Artificial ventilation during pneumoperitoneum

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Summary
Laparoscopic surgery has been increasingly used in many surgical subspecialties, due to its various post-operative benefits. On the other hand, it presents intra-operative challenges to the anesthesia management. The inflation of the abdominal cavity with carbon dioxide leads to hemodynamic changes, mechanical respiratory system derangements (increased elastance, resistance and airway pressure), augmented V'CO₂, and alterations of the V'/Q' ratio and of the PaCO₂-PetCO₂ gradient. All these changes may be influenced by other factors, such as body position and baseline characteristics of the patient. To minimize the negative consequences of these modifications a protective ventilation strategy with the use of low tidal volumes and PEEP, eventually associated with recruitment maneuvers, is suggested. No ventilatory mode or anesthetic drug has been proven better than the others. It has been suggested that the use of supraglotic devices may be a safe alternative to endotracheal intubation during laparoscopic surgery. It is important that the anesthetist be aware of the complications pertaining to pneumoperitoneum to solve them quickly, paying particular attention to the patients at higher risk, such as elderly, obese, and those with cardiopulmonary disease.

KEY WORDS: pneumoperitoneum, artificial ventilation, obesity, laparoscopy, anesthesia.

Introduction
Laparoscopic surgery has been increasingly employed in various surgical subspecialties because of its innumerable benefits. These are evident during the post-operative period and result from the less important organ/tissue trauma caused by laparoscopic approaches than those triggered by open surgery. The main advantages of laparoscopic surgery are: reduction of the inflammatory and metabolic responses (1-3), reduced post-operative pain and analgesic consumption (2, 3), smaller incidence of respiratory complications (2), faster resolution of post-operative ileus and recovery (1). Taken together, these outcomes reduce hospital stay, promote a quicker return to normal daily activities (2-4), and reduce the cost of the treatment (4).

On the other hand, laparoscopic surgery presents some challenges regarding the intra-operative anesthesia management, since there are respiratory and hemodynamic changes pertaining to the general anesthesia itself, to the abdominal insufflation, and to the intra-operative positioning of the patient (5). These issues become even more evident in patients with cardiopulmonary disease or obesity (6). This review focuses on the intra-operative respiratory alterations caused by laparoscopy and on the ventilatory strategies that are prone to minimize the modifications evoked by the technique.

Alterations of the respiratory system
In order to allow an adequate observation of the surgical field, laparoscopic surgery requires controlled gas insufflation into the peritoneal cavity (pneumoperitoneum). For this purpose, carbon dioxide is regularly used under a pressure of 10-15 mmHg. Naturally, respiratory issues related to mechanics and CO₂ overload
owing to the absorption of the gas into the circulation ensue.

**Respiratory system mechanics**

Pneumoperitoneum distends the abdominal wall and cranially displaces the diaphragm, which diminishes lung volumes, including the functional residual capacity (FRC) (7, 8), and, thus, increases the amount of atelectasis. Computed tomography scanning has also registered these alterations, showing a 1-3 cm cephalad diaphragmatic displacement and a higher incidence of atelectasis, especially in the dependent zones of the lung (9).

Furthermore, the high intra-abdominal pressure (Pab) increases respiratory resistance and elastance (i.e., reduces compliance). As a result, airway pressure augments (6, 7, 10, 12-16).

One should bear in mind that respiratory system elastance (Ers) equals the sum of lung (EL) and chest wall (Ew) elastances, that are both increased by pneumoperitoneum. The higher EL results from the reduced lung volumes, the more important degree of atelectasis, the shift of blood from the abdomen into the thorax (17) and the surfactant alterations (7). Ew augments because of the stiffer diaphragm (7) and chest wall conformational changes (6, 12).

Some authors found that Ew increases more than EL (7, 12, 15, 16). Pneumoperitoneum rises respiratory system resistance (Rrs) (6, 7; 10-13) mainly due to lung and chest wall viscoelastic properties and mechanical heterogeneities (12). Airway resistance (Raw) remains unaltered (7, 12). Hence, the increase in elastance represents the main component of the larger respiratory system impedance (which depends on both Ers and Rrs) triggered by pneumoperitoneum (10).

