cephalic shift of the diaphragm; and 3) redistribution of blood volume. The suggested mechanisms responsible for the occurrence of atelectasis are: 1) cranial diaphragmatic shift; 2) collapse of small airways due to a reduction in closing capacity; 3) lung compression of the heart in the supine position.

These pulmonary complications were previously described for different types of surgery according to their particular features. Since reduction in FRC and atelectasis are sustained at the end of anaesthesia, optimal intraoperative ventilation strategies are needed to prevent or ameliorate the occurrences of intra-operative and post-operative pulmonary complications.

The aim of this review is: 1) to analyse different proposed strategies of protective mechanical ventilation during general anaesthesia for laparoscopic, open-abdominal and cardiac surgery and 2) to overview the different ventilatory modes commonly used during general anaesthesia in theatre.

Laparoscopic surgery

Laparoscopic surgery is widely used for the treatment of many diseases. Gas insufflation into the abdomen, called pneumoperitoneum (PnP), is the main feature of this surgery; it allows surgical manoeuvres without opening the abdominal wall as in conventional surgery. Conversely, abdominal gas insufflation during laparoscopic procedures may alter patient's respiratory mechanics. In this situation, there is a cephalic shift of the diaphragm causing a further reduction of FRC and lung compression. As a result of this altered interaction between the abdominal and thoracic system, patients suffer from a reduction in lung total volume, an increase of end-tidal carbon dioxide (CO_2), and a rise of airway pressure (1-3).

The ideal strategy for ventilating patients undergoing laparoscopic surgery includes recruitment of collapsed lung parenchyma and reduction in end-tidal CO_2 without causing an increase in airway pressure In the following text, we discuss the effects of different levels of tidal volume (VT), positive end-expiratory pressure (PEEP) and recruitment manoeuvres as described in prospective randomized clinical trials on laparoscopic surgery (Table 1).

The usefulness of PEEP in mechanical ventilation during PnP was evaluated by Meinenger et al. (4) in 2005. Two groups of patients were ventilated with PEEP set at 5 or 0 cmH_2O; intraoperative and postoperative arterial oxygenation(PaO_2) were registered. Patients in the PEEP-group had a significantly higher level of PaO_2 after 3h and 4h of PnP, after disinflation a PaO_2 value below the pre-inflation value (4). Whalen et al. (5) investigated the effect of different PEEP levels (4 and 8 cmH_2O) and recruitment manoeuvres at a fixed level of VT set at 8 mL kg^{-1} on intraoperative arterial oxygenation. Recruitment manoeuvres (RM) were obtained with a progressive PEEP increase from 10 to 20 cmH_2O. As a result, the PaO_2/FiO_2 ratio significantly increased during PnP in the PEEP+RM-group, but it was promptly dissipat-

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ed at extubation (5). The usefulness of mechanical ventilation with different levels of PEEP at a fixed level of VT during laparoscopic procedure was investigated also by Kim et al. (6). In this study, VT was set at 8 mL kg^{-1} with PEEP at 0 or 8 cmH_20 in two randomized groups of patients. PaO_2/FiO_2 ratio was significantly higher in the PEEP group (8 cmH_2O) than in the ZEEP group at the induction of anaesthesia and 30 minutes after the inflation of PnP (6). Talab et al. (7) investigated the effects of different PEEP levels and VT on postoperative oxygenation and pulmonary complications. Patients were randomized in 3 groups receiving 0, 5, and 10 cmH_2O respectively of PEEP and 8-10 mL kg^{-1} of VT. The group with 10 cmH_2O of PEEP showed a better intraoperative and postoperative oxygenation and a lower incidence of atelectasis at the CT scan performed 2h after surgery (7). Pang et al. (8) evaluated the effect of PEEP and RM in laparoscopic cholecystectomy arterial oxygenation. A group of patients were ventilated with zero PEEP and 10 mL kg^{-1} of VT, and the second group with 10 cmH_2O of PEEP and RM (airway pressure set at 40 cmH_2O for 1 minute). The group with PEEP and RM showed an improvement in intraoperative oxygenation (8). Almarakbi et al. (9) performed a study to determine the effect of RM with or without PEEP on respiratory mechanics and arterial oxygenation in laparoscopic surgery. Patients were randomized in two groups; the PEEP-group receiving mechanical ventilation with 10 cmH_2O of PEEP and VT of 10 mL kg^{-1} and the PEEP+RM-group with repeated RM (airway pressure=40 cmH_2O per 15 seconds) followed by the previous ventilation setting (9). The respiratory compliance and arterial oxygenation were significantly improved by the RM strategy (9). Recently, Futier et al. (10) investigated the effect of RM on the end-expiratory lung volume (EELV) and oxygenation in patients undergoing laparoscopic surgery. Mechanical ventilation was obtained with VT of 8 mL kg^{-1}, PEEP of 10 cmH_2O and only one group received RM set with an airway pressure at 40 cmH_2O for 40s. As a result, the use of PEEP and RM improved the EELV and arterial oxygenation during PnP (10).

