Carbon dioxide pneumoperitoneum, physiologic changes and anesthetic concerns

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Abstract

Objective: To review the different changes in physiology during carbon dioxide pneumoperitoneum, and the necessary adjustments to minimize and manage them.

Data sources: Data were obtained from searches in PubMed years 1997 to 2009, using key words: laparoscopy and anesthesia, effects of pneumoperitoneum on cardiovascular system, pneumoperitoneum and respiratory system, renal perfusion during laparoscopy.

Results: Many physiological changes occur during CO_2 pneumoperitoneum. The severity of these changes depends on the intra-abdominal pressure being used, and also the position of the patient on the operating table plays an important role. With adequate adjustments and pharmacologic therapy, many of these alterations can be safely managed and prevented.

Conclusion: A thorough understanding of the pathophysiology which occurs during carbon dioxide intra-abdominal insufflation is mandatory to manage promptly any complications that arise. Anesthetists and surgeons should also put much emphasis on ways and techniques to reduce these alterations, therefore reducing patients' exposure to complications that might follow.

Keywords: Pneumoperitoneum; Elevated abdominal pressure; Insufflation; Hypercarbia; Desufflation; Cardiac output

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Introduction

Laparoscopic surgery is nowadays a common daily-performed procedure worldwide, replacing many types of open surgeries. It has the benefits of small incision, improved cosmetic aspects, less postoperative pain, and quick recovery time to normal activities [1, 2]. The most commonly used gas for insufflation is carbon dioxide. Carbon dioxide CO_2 pneumoperitoneum and increased intra-abdominal pressure can induce many pathophysiologic disturbances, requiring the anesthesiologist to be well alert during the operation for necessary management. Moreover, advanced laparoscopic surgeries are being used also on older patients and in critically ill patients, requiring technically demanding anesthesia.

Pathophysiologic changes

Respiratory changes

The physiology of respiratory system is affected by pneumoperitoneum. With insufflation, causing an increase in intra-abdominal pressure (IAP), the diaphragm is pushed upwards causing stiffness of the chest wall, causing the total volume of the lungs to be reduced. Hence the pulmonary compliance is decreased to 35–40% and also a non-negligible increase in the maximum respiratory system resistance [3, 4, 5, 6]. Hypoxemia may occur from a ventilation-perfusion mismatch and intrapulmonary shunting [7] but is rare in healthy patients.

Carbon dioxide is usually administered at a rate of 1–2 ml/min. Being a highly soluble gas, it is readily absorbed into the circulation through the peritoneum, causing hypercapnia and acidosis. Several studies have shown the effect of CO_2 pneumoperitoneum on the arterial partial pressure of CO_2 ($PaCO_2$) and end-tidal CO_2 ($ETCO_2$). One study has compared laparoscopic Roux-en-Y gastric bypass (GBP) against open surgery. It found that $ETCO_2$ was raised from 35 mmHg to 40 mmHg, i.e. by 14%, whereas PaCOv also was raised by 10%, from 38 mmHg to 42 mmHg [8]. $PaCO_2$ levels were initially 34 mmHg and increased to 42 mmHg with pneumoperitoneum as reported by Demiroluk and al [9]. Wittgen et al [10] found that patients with normal cardio-respiratory system had increased $ETCO_2$ and PaCOv, decreased pHa values in a study comparing ventilatory effects of laparoscopic cholecystectomy in 10 ASA I and II patients and in 10 ASA III and IV patients. However, changes were more pronounced in the ASA III and IV patients.

Carbon dioxide is mainly excreted by the lungs, depending on alveolar and mixed venous CO_2 exchange rates, which are themselves controlled by the cardiac output, alveolar ventilation and respiratory quotient [11]. Normal excretion of CO_2 is 100–200 mL/min and is increased by 14–48 mL/min when CO2 is administered intraperitoneally [12, 13, 14, 15]. After a long laparoscopic operation, achieving a normal CO_2 value can take several hours after desufflation, [16, 17] since high use of peripheral storage capacity will lengthen the duration of increased $PaCO_2$.

