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ORIGINAL ARTICLE

Impact of AirSeal® insufflation system on respiratory and circulatory dynamics during laparoscopic abdominal surgery

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Abstract

The effect of the AirSeal® insufflation system on hemodynamic parameters, especially end-tidal carbon dioxide ($EtCO_2$), during laparoscopic abdominal surgery remains unclear. This retrospective single-center study included 333 consecutive patients who underwent laparoscopic hepatectomy ($n = 43$), gastrectomy ($n = 69$), colectomy ($n = 137$), or proctectomy ($n = 84$) using the AirSeal®. Patient demographics and intraoperative hemodynamic parameters, such as $EtCO_2$, peripheral capillary oxygen saturation (SpO_2), and arterial systolic blood pressure (ABP), were collected and analyzed. $EtCO_2$ was evaluated during the entire operative period (whole period) as well as the pneumoperitoneum period until specimen removal (pneumoperitoneum period). We defined "positive respiratory and circulatory responses" (positive responses) as a decrease in $EtCO_2 \geq 3$ mmHg in addition to decreases in $SpO_2 \geq 3\%$ and ABP ≥ 10 mmHg simultaneously, which suggest possible carbon dioxide (CO_2) embolism. The median $EtCO_2$ values of hepatectomy, gastrectomy, colectomy, and proctectomy in the whole period/pneumoperitoneum period were 37.3/37.4, 37.1/37.3, 37.4/37.9, and 38.2/38.4 mmHg, respectively. The $EtCO_2$ of proctectomy was significantly higher than that of gastrectomy during the whole and pneumoperitoneum periods ($P < 0.05$). In contrast, the $EtCO_2$ of hepatectomy was comparable to that of the other three surgeries in the whole and pneumoperitoneum periods. Meanwhile, nine (2.7%; eight hepatectomies and one proctectomy) patients showed positive responses, and one who underwent a partial hepatectomy developed a clinically manifested CO_2 embolism. Positive responses occurred during venous exposure or bleeding in all nine cases. Although the $EtCO_2$ of hepatectomy was comparable to that of the other surgeries using the AirSeal®, laparoscopic hepatectomy showed a tendency of CO_2 embolism. Thus, a secure and careful surgical approach is mandatory for laparoscopic hepatectomy using the AirSeal® insufflation system.

Keywords Laparoscopic surgery · Abdominal surgery · Laparoscopic hepatectomy · AirSeal® · Pneumoperitoneum

Introduction

To successfully perform laparoscopic surgery, establishing an adequate working space and a clear view of the operative field with pneumoperitoneum is essential. The AirSeal® (ConMed, Utica, NY, USA) is a valve-free insufflation system that maintains a stable pneumoperitoneum by continuously monitoring and adjusting carbon dioxide (CO_2) flow rates despite constant suction; it also provides satisfactory visualization by continuously evacuating surgical smoke. Its on-board CO_2 recirculation system is ideal during the coronavirus disease 2019 pandemic [1].

Several studies to date have compared the AirSeal® with conventional CO_2 insufflation systems and demonstrated the advantages of the former including reduced CO_2 use [2], lower intraperitoneal pressure [3, 4], shortened operative time [5], improved visualization of the operative field [6], and less postoperative shoulder pain [4] than conventional insufflation systems.

These studies evaluating the systemic effect of AirSeal® were mostly performed in the urological or gynecological fields [7], and only a few have examined the physiological effect of the AirSeal® on respiratory and hemodynamic function during laparoscopic abdominal surgery [3, 8]. We investigated the respiratory and circulatory effects of the AirSeal® during laparoscopic abdominal surgery with focus

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on end-tidal carbon dioxide ($EtCO_2$), a surrogate marker for CO_2 absorption [2].

Pneumoperitoneum can cause systemic absorption of CO_2 and result in hypercapnia and acidosis, leading to cardiac arrhythmias or various effects on myocardial contractility [9]. Increased CO_2 absorption can also cause CO_2 embolism, a rare but potentially life-threatening complication of laparoscopic surgery [10]. To prevent hypercapnia or CO_2 embolism, close intraoperative monitoring of $EtCO_2$ is recommended [9, 11].

This retrospective study aimed to investigate the effect of the AirSeal® on four major laparoscopic abdominal surgeries (hepatectomy, gastrectomy, colectomy, and proctectomy) by analyzing intraoperative hemodynamic parameters, such as $EtCO_2$, peripheral capillary oxygen saturation (SpO_2), and arterial systolic blood pressure (ABP). It also included patients with significant "positive respiratory and circulatory responses" (positive responses) (defined as a drop in $EtCO_2 \geq 3$ mmHg [12], $SpO_2 \geq 3\%$, and ABP ≥ 10 mmHg at the same instant), which may suggest possible CO_2 embolism and reflect or progress to clinically meaningful CO_2 embolism.