According to the randomized clinical trials previously reported, the optimal strategy for ventilating patients undergoing laparoscopic procedure may include PEEP and RMs in order to improve intraoperative arterial oxygenation and postoperative atelectasis. Further studies may assess the usefulness of this protective strategy.

Cardiac surgery

Impaired pulmonary function during cardiac surgery is well described. Altered lung mechanics and gas exchange are the main dysfunctions after cardiopulmonary bypass (11). Pulmonary dysfunctions in cardiac surgery have been attributed to a number of conditions as surgery “per se”, extracorporeal circulation, hypothermia, temporary cardiac dysfunction as well as anaesthesia. In particular, the small airway collapse and the cephalic shift of the diaphragm, due to patient position and anaesthesia, are responsible for the reduction in FRC and increase of bronchial tone.

Mechanical ventilation in open cardiac surgery may be challenging for the anaesthetists. We report randomized clinical trials evaluating the effect of different ventilator settings during this type of surgery (Table 2).

Mechanical ventilation with lower VT was probably the first protective approach to preventing lung injury in cardiopulmonary bypass. Wrigge et al. (12) evaluated the effect of low VT (6 mL kg^{-1}) compared to high VT (12 mL kg^{-1}) on inflammatory response in open cardiac surgery. As a result, the circulating cytokines did not change, while it was found at a higher level of TNF-α in the bronchoalveolar fluids of patient with high VT. Koner et al. (13) introduced the use of PEEP in mechanical ventilation for cardiopulmonary bypass. In this study, patients were ventilated with protective ventilation (PEEP=5 cmH_2O, VT=6 mL kg^{-1}), conventional ventilation (PEEP=5 cmH_2O, VT=10 mL kg^{-1}) and conventional ventilation without PEEP (VT=10 mL kg^{-1}). The authors found no difference in inflammatory response while the plateau pressure was lower in the protective ventilation group than the other groups. Interestingly, arterial oxygenation was better in all the PEEP groups than in the conventional ventilation group without PEEP (13). Zupancich et al. (14) evaluated the effect of different levels of PEEP and VT on inflammatory response in cardiopulmonary bypass. Patients were randomized in a group with high VT/low PEEP (12 mL kg^{-1}, 2-3 cmH_2O) and low VT/high PEEP (8 mL kg^{-1}, 10 cmH_2O). IL-6 and IL-8 were checked in bronchoalveolar fluid and plasma at baseline,

Table 1. Randomized studies on mechanical ventilation in laparoscopic surgery as reported according the year of publication

Author/Years	Patients	Conventional ventilation	Protective ventilation
Pang 2003	24	PEEP=0 cmH_2O	PEEP=5 0 cmH_2O
		TV=10 mL kg^{-1}	TV=10 mL kg^{-1}
Meininger 2005	20	PEEP=0 cmH_2O	PEEP=5 cmH_2O
Whalen 2006	20	PEEP=4 cm H_2O	PEEP=12 cmH_2O
		TV=8 mL kg^{-1}	TV=8 mL kg^{-1}
Talab 2009	66	PEEP=0 cmH_2O	PEEP=5/10 cmH_2O
		TV=8/10 mL kg^{-1}	TV=8/10 mL kg^{-1}
Almarakbi 2009	60	PEEP=10 cmH_2O	PEEP=10 cmH_2O +RM
		TV=10 mL kg^{-1}	TV=10 mL kg^{-1}
Kim 2010	30	PEEP=0 cmH_2O	PEEP=5 cmH_2O
		TV=8 mL kg^{-1}	TV=8 mL kg^{-1}
Futier 2010	60	PEEP=10 cmH_2O	PEEP=10 cmH_2O + RM
		TV=8 mL kg^{-1}	TV=8 mL kg^{-1}