Cardiovascular changes

Cardiovascular system effects during CO_2 pneumoperitoneum are caused mainly by hypercarbia followed by acidosis and increased intra-abdominal pressure. A euvolemic status is of great importance prior to surgery to reduce any cardiac depression via reduced preload caused by the pneumoperitoneum. Hypercarbia has direct and indirect sympathoadrenal stimulating effects on cardiovascular functions. These effects are not pronounced with mild hypercarbia ($PaCO_2$ 45–50 mmHg), whereas moderate to severe hypercarbia affects cardiac function [18] since it is then a myocardial depressant and has direct vasodilatary effect. Dexter et al [19] studied 2 groups of patients, one with pneumoperitoneum of 7 mmHg and the other with a pressure of 15 mmHg. Both groups showed an increase in heart rate and mean arterial pressure, but the cardiac output and stroke volume were more considerable depressed in the 15 mmHg group. Westerban et al [20] studies showed a 30% decrease of cardiac index in patients during laparoscopic cholecystectomy. Kraut et al [21] showed a mild decrease in cardiac output and stroke volume using insufflation pressure of 15 mmHg. The addition of 10 cm of PEEP resulted in significantly reduced cardiac output and stroke index. Those authors therefore concluded that combination of increased IAP and PEEP should be avoided. With a post-inflation IAP of 15 mmHg, Joris et al [22] showed a mean arterial pressure increase of 35%, systemic vascular resistance increase of 65%, pulmonary vascular resistance increase by 90%, and a decrease in cardiac index by 20%. The authors suggested that increased vascular resistance could partly increase the cardiac index.

Renal changes

Oliguria is the most common renal effect of pneumoperitoneum [23, 24, 25]. Different mechanisms are involved in the reduction of the urine amount during IAP. Shuto et al. showed that compression of the renal vessels and parenchyma with an insufflation pressure of 20 mmHg causes a significant decrease in renal blood flow(RBF) [26]. IAP also activates of the renin-angoitensin-aldosterone system following decreased renal perfusion, which results in renal cortical vasoconstriction. Nguyen et al [27] concluded that the level of ADH, renin, and aldosterone significantly increased during laparoscopic GBP. Chui et al [28] reported a decrease of 60% in renal cortical flow, which however returned to normal after desufflation. Otega et al [29] reported a precipitous rise in ADH concentration during laparoscopic cholecystectomy, which was not seen in open cholecystectomy. The exact mechanism of renal blood flow disturbance by pneumoperitoneum is still to be concluded, although volume status may play a major role. Renal blood flow has been measured during increasing IAP, and a gradual decrease in RBF up to 75% was observed upon reaching a pressure of 15 mmHg [30]. London et al [31] measured the RBF in pigs using a renal artery flow probe during IAP of 15 mmHg. Pigs were given maintenance fluids, bolus fluids, or hypertonic saline. A 30% drop in RBF was found in those with maintenance fluid, whereas this change was not noticed in well-hydrated animals with adequate volume loading. Controversially, there are also studies that reported no RBF changes during pneumoperitoneum. Yavuz et al [32] compared IAP of more that 15 mmHg and less that 10 mmHg using color microspheres to measure perfusions in pigs. A decrease was found in splenic, pancreatic, gastric mucosal blood flow, but the RBF was preserved in both high and low pressure groups. Ali et al [33], with an IAP of 15 mmHg, using ethyl nitrate and without on pigs found out that neither groups had a decreased RBF compared with the baseline. The serum creatinine levels have also been seen to rise during pneumoperitoneum. Krisch et al [34] using an IAP of 5 or 10 mmHg, reported a significant increase of serum creatinine in rats within the 10-mmHg group. The creatinine level however returned to baseline level after 2 hours following desufflation. Nguyen et al [23] found in their studies that urine output was decreased during IAP but found no significant changes in postoperative creatinine levels. Miki et al [35] compared IAP and wall lifting technique during cholecystectomy laparoscopy. They reported a decrease in urine output and GFR, with effective renal plasma flow, during laparoscopy but these changes were not seen with the abdominal wall lift device technique.

Splanchnic changes

The splanchnic circulation is also affected during raised IAP. Depending on intra-abdominal pressures, studies in animals have show decrease in splanchnic macro and micro-circulation [36, 37]. Signs of hepatocytic damage [38] were noticed, with increase of glutamic oxaloacetic transaminase and glutamic pyruvic transaminase. Impaired Kupffer cell function [39] and gastric intramucosal pH drop were also noticed [40]. One study in human looking at splanchnic circulation changes during IAP increasing form 10 to 15 mmHg showed reduction in blood flow of 40–54% in stomach, 32% in jejunum, 44% in colon, 39% in liver, and 60 % in peritoneum [41].