According to Eq. 1, the increased Ers and Rrs induce larger Paw:

\[ \text{Paw}(t) = \text{Ers}.V(t) + \text{Rrs}.V'(t) \quad \text{(Eq.1)} \]

where V, V' and t are volume, flow and time, respectively.

It has been demonstrated that both peak and plateau Paw are higher during pneumoperitoneum (13, 15, 16), as shown in Figure 1. It should be stressed that Paw does not allow the identification of which respiratory system mechanical component is altered. It reflects both pulmonary and chest wall phenomena, which are measured using transpulmonary (PL) and transthoracic pressures (Pw), respectively. To pinpoint these components, one should use the intrapleural pressure, which is more easily and safely represented by the esophageal pressure (18).

Taking into consideration that the increased Ew generates most of the additional mechanical load generated by pneumoperitoneum, most of the increased Paw is spent to overcome it (higher Pw). This additional pressure is not transmitted to the lungs (PL does not change appreciably) and, thus, does not harm them. Consequently, right after the beginning of abdominal insufflation the anesthetist should establish a new set point to monitor Paw (19).

Clinically, an increase in intrathoracic pressure can diminish cardiac output (6) and trigger ventilator-induced...
Pneumoperitoneum elevates both the CO₂ level in the organism and the CO₂ production (V'CO₂). These alterations may lead to hypercapnia and respiratory acidosis (7, 28, 29) that are more commonly found in patients with cardiopulmonary impairment (31). The increase in V'CO₂ results solely from the higher peritoneal absorption of CO₂ and not from either a higher metabolic rate (28, 29, 32) or an increased dead space (26, 27). The higher CO₂ absorption is time-limited, generally reaching a steady-state 15-30 minutes post-insufflation (28, 33). It is also restrained by Pab: when it reaches about 10 mmHg CO₂ absorption stabilizes, probably owing to compression of the peritoneal capillaries (32). In practice, the changes in V'CO₂ found after the steady-state is reached probably result from other causes, e.g., V'/Q' mismatch, hypventilation, or CO₂ absorption by other tissues, as in subcutaneous emphysema (32) or carbothorax (34), which are complications of the pneumoperitoneum. It should be noted that CO₂ absorption is more important (40-60% vs 10-15%) (29) and does not reach a plateau in extraperitoneal laparoscopic procedures, as pelviscopy or urologic surgery (28, 29). Possibly, the higher density of blood vessels in these areas and the continuous dissection of the extraperitoneal space could explain these findings (28, 29).

Carbon dioxide output remains elevated and is well tolerated even after the resolution of the pneumoperitoneum in patients with normal cardiorespiratory function (35). However, it can cause post-operative hypercapnia in sedated subjects or in those with cardiopulmonary disease (31, 36).

Clinically, the partial pressure of end-tidal CO₂ (PetCO₂) is used to monitor the arterial partial pressure of CO₂ (PaCO₂). Even though a correlation between these two parameters has been reported during laparoscopy (7, 11), there is evidence that PetCO₂ does not properly estimates PaCO₂, especially in patients with cardiorespiratory disease (31, 37) and in elderly subjects (23). In both cases, the PaCO₂-PetCO₂ gradient increases unpredictably. This gradient varies inter-and intra-individually, since it increases with time in the same patient (5). The origin of this variation is not clear, though. Putative candidates to explain this phenomenon are: redistribution of the V'/Q' ratios throughout the lung (that occurs during anesthesia), decubitus, and the variable efficiency of the hypoxic pulmonary vasoconstriction produced by the anesthetic drugs (5, 38-40). Interestingly, the degree of atelectasis during pneumoperitoneum is associated with the PaCO₂-PetCO₂ gradient, but not with the PaO₂/FIO₂ ratio (41). In conclusion, one should repeatedly monitor PaCO₂ by blood gas analysis, at least in patients with compromised cardiopulmonary function (37) and eventually in the elderly.

Body position

The aforementioned parameters can undergo variations according to the intra-operative positioning of the patient. The literature presents diverging results, though. Some studies state that elastance does not vary among supine, Trendelenburg and anti-Trendelenburg positions, which represent body postures frequently used in laparoscopic surgery, even in obese patients.
obese patients (11). A putative explanation for this finding stems from the fact that the diaphragm is overdistended by CO\textsubscript{2} to a degree impossible to be modified by simply changing body position (11, 14). On the other hand, lung elastance and resistance may increase in Trendelenburg position (6), the beach chair position improves lung volumes, resistance and oxygenation in obese patients (16), and in obese hypertensive patients with chronic obstructive pulmonary disease similar results have been reported in anti-Trendelenburg position (42).