VT: Tidal volume, RM: Recruitment manoeuvres

Table 2. Randomized studies on mechanical ventilation in open abdominal surgery as reported according the year of publication

Author/Years	Patients	Conventional ventilation	Protective ventilation
Tusman 1999	30	PEEP=0 cmH_2O	PEEP=5 cmH_2O±RM
		TV=7/9 mL kg^{-1}	TV=7/9 mL kg^{-1}
Wetterslev 2001	40	PEEP=0 cmH_2O	Best PEEP
Walthius 2008	46	PEEP=0 cmH_2O	PEEP=10 cmH_2O
		TV=12 mL kg^{-1}	TV=6 mL kg^{-1}
Determan 2008	40	PEEP=0 cmH_2O	PEEP=10 cmH_2O
		TV=12 mL kg^{-1}	TV=6 mL kg^{-1}
Reinius 2009	30	PEEP=0 cmH_2O	PEEP=10 cmH_2O
		TV=10 mL kg^{-1}	TV=10 mL kg^{-1}

VT: Tidal volume, RM: Recruitment manoeuvres

Table 3. Randomized studies on mechanical ventilation in cardiac surgery as reported according the year of publication

Author/Years	Patients	Conventional ventilation	Protective ventilation
Dyhr 2002	16	PEEP=0 cmH_2O	Best PEEP
		TV=6 mL kg^{-1}	TV=6 mL kg^{-1}
Koner 2005	44	PEEP=0 cmH_2O	PEEP=5 cmH_2O
		TV=5 mL kg^{-1}	TV=10 mL kg^{-1}
Wrigge 2005	44	PEEP=0 cmH_2O	PEEP=0 cmH_2O
		TV=12 mL kg^{-1}	TV=6 mL kg^{-1}
Reis Miranda 2005	62	PEEP=5 cmH_2O	PEEP=10 cmH_2O
		TV=9 mL kg^{-1}	TV=4/6 mL kg^{-1}
Zupancich 2005	40	PEEP=2/3 cmH_2O	PEEP=10 cmH_2O
		TV=12 mL kg^{-1}	TV=8 mL kg^{-1}
Celebi 2008	60	PEEP=5 cmH_2O	PEEP=5 cmH_2O+RM
		TV=7 mL kg^{-1}	TV=7 mL kg^{-1}
Sundar 2011	149	Best PEEP	Best PEEP
		TV=10 mL kg^{-1}	TV=6 mL kg^{-1}

VT: Tidal volume, RM: Recruitment manoeuvres

after cardiopulmonary bypass separation (timing1) and after 6 h of mechanical ventilation (timing 2). The cytokines decreased in both groups at the first timing but, at the second timing, they were only found in the high VT/low PEEP group (14). In the study by Reis Miranda et al. (15) patients were ventilated with conventional ventilation (VT=9 mL kg^{-1}, PEEP=5 cmH_2O) or protective ventilation (VT=4/6 mL kg^{-1}, PEEP=10 cmH_2O). IL-8 decreased more rapidly in the protective ventilation group. Sundar et al. (16) evaluated the effect of low VT associated to the best PEEP in patients undergoing elective cardiac surgery. Mechanical ventilation with 10 mL kg^{-1} and the best PEEP of VT were compared with protective with 6 mL kg^{-1} of VT and best PEEP. Patients with protective ventilation were extubated quickly and several improvements were found in the lung mechanics and gas exchange (16).