Materials and methods

Patients

This retrospective single-center study included 333 consecutive patients who underwent elective laparoscopic (or robotic) hepatectomy ($n = 43$), gastrectomy ($n = 69$), colectomy ($n = 137$), or proctectomy (n = 84) using the AirSeal® insufflation system at Fukuoka University Hospital between January and December 2020.

We excluded patients who underwent accidental thoracotomy during gastrectomy, prone surgical position, emergency surgery, total colectomy, conversion to open surgery, or more than two surgeries. The subtypes of each surgery are listed in Table 1.

This study was approved by the institutional review board of Fukuoka University Hospital (H22-04-001). Informed consent was substituted by an informed opt-out procedure owing to the retrospective study design, and anonymized data were used.

Surgical protocol

All laparoscopic procedures were performed under general anesthesia. Hepatectomy, gastrectomy, and colectomy (except sigmoidectomy) were performed in the reverse Trendelenburg (head up) position, whereas sigmoidectomy and proctectomy were performed in the Trendelenburg (head down) position.

Table 1 Surgery subtypes and quantities

	n
Hepatectomy	43
Anatomical major hepatectomy	14
Non-anatomical minor hepatectomy	29
Gastrectomy	69
Proximal gastrectomy	12
Distal gastrectomy	42
Total gastrectomy	15
Colectomy	137
Right colectomy	60
Transverse colectomy	7
Left colectomy (sigmoid resection included)	70
Proctectomy	84
Transabdominal proctectomy	72
Combined transabdominal and trans-perineal proctectomy	12
Total	333

Pneumoperitoneum was induced using the AirSeal® insufflation system (ConMed, Utica, New York, USA). Intraperitoneal pressure (IPP) was set at 10 mmHg during hepatectomy, gastrectomy, colectomy, and transabdominal proctectomy. For combined transabdominal and trans-perineal proctectomy, CO_2 was insufflated into the abdominal and perineal cavities at pressures of 10 and 12 mmHg, respectively.

For hepatectomy, the Pringle maneuver, a hemostatic technique that involves clamping the hepatoduodenal ligament, was not routinely applied; rather, it was only used in cases of significant bleeding during liver parenchymal transection [13].

Anesthetic protocol

Induction of general anesthesia included hypnotic propofol, analgesic remifentanil, and muscle relaxant rocuronium, followed by endotracheal intubation and maintenance with desflurane (or sevoflurane) and remifentanil. The tidal volume and respiratory rate were set at 6–8 mL/kg and 12–15 breaths/min, respectively. The positive end-expiratory pressure (PEEP) was set at 5 cmH_2O. Tidal volume, respiratory rate, and PEEP were adjusted during the procedure at the anesthesiologist's discretion.

Data collection

Patient demographics and intraoperative hemodynamic parameters, such as $EtCO_2$, SpO_2, and ABP, were collected from the hospital's medical records. Intraoperative data were recorded every minute during surgery. In each patient, the average $EtCO_2$ per minute was calculated during the entire operative period (whole period) and the pneumoperitoneum period until specimen removal (pneumoperitoneum period). We also defined positive respiratory and circulatory responses (positive responses) as a decrease in EtCO2 ≥ 3 mmHg [12] in addition to decreases in $SpO_2 \geq 3\%$ and ABP ≥ 10 mmHg in the same time period, as this may reflect possible CO_2 embolism.

Statistical analyses

Data are expressed as median (interquartile range) or number of patients. Continuous and categorical variables were compared among the four groups using the Kruskal–Wallis test with Bonferroni adjustment and the chi-squared test, respectively.

All P values were two-sided, and those < 0.05 were considered statistically significant. All statistical analyses were performed using EZR (Saitama Medical Centre, Jichi Medical University), a graphical user interface for R (The R Foundation for Statistical Computing, Vienna, Austria) [14].

Results

Patient characteristics

The perioperative characteristics (Table 2) differed significantly among surgery types (age [$P = 0.002$], sex [$P = 0.007$], body mass index [BMI; $P = 0.002$], operative time [$P < 0.0001$], and estimated blood loss [EBL; $P < 0.0001$]).