Obese patients

Laparoscopic bariatric surgery has been increasingly performed. In this condition, besides the challenges presented by laparoscopy itself, there are anesthesiological issues characteristic of obese patients. Under baseline conditions they present increased chest wall (43) and, possibly, pulmonary elastances (44, 45), reduced lung volumes (including FRC), and higher closing capacity. As a result, V’/Q’ mismatch, impaired oxygenation and increased shunt (46) can be found. These pathologic conditions worsen during general anesthesia (47).

Pneumoperitoneum adds an extra burden to those promoted by general anesthesia. The increase in Rrs is relatively larger than that displayed by non-obese subjects, possibly because of the narrower airways secondary to the lower lung volumes (11). Elastance also increases (16, 48, 49), but to a lesser extent than in normal weight individuals (11). Indeed, the higher baseline Pab renders the additional load generated by pneumoperitoneum a small fraction of the overall pressure (48). Oxygenation is inversely correlated with body mass (47), and remains unaltered or improves in the presence of pneumoperitoneum (11, 16, 48, 49). Carbon dioxide elimination is not as efficient as in normal weight subjects, which requires a higher minute ventilation to reach and maintain a given PaCO\textsubscript{2}. Consequently, the control of hypercapnia poses an extra difficulty to the physician (11, 49).

Mechanical ventilation

Protective ventilation and hypercapnia

Protective ventilation (small tidal volumes and positive end-expiratory pressure, PEEP) has been claimed to reduce pulmonary inflammation and mortality in patients with acute respiratory distress syndrome (ARDS) (50). Protective ventilation would avoid as much as possible lung injury. In fact, it has been already proven that artificial ventilation may worsen (50) or cause VILI (51), which triggers lung inflammation (biotrauma), production of pro-inflammatory mediators, systemic inflammation, and, possibly, injures other organs (50). High tidal volumes, since they can overdistend alveoli (volutrauma) (52), and the absence of adequate PEEP levels, which leads to cyclic alveolar opening-closing (atelectrauma) (53) constitute the probable main culprits of VILI.

A ventilatory strategy with a tidal volume of 6-8 ml/kg BW and a PEEP amounting to 6-8 cmH\textsubscript{2}O used in either open or laparoscopic surgery improves post-operative respiratory function, reduces the incidence of pulmonary and extra-pulmonary complications and hospital stay in comparison with a strategy with high tidal volume and no PEEP (54). Additionally, a tidal volume of 7 ml/kg BW plus a 10-cmH\textsubscript{2}O PEEP employed per-operatively (open surgery) produced a better post-operative respiratory function than a non-protective ventilation (55). A recent meta-analysis, which includes these studies, confirms that a protective ventilation strategy can decrease the development of ARDS, pulmonary infection and atelectasis, but not mortality, in previously non-injured lungs in the peri-operative period and in the intensive care unit (56). It would be interesting to perform similar studies in laparoscopic surgery.

The use of low tidal volumes predisposes to the development of hypercapnia, which is commonly present during laparoscopy. Minute ventilation must be augmented to maintain normocapnia (33, 57). To accomplish such goal, one should increase respiratory rate instead of tidal volume. Such setting increases the risk of developing intrinsic PEEP (PEEPi), which demands a closer control by the anesthetist. Such risk is further increased by pneumoperitoneum that elevates Rrs (6, 7, 10-13) especially in obese (11), COPD, and elderly patients, who present a higher closing capacity. However, the quest for normocapnia is still debatable, since hypercapnia possibly plays a protective role against the development of VILI (58-60).

Ventilatory modes

There are two modes of controlled ventilation: volume-controlled ventilation (VCV), in which the ventilator delivers a chosen tidal volume with a constant flow, and pressure-controlled ventilation (PCV), where a constant set pressure is applied with a pre-established duration. In the former and latter cases pressure and volume vary, respectively, as a function of the respiratory system mechanical properties.