The beneficial role of different types of RMs was investigated in 3 studies. Dyhr et al. (17) associated a RM, performed with the airway pressure set at 45 cmH_2O for 20s, to mechanical ventilation with zero or 5 cmH_2O of PEEP and 10 mL kg^{-1} of VT. The authors reported an improvement in EELV and oxygenation in the PEEP+RM group. Celebi et al. (18) investigated the effect of two different RMs associated to a mechanical ventilation with 5 cmH_2O of PEEP in cardiopulmonary bypass. Recruitment maneuver was obtained in the first group with continuous positive airway pressure (CPAP) applying an airway pressure of 40 cmH_2O for 30s, while in the second group RM was performed with 20 cmH_2O of PEEP for 2 minutes. The patient oxygenation and the incidence of atelectasis were ameliorated in both RM groups (18).

A ventilation strategy with low VT, PEEP and RM seems to be useful in cardiac surgery, but further studies are needed to assess the validity of this clinical condition.

Abdominal surgery

Postoperative respiratory complications, as well as pneumonia and atelectasis, are common after open abdominal surgery. They are responsible for an increase of morbidity and mortality in the postoperative period. Randomized clinical trials have investigated the effect of different patterns of mechanical ventilation in this type of surgery with the aim of reducing intraoperative and postoperative pulmonary complications. Randomized clinical trials evaluated the effect of different ventilator settings during this abdominal surgery (Table 3).

Walthius et al. (19) investigated the effects of mechanical ventilation with low VT and high PEEP (6 mL kg^{-1}, 10 cmH_2O) and high VT (10 mL kg^{-1}, without PEEP) on systemic and pulmonary inflammatory responses in patients undergoing open abdominal surgery with a duration ≥5 hours. In the PEEP group, the author found a decrease of pulmonary IL-8 and an improvement in intraoperative and postoperative oxygenation (19). Determann et al. (20) evaluated the influence of two different patterns on biomarkers of lung injury in abdominal surgery with a duration ≥5 hours. Patients were randomized in a group receiving mechanical ventilation with TV of 10 mL kg^{-1} plus best PEEP and a group with VT of 6 mL kg^{-1} plus best PEEP. As a result, there was no difference in the levels of different lung biomarkers analysed (20). Tusman et al. (21) investigated the PEEP effects in expanding collapsed alveoli during anaesthesia for abdominal surgery. Patients were randomized in 3 groups receiving the same VT set at 7-9 mL kg^{-1} but different PEEP levels set at zero, 5 cmH_2O and 5 cmH_2O plus RM. The Authors concluded that the use of PEEP might improve intraoperative and postoperative PaO_2, but this improvement was more evident in the PEEP plus RM group (21). Watterslev et al. (22) investigated the effect of best PEEP and fixed PEEP plus RM on compliance and oxygenation of patients in upper abdominal surgery. Arterial oxygenation was increased and pulmonary postoperative complications reduced in the PEEP groups compared to the ZEEP group. Recently, Reinius et al. (23) analysed the effects of 3 ventilation strategies on the incidence of atelectasis and respiratory function. Patients were randomized in 3 groups, with PEEP=10 cmH_20, RM with 55 cmH_2O of airway pressure without PEEP and RM with 55 cmH_2O of airway pressure and PEEP=10 cmH_2O. Atelectasis was investigated with CT scan and respiratory gas exchange with repeated blood gas analysis. The main results of this study were: RM plus PEEP reduced atelectasis, increased end-expiratory lung volume and PaO_2/FiO_2 ratio; PEEP alone did not reach the previous results; RM without PEEP had only a transient positive effect on respiratory function.

The use of PEEP with RM, associated with protective VT seems to be a good strategy for improving oxygenation and reducing atelectasis in open abdominal surgery but further studies are needed to assess the validity of this mechanical ventilation setting.

Ventilation modes in the operating room

Due to recent technological improvements, different modes of ventilation are currently available for general anaesthesia in the operation room. Generally, ventilation modes are divided into pressure, volume and time cycled or into control, assist-control and assisted ventilation. Actually in the operating room, the anaesthetists can choose the most appropriate ventilator mode according to the patient's condition, surgical procedure and type of anaesthesia.