Complications

Anesthetists should always bear in mind the possible pulmonary complications of pneumoperitoneum like gas embolism, barotraumas, hypoxemia, pulmonary edema, atelectasis, subcutaneous emphysema, pneumothorax, pneumomediastinum and pneumopericardium. Carbon dioxide embolism is rare, occurring in about 0.0014–0.6% of laparoscopic surgeries [42, 43, 44], but with a mortality rate of about 28% [45]. Carbon dioxide enters the circulation through an opening in a damaged vessel under raised IAP. It can also occur if the Veress needle is misplaced into a vessel or parenchymal organ. Transesophagal echocardiography studies have shown bubbling of CO_2 in the right heart chamber in 68% asymptomatic patients during pneumoperitoneum [46]. Clinical manifestations of gas embolism are severe drop in blood pressure, cyanosis, cardiac arrhythmias or asystole. A mill-wheel murmur may be heard on auscultation of the heart, and $ETCO_2$ will increase.

Subcutaneous emphysema occurs in 0.3–3.0% laparoscopic surgeries [42, 46, 47]. Mild to severe subcutaneous emphysema has generally not been shown to have clinical effects, but upper airway obstruction must be considered if there is neck involvement. Pneumothorax can occur following peritoneum visceral tear, parietal pleura tear during resection around the esophagus or congenital defect in the diaphragm through which CO_2 gas travels [48, 49, 50]. Extension of emphysema can also occur, causing pneumothorax and pneumomediastinum. It has been reported that even subcutaneous emphysema arising from extraperitoneal inguinal hernia repair has extended to cause pneumothorax and pneumomediastinum [51, 52, 53, 54]. Pneumothorax should be differentiated with capnothorax following CO_2 diffusion into the intrapleural space. With both pneumothorax and capnothorax, the $ETCO_2$ increases, so capnothorax can be suspected if the mean airway pressure increases with a drop in SpO_2, and confirmation should be made with a chest x-ray. Pneumopericardium can develop when CO_2 is forced into the mediastinum and pericardium [55]. It can also occur if CO_2 enters the defect in the membranous portion of the diaphragm, resulting in a communication between the pericardial and peritoneal cavities [56].

Cardiovascular complications such as hypertension, arrhythmias, hypotension and cardiac arrest have been reported with pneumoperitoneum. Hypertension seems to have a higher incidence at the beginning of insufflation when the blood volume in the splanchnic vasculature is reduced due to increased IAP, thereby increasing preload and arterial pressure [57, 58]. Arrhythmias occur in up to 14–27% of laparoscopies [45]. These must be differentiated from arrhythmias caused by release of catecholamine. Sinus tachycardia and ventricular extrasystoles are usually more benign, and dangerous ones like bradyarrhythmias (bradycardia, nodal rhythm, atrioventricular dissociation and asystole) are also seen. Bradyarrhythmias arise due to the vagal nerve mediated cardiovascular response following acute stretching of the peritoneum [45]. Hypotension, which occurs in up to 13% of laparoscopies, is a potentially serious complication [59]. IAP of 20 mmHg or more results in compression of the inferior vena cava, reducing the venous return. Cardiac output is reduced, leading to hypotension. This complication is aggravated by high intrathoracic pressure. Cardiac arrest has been reported 2–20 per 100,000 laparoscopies performed [45]. Vasovagal responses to quick intraperitoneal CO_2 insufflation and gas embolism have both been related to cardiac arrest.

The possible development of acute tubular necrosis in response to long lasting hypoperfusion from pneumoperitoneum is controversial. Koivusalo et al [60] compared 2 groups of patients during laparoscopic cholecystectomy using pneumoperitoneum 12 to 13 mmHg with an abdominal wall lift device. Urine-N-acetyl-B-D-glucosamonidase (marker for proximal tubular cell damage) level was higher in the pneumoperitoneum group. However, Micali et al [61] studied 31 patients during laparoscopic surgery, and 28 patients with open surgery. No differences were found in the two group's urine-N-acetyl-B-D-glucosamonidase, concluding that in their study pneumoperitoneum had no role in renal tubular injury.

Free radicals are released by inflation and deflation of the peritoneum [62]. Oxygen and organic free radicals may contribute to ischemia reperfusion phenomena or chemical carcinogenesis. Still, the impact of production of free radicals is smaller than with open surgery injury [63, 64].