During laparoscopy, PCV reduces peak pressure, keeps (61) or slightly diminishes (62) mean Paw, increases respiratory system dynamic compliance, and does not modify gas exchange and cardiac function (61, 62). One study states that in obese patients oxygenation and Paw are not influenced...
by the ventilatory mode (63), whereas another found better oxygenation, pH and PaCO2 in obese patients ventilated in PCV, remaining mean and plateau Paw's similar in both modes. The authors suggest that an improved V'/Q' could respond for a better gas exchange in PCV (64).

One disadvantage of PCV rests on the tidal volume variability and, hence, the impossibility of assuring a constant minute ventilation. However, some recently introduced operating room ventilators incorporate a pressure-controlled volume-assured ventilatory mode. In this case, the anesthetist sets tidal volume that is delivered under decelerating airflow and constant pressure. The ventilator automatically regulates the latter.

Increasing inspiratory duration can improve V'/Q'. A study demonstrated that the ventilation in VCV mode with an inspiratory/expiratory ratio (I:E) of 1:1 or 2:1 rises mean Paw and maintains oxygenation during pneumoperitoneum (65). A 5-cmH2O PEEP with I:E=1:2 produces the same outcomes, but increases peak and plateau pressures. PEEP was detected in some patients with augmented I:E, which could explain the better oxygenation. Furthermore, CO2 removal is improved in patients with augmented I:E (65), suggesting that PEEP can increase dead space (66). It should be stressed that a high inspiratory duration should be cautiously used in patients with a slow alveolar emptying, as those with COPD.

A better oxygenation in pressure-support ventilation (PSV, in which the patient triggers tidal volume delivery) than in PCV was found in pigs with pneumoperitoneum (67). The beneficial effect of PSV probably results from the diaphragmatic contractions that better distribute ventilation, even to normally less ventilated regions (68).

Briefly, there is no net superiority among ventilatory modes. The anesthetist should in fact choose the mode that suits her/him, based on personal experience.

Alveolar recruitment and PEEP

Applied PEEP increases lung volume (8) and avoids end-expiratory airway closure (69), thus reducing atelectrauma (70). A 5-cmH2O PEEP diminishes intrapulmonary shunt and improves oxygenation in the presence of pneumoperitoneum (71). EIT confirmed that PEEP augments ventilation in the dependent lung zones during pneumoperitoneum (30, 72). Furthermore, the improved V' distribution may indicate that there is a less intense alveolar stretching in the non-dependent lung regions (72). On the other hand, PEEP can excessively distend the alveoli, increasing the risk of barotrauma and decreasing cardiac output, especially in hypovolemic patients, impairing V'/Q' and oxygenation (73, 74).

It is quite possible that the individual response to PEEP results from the balance between its positive and negative outcomes. For instance, a 10-cmH2O PEEP improves oxygenation in obese subjects but not in normal weight individuals, possibly because in the former its beneficial effects overcome their negative counterparts (47).

Recruitment maneuvers (RM), which require a high Paw, aim at the reopening of atelectatic alveoli (75) that are maintained open by the subsequent use of PEEP. In normal weight and obese patients, a 10-cmH2O PEEP partially overcomes the negative consequences of pneumoperitoneum because it increases FRC and diminishes Ers. Oxygenation also improves when PEEP is associated with a RM of 40 cmH2O during 40 s (8). The fall in Ers, which is due mainly to EL (15), possibly indicates that the higher FRC results from alveolar recruitment and not from overdistension (8). These findings have been recently confirmed by the use of a RM generated by a progressive increase in the PEEP level (under PCV) until peak pressure equalled 40 cmH2O, followed by a 5-cmH2O PEEP. Furthermore, even Ew decreases, probably because of the higher pulmonary expansion that resembles to a better extent the physiological conformation not only of the lung, but also of the chest wall (13). Additionally, PEEP can reduce Rrs because it opens and stabilizes air spaces (13, 15).

PEEP associated with repeated RM's improves oxygenation (76, 77) and respiratory mechanics in obese patients with pneumoperitoneum (77). It should be mentioned that in one study the patients required more vasopressor agents (76). Interestingly, repeated RM associated with a PEEP of 10 cmH2O or the beach chair position could improve respiratory mechanics and oxygenation in the absence of pneumoperitoneum; however, the association of these maneuvers was wanted during abdominal inflation (16).