$EtCO_2$ values

Table 3 presents the $EtCO_2$ values for each surgical type. The median $EtCO_2$ of hepatectomy, gastrectomy, colectomy, and proctectomy in the whole period/pneumoperitoneum period was 37.3/37.4, 37.1/37.3, 37.4/37.9, and 38.2/38.4 mmHg, respectively. They significantly differed across the four groups in the whole period ($P = 0.045$) and in the pneumoperitoneum period ($P = 0.035$). The $EtCO_2$ of proctectomy was significantly higher than that of gastrectomy during the entire period ($P < 0.05$) and the pneumoperitoneum period ($P < 0.05$). In contrast, the $EtCO_2$ of

Table 2 Patient characteristics

	Hepatectomy ($n = 43$)	Gastrectomy ($n = 69$)	Colectomy ($n = 137$)	Proctectomy ($n = 84$)	P value
Age (year)	70 (61–74)	71 (66–80)	72 (63–80)	68[a] (57–74)	0.002
Sex (M/F)	33/10	51/18	74/63	56/28	0.007
BMI (kg/m^2)	24.7[b] (21.9–27.1)	23.9 (20.7–25.7)	22.3 (19.7–24.7)	22.7 (19.8–25.5)	0.002
Operative time (min)	337 (273–415)	388 (340–457)	298[c] (250–372)	377 (297–466)	< 0.0001
Estimated blood loss (ml)	100[d] (52–150)	10 (2–55)	5 (0–11)	5 (0–26)	< 0.0001

BMI, body mass index

Data are presented as median (interquartile range) or number of patients

[a]Adjusted P value < 0.01 versus gastrectomy or colectomy

[b]Adjusted P value < 0.01 versus colectomy

[c]Adjusted P value < 0.01 versus gastrectomy or proctectomy

[d]Adjusted P value < 0.01 versus gastrectomy, colectomy, or proctectomy

Table 3 End-tidal carbon dioxide values

	Hepatectomy ($n = 43$)	Gastrectomy ($n = 69$)	Colectomy ($n = 137$)	Proctectomy ($n = 84$)	P value
Whole period (mmHg)	37.3 (36.2–39.5)	37.1 (36.2–38.5)	37.4 (36.4–38.8)	38.2[a] (36.8–39.2)	0.045
Pneumoperitoneum period (mmHg)	37.4 (36.1–39.8)	37.3 (36.5–38.8)	37.9 (36.5–39.2)	38.4[a] (37.2–39.8)	0.035

Data are presented as median (interquartile range)

[a]Adjusted P value < 0.05 versus gastrectomy

hepatectomy was comparable to that of the other three types of surgeries in the whole and pneumoperitoneum periods.

Patients with positive responses

Of the 333 patients, nine (2.7%) showed significant positive responses, defined as a simultaneous drop in all three parameters: $EtCO_2 \geq 3$ mmHg [12], $SpO_2 \geq 3\%$, and ABP ≥ 10 mmHg, which can indicate possible CO_2 embolism. Detailed information on these nine patients is presented in Table 4. Eight of the nine patients (88.9%) with positive responses underwent laparoscopic hepatectomy, while the other underwent transabdominal proctectomy. Regarding hepatectomy, four (50.0%) patients underwent anatomical major liver resection, while another four patients (50.0%) underwent non-anatomical minor hepatectomy.

We retrospectively reviewed the surgical videos of these nine patients. All events in which all three parameters deteriorated during laparoscopic hepatectomy corresponded with hepatic venous exposure or bleeding. In the other proctectomy case, the three parameters decreased when the right neurovascular bundles of the rectum were dissected with subsequent mild bleeding.

One patient who underwent non-anatomical minor hepatectomy (Case 6) showed clinically manifested CO_2 embolism, in which all three parameters drastically decreased ($EtCO_2$ by 25 mmHg/SpO_2 by 20%/ABP by 61 mmHg) almost simultaneously when the peripheral right hepatic vein was injured with bleeding during liver parenchymal transection. The tumor was located in the right posterior sector of the liver, and surgery was performed with the patient in the left decubitus position. Emergency trans-esophageal echocardiography (TEE) confirmed the presence of significant gas bubbles in the right atrium of the heart. The patient required cessation of pneumoperitoneum and the administration of pure oxygen and inotropic agents, after which no further complications occurred.

Discussion

CO_2 embolism is a potentially life-threatening complication of laparoscopic surgery [10], but its overall incidence is reportedly rare (0.15%) [15]. The drainage vein of the liver, namely the hepatic vein, drains directly into the inferior vena cava. Due to this unique anatomical feature of the liver, laparoscopic hepatectomy is theoretically more prone to CO_2 embolism than other laparoscopic abdominal surgeries. Moreover, laparoscopic major anatomical liver resection is believed to carry a higher risk of CO_2 embolism than minor hepatectomy because it involves an extensive hepatic transection plane, longer operative duration, and the dissection of large hepatic veins or the vena cava [16]. However, the incidence of CO_2 embolism during laparoscopic hepatectomy varies among reports (0–4.5%) [16], and the risk of CO_2 embolism during laparoscopic hepatectomy has not been fully elucidated.