Volume or pressure controlled ventilation is mainly used when patients cannot breathe spontaneously during general anaesthesia. In volumetric ventilation, the close control of tidal volume allows a better control of end-tidal carbon dioxide. In pressometric ventilation, the control of respiratory pressure might minimize the risk of an excessive and deleterious airway pressure in particular surgical conditions and allow attainment of an adequate ventilation in case of leakage. In patients undergoing posterior lumbar spine surgery, pressure-controlled ventilation (PCV) provided a lower peak airway pressure than volume-controlled ventilation when the ventilator is set to deliver the same VT (24). Obese patients undergoing laparoscopic cholecystectomy and ventilated with PCV, required lower respiratory rate and VT to maintain normorcarbia compared with patients ventilated with volume controlled ventilation (VCV) (25). In the previous study, patients in PCV showed a significantly lower value of alveolar-arterial oxygen gradient than with VCV (25). The beneficial effects of PCV are probably due to a more homogeneous distribution of pressure within the respiratory system and to a decelerating inspiratory flow profile that enhances the distribution of ventilation in the alveolae, improving gas exchange (26). Many advantages and disadvantages have been described for different ventilation modes, but actually there is no evidence of the superiority of one mode over another. Probably PCV may offer advantages in particular conditions requiring variable flow rates or pressure and volume limitation (27).

Recently, some ventilators associated volume controlled ventilation to autoflow, also called pressure-regulated volume-controlled ventilation (PRVCV) that automatically regulates the inspiratory flow to reach the set tidal volume without a high increase in airway pressure (28). PRVCV may have different advantages over PCV, providing the set VT with the minimal available pressure in cardiac surgical patients (29). The patients ventilated by PRVCV showed a better long-term oxygenation and a lower mean airway pressure than PCV in cardiac surgery (29).

Airway pressure release ventilation (APRV) is anew pressure-controlled ventilation mode, with an inverse ratio, developed on the basis of the open lung approach (30). In this ventilation, a higher continuous airway pressure is kept for a period of time usually more than 2 seconds and released until PEEP for one second. This ventilation has been previously investigated in moderate and severe acute lung injury and it was associated with less detrimental effects on the pulmonary system (31). Maung et al. (32) demonstrated that APRV is a safe mode of ventilation for hypoxemic or hyperbaric respiratory failure. APRV with moderate inverse ratio showed beneficial effects in gynaecological laparoscopy procedures with a laryngeal airway mask compared to conventional PCV (33). APRV increased VT, mean airway pressure and dynamic lung compliance but with comparable effects on oxygenation and peak airway pressure with PCV (33).

Biphasic airway pressure ventilation (BIPAP) is quite similar to APRV, as it allows the setting of two levels of airway pressure with the inspiratory period longer than expiratory period (34). BIPAP was useful for switching the patient from controlled to assisted spontaneous breathing at the end of surgery and to maintain an adequate ventilation in the presence of restrictive lung disease and neuromuscular blocking (35). BIPAP in general anaesthesia may prevent alveolar collapse due to cephalic diaphragm movements. Compared to conventional intermittent positive pressure ventilation, BIPAP showed beneficial effects in decreasing ventilation-perfusion mismatch and improving oxygenation during general anaesthesia (36).

Pressure support ventilation (PSV) was originally invented for the weaning of patients in intensive care units (37). It is characterized by a decelerating inspiratory flow supporting every triggered breath with positive pressure (38). PSV is frequently used in different clinical conditions, it allows assisted-spontaneous breathing, unloading respiratory muscles and, thus, reducing the work of breathing. PSV during general anaesthesia may ameliorate the distribution of regional lung ventilation (39). In a clinical study by Radke et al. (39) PSV induced a redistribution of ventilation toward the ventral lung region, checked by electrical impedance tomography during general anaesthesia. This data suggests to us that PSV may be an alternative method of ventilation during general anaesthesia for selected procedure and selected patients.

Conclusion

Protective mechanical ventilation during general anaesthesia, for different types of surgery, as provided by lower VT, adequate PEEP and RM, might improve respiratory function in the intraoperative period and have beneficial effects continuing in the post-operative period. However, future large prospective randomized controlled trials are warranted before these recommendations could be applied in daily clinical practice.

Conflict of interest

No conflict of interest was declared by the authors.

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