Roles of patient positioning

Usually patients are put in Trendelenburg or reverse Trendelenburg position to facilitate the surgeon's view, and these positions have clinical impact. Joris et al [65] positioned patients on reverse Tredelenburg position for laparoscopic cholecystectomy. A reduced mean arterial pressure by 17% and cardiac index by 14% was noticed to patients on horizontal position. Gynecologic laparoscopic procedures are done in the Trendelendurg position. This tends to cause an increase in cardiac output with an increase in central venous pressure compared to horizontal position. This may help counteract the effects of insufflation [66]. Raised intracranial pressure and also intraocular pressure may be found in long procedures. Venous stagnation may lead to cyanosis and facial edema. Cephalad movement of the carina, which can lead to bronchial intubation, is also related to Trendelenburg position [67].

Other positions may be used as well. During lithotomy position, preload of the heart is increased, while pneumoperitoneum further increases the venous return. Patient's circulatory filling status plays a major role in the cardiac output. Right lateral decubitus position can cause compression of the inferior vena cava, resulting in hypotension.

Approach to general anesthesia, and management

Absolute contraindications to laparoscopy and pneumoperitoneum are rare. Nonetheless, pneumoperitoneum in patients with increased intracranial pressure or with significant hypovolemia is undesirable. Laparoscopy can be performed safely in patients with ventricular peritoneal shunt and peritoneojugular shunt if the shunts have a unidirectional valve resistant to the IAPs used during pneumoperitoneum. Anesthetic preparation is of utmost importance to face any of the possible complications that may occur during the procedure. Non-invasive blood pressure monitoring, electrocardiogram, pulse oximeter, $ETCO_2$ concentration monitoring, airway pressure monitoring and body temperature are used routinely. In patients with poor cardiopulmonary function or hemodynamic instability, invasive blood pressure monitoring should be used as well as blood gas analysis and urine output measurement. In patients with serious cardiac diseases, intraoperative assessment of cardiac function should be considered.

General anesthesia techniques for laparoscopy have been achieved using inhalation agents, intravenous agents and muscle relaxant. Among inhalation agents nitrous oxide, isoflurane, desflurane and sevoflurane have been widely used. Although nitrous oxide has repeatedly been linked to post operative nausea and vomiting(PONV), the actual contribution of N_2O to PONV is probably less than previously considered [68]. Intravenous induction agents such as propofol, thiopentone, etomidate, and muscle relaxants such as succinylcholine, mivacuronium, atracurium and vecuronium have all been reported to be used. Propofol among these has the advantage of less occurrence of PONV with ambulatory procedures [69], and etomidate with more PONV. Succinylcholine has been associated to muscular pain postoperatively, although after laparoscopy, pain may not be distinguishable when vecuronium. is used; nondepolarizing neuromuscular blocking drugs are usually preferred. Opioid supplementation namely, fentanyl, remifentanyl, alfentanyl and sufentanyl are commonly being used. Remifentanyl, which is rapidly hydrolysed by circulating and tissue nonspecific esterases, provides better control of hemodynamic responses compared with alfentanyl [70] and may therefore be preferable for infusions.

General anesthesia with tracheal intubation is certainly the safest technique recommended for patients with long laparoscopic intervention. The laryngeal mask (LMA) airway results in fewer cases of sore throat and may be used instead of endotracheal intubation [71, 72]. However, LMA does give any protection from aspiration of gastric contents in the airway [73, 74]. The ProSeal laryngeal mask airway may be an alternative to guarantee an airway seal up to 30 cm H_2O [75].

Settings of the IAP also should be monitored by the anesthesiologist during anesthesia. Recent studies recommend a moderate to low IAP of <12 mmHg to limit changes in splanchic perfusion, and resulting organ dysfunction will be minimal, transient and will not influence the outcome [76]. Using an IAP of 12mmHg or less is considered as the best approach to laparoscopic surgeries for safety considerations.

To enhance proper elimination of CO_2, and avoid hypercapnia and acidosis, ventilatory patterns must be adjusted. In order to maintain a eucapneic state in healthy patients, the ventilation minute volume should be increased by 15–25%. Use of positive end respiratory pressure (PEEP) also improves the gas exchange in the lungs [77], and maintains proper arterial oxygenation during long procedures [78]. However, PEEP combined with raised abdominal pressure, increases the intrathoracic pressure, thus reducing the cardiac output. Therefore, the use of PEEP should be used very cautiously in such circumstances [79, 80, 81, 82] and avoided in patients with cardiac dysfunction, or if hemodynamically unstable. The alveolar recruitment strategy has been proved to be efficient in improving arterial oxygenation during laparoscopic operations without any clinically adverse effect on cardio-respiratory system [83]. One version of this technique consists of manual ventilation with an airway pressure up to 40 cm H_2O for 10 breaths over 1 minute, shifting to mechanical ventilation with mild PEEP.