The possible reduction of central nervous system perfusion and oxygenation owing to PEEP in the presence of pneumoperitoneum raises an important issue. PEEP by itself increases central venous pressure (CVP) and reduces mean arterial pressure (MAP), whereas pneumoperitoneum alone triggers vasodilation of the cephalic blood vessels, as a result of hypercapnia, and may, thus, increase intracranial pressure (78), especially in Trendelenburg position (79). Recently, however, it has been reported that a 10-cmH2O PEEP and Trendelenburg position maintain cerebral oxygenation even in the presence of reduced perfusion pressure (calculated as the difference between PAM and PVC) during pneumoperitoneum (80).

In summary, it seems that PEEP represents a valid tool to maintain oxygenation during pneumoperitoneum. Particularly in obese patients, it should be associated with recruitment maneuvers.

Inspiratory oxygen fraction ($\text{FiO}_2$)

It is well known that a $\text{FiO}_2$ equal to 1 is associated with the quick installation of atelectasis and a worsening of intrapulmonary shunt during general anesthesia in patients with normal lungs (81). Additionally, an experimental study demonstrated an exacerbation of lung damage when high tidal volumes are associated...
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with a FiO₂ equal to 0.5 (82). Thus, low levels of FiO₂ and low tidal volumes are recommended during surgery to avoid such undesired outcomes. This rationale can possibly be cautiously extended to laparoscopic surgery for the time being, since no report was found in the literature dealing with this issue.

Supraglottic devices

Commonly, laparoscopic surgery demands muscle relaxation, intubation, and controlled ventilation. However, this surgery can also be performed with supraglottic devices under spontaneous (83), assisted (84) or controlled ventilation (85–88). Laryngeal mask airway (LMA) was proven efficient during cholecystectomy (85, 87) and gynecological interventions (83, 84, 86, 88). LMA’s, particularly those with a conduit to allow the placement of a nasogastric tube, have a high oropharyngeal leak pressure and can, hence, provide adequate ventilation during laparoscopy (85, 87, 89). Additionally, they induce less post-operative pharyngolaryngeal discomfort than the tracheal tube (89), and present a very low risk of regurgitation in patients without any other risk factors under controlled ventilation (88). The latter observation raises an important issue, since it is generally accepted (90) that laparoscopy, especially in the Trendelenburg position, increases the risk of regurgitation and that LMA does not protect the airway against aspiration. Noteworthy, surgery with LMA results shorter than with tracheal tube (83, 84).

Anesthesia

The choice of the anesthesia procedure is undoubtedly reserved to the anesthetist. Nevertheless, isoflurane leads to a smaller PaO₂ and higher PaCO₂ than propofol during laparoscopic cholecystectomy (38). Possibly, the maintenance of the hypoxic pulmonary vasoconstriction by propofol may explain this finding (91). Desflurane and sevoflurane seem to exhibit the same pharmacological property of propofol (40). Studies dealing with the role of anesthetic agents on lung inflammation produced conflicting results. Indeed, propofol yields a pro-inflammatory effect, contrasting the halogenated anesthetics (92, 93). A recent work on pigs reports just the opposite (94), whereas no difference has also been described (95). In the absence of more precise data, it thus seem more appropriate that the anesthetist chooses the pharmacological agent to be used, carefully considering the hemodynamic changes produced by the anesthetics. The neuromuscular blockers, commonly considered essential for the laparoscopic surgery, do not importantly change respiratory mechanics during pneumoperitoneum in intubated patients (15). The insertion of the trocar in spontaneously breathing patients with LMA seems to be more difficult than in intubated paralyzed subjects; however, after the placement of the trocar, both approaches allowed a good observation of the surgical field (83).

In conclusion, laparoscopic surgery presents evident pre-operative risks besides the beneficial outcomes observed after surgery. It is imperative that the anesthetist be thoroughly aware of the possible respiratory and hemodynamic impairments and of the complications pertaining to the pneumoperitoneum to solve the undesired outcomes adequately and quickly. Finally, one must bear in mind that there are patients presenting a more important risk to develop complications and deserving a closer observation, as the elderly or obese, and those with cardiopulmonary disease.

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