Among the pulmonary complications of pneumoperitoneum, gas embolism may be the most feared and dangerous complication. This complication develops principally during the induction of pneumoperitoneum, particularly in patients with previous abdominal surgery. For prevention of such complication the Veress needle should be inserted with the tap open and without connection to the insufflation machine. If the needle has been unintentionally introduced into a large vein, blood would be seen escaping via the open end. Volume preload diminishes the risk of gas embolism and of paradoxical embolism. Suspicion of gas embolism should be quickly managed with the following steps [84, 85, 86]:

- The surgeon should be asked to deflate the pneumoperitoneum
- Position the patient in the left lateral position with head down, which allows the gas embolus to accumulate in the right ventricular apex, thus preventing it reaching the pulmonary artery or impeding blood flow through the heart.
- Rapid elimination of CO2 by increasing the minute ventilation and administer high flows of 100% oxygen.
- Cardiopulmonary resuscitation must be performed in case of asystole, and insertion of a central venous catheter may be considered to aspirate the gas, although this may not be timely
- Hyperbaric oxygen therapy can be used if available.

Pneumothorax requires treatment if there is cardiopulmonary compromise. If minimal compromise, treatment can be conservative, but if there is moderate to severe compromise, severe pneumothorax needs placement of a chest drain. In patients with chronic obstructive pulmonary disease (COPD) and in patients with a history of spontaneous pneumothorax or bullous emphysema, an increase in respiratory rate rather than tidal volume is preferable to avoid increased alveolar inflation and thereby reduce the risk of pneumothorax [87]. Capnothorax is usually reabsorbed after desufflation, with rapid re-expansion of the lung [88, 89]. Pneumopericardium is also managed according to severity of cardiopulmonary changes. Usually deflation of the peritoneum is enough for the symptoms to subside.

Hypertension is well managed pharmacologically, to prevent further complications like hemorrhagic stroke, pulmonary edema and cardiac depression. If pharmacological interventions remain ineffective, deflation of the peritoneum is advised till cardiac status is stabilized. Persisting symptoms may require conversion to open surgery.

Hemodynamic changes can also be reduced during beginning of insufflation by placing the patient in horizontal position rather than head up or head down [90]. Preoperative intravascular volume loading of 10–12 mL/kg helps to reduce the drop in cardiac output related to raise IAP. Intermittent pneumatic compression of the legs also increases venous return and cardiac preload [91] Reducing the IAP, increasing the minute ventilation and administering 100% oxygen terminate almost all of the arrhythmias [59, 92]. Anticholinergic drugs such as atropine and glycopyrrolate can be used accordingly.

Volume loading helps to prevent renal complications and low dose dopamine 2µg/kg/min may prevent renal dysfunction in long standing pneumoperitoneum with increase IAP >15 mmHg [93]. Insufflation of warmed CO_2 gas has shown to increase urine output, possibly due to local renal vasodilation and may be beneficial in patients with borderline renal function [94]. Use of esmolol may minimize renal hypoperfusion during laparoscopy since it inhibits renin release and attenuate the pressor effects to pneumoperitoneum [95, 96].

Abdominal wall lift

Many pathophysiological changes have been seen to occur with CO2 pneumoperitoneum. To minimize these changes, an abdominal wall lift technique has been used [97, 98]. With this method, very low IAP of 1–4 mmHg can be employed with low volumes of CO2, from 2–6 litres [98]. Reduction in circulatory changes and CO2 absorption has been reported using abdominal wall lift [22,99].

Conclusion

Large numbers of laparoscopic surgeries are performed each year. There are several non-negligible pathophysiologic changes that occur during pneumoperitoneum, and the anesthesiologist must have a very sound knowledge and understanding to act quickly and accurately whenever required. It is obvious now that with excellent understanding of the factors causing alterations in physiology, many measures can be undertaken to prevent complications that sometimes can prove to be fatal. Much careful attention must be shown about the details of proper patient selection and use of appropriate surgical technique. Good communication between the surgeon and the anesthetist is also of great importance. Also, low intraabdominal pressures during laparoscopic surgery should be encouraged to minimize the potential for numerous complications. The use of the abdominal wall lift technique should be encouraged. Thereby, the incidence of pathophysiologic changes associated with the use of CO_2 for pneumoperitneum may be reduced to a great extent.

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