Despite this unique anatomy of the liver, the $EtCO_2$ of hepatectomy in our study was comparable to that of the other three surgeries during the whole and pneumoperitoneum periods, during which the hepatic vein is dissected and exposed in the case of hepatectomy and the chance of CO_2 absorption may increase. Meanwhile, eight of nine patients who showed positive responses underwent hepatectomy. In addition, one patient who underwent partial hepatectomy developed a clinically significant CO_2 embolism. This result suggests that CO_2 embolism is a rapid and bolus event of CO_2 absorption, which cannot be reflected in the average $EtCO_2$ recorded every minute.

With the recently increased use of TEE, which can diagnose CO_2 embolism more sensitively by monitoring gas bubbles in the right chamber of the heart, the reported incidence of CO_2 embolism has increased [17]. Kim et al. [18] reported that the incidence of CO_2 embolism evaluated using TEE was 100% in patients undergoing total laparoscopic hysterectomy. Although none of the patients in this study showed hemodynamic instability, TEE was helpful in detecting subclinical or early signs of CO_2 embolism.

Reviewing the recorded surgical videos of the other eight patients who demonstrated positive responses without cardiovascular collapse (seven hepatectomy, one proctectomy) revealed that all three parameters ($EtCO_2$, SpO_2, and ABP) dropped at the scene of venous exposure or bleeding in all eight patients. While the details remain unknown since TEE was not routinely adopted in our study, we speculated that these eight patients might have experienced transient subclinical CO_2 embolism without clinical deterioration.

Regarding patient positioning during laparoscopic surgery, the Trendelenburg position (head-down) is a known risk factor for CO_2 embolism because the resultant negative venous pressure gradient can promote CO_2 entrainment [19]. To prevent CO_2 entrapment in the blood, placing the patient in the reverse Trendelenburg position (head up) is recommended [10]. Once CO_2 embolism is suspected, the patient should be placed in Durant's (head down, left decubitus) position to keep gas bubbles at the apex of the right atrium and to avoid entry into the pulmonary artery [17, 20].

All laparoscopic hepatectomies were performed in the reverse Trendelenburg position in this study. The IPP of hepatectomy was maintained at 10 mmHg, the same pressure as that of gastrectomy, colectomy, and transabdominal proctectomy but lower than that of combined transabdominal and trans-perineal proctectomy (12 mmHg). Despite these favorable conditions, patients who underwent laparoscopic hepatectomy showed frequent positive responses compared to those who underwent the other three types of

Table 4 Patients with positive responses

No	Surgery type	Surgery subtype	Surgical position	Age (years)	Sex	BMI (kg/m^2)	Operative time (min)	Estimated blood loss (ml)	Average $EtCO_2$ in whole period (mmHg)	Average $EtCO_2$ in pneumoperitoneum period (mmHg)	SpO_2 down (%)	$EtCO_2$ down (mmHg)	ABP down (mmHg)	Situation
1	Proctectomy	Transabdominal	Head-down	54	M	27.4	442	50	38.0	38.2	3	25	23	Venous bleeding
2	Hepatectomy	Anatomical	Head-up	70	F	26.1	337	50	40.2	40.0	3	10	71	Venous bleeding
3	Hepatectomy	Non-anatomical	Head-up	76	M	26.4	299	125	40.3	39.8	9	15	11	Venous exposure
4	Hepatectomy	Anatomical	Head-up	68	F	25.6	402	520	43.1	44.3	4	6	72	Venous exposure
5	Hepatectomy	Non-anatomical	Head-up	70	M	21.8	472	300	36.2	36.6	4	11	30	Venous bleeding
6	Hepatectomy	Non-anatomical	Head-up	60	F	26.9	369	403	37.9	35.9	20	25	61	Venous bleeding
7	Hepatectomy	Anatomical	Head-up	63	M	30.2	444	89	35.7	35.7	5	4	34	Venous bleeding
8	Hepatectomy	Anatomical	Head-up	77	M	21.9	490	180	39.1	39.0	4	6	18	Venous exposure
9	Hepatectomy	Non-anatomical	Head-up	73	M	25.0	273	100	32.6	32.3	5	12	36	Venous bleeding

Case 6 showed a clinically manifested CO_2 embolism

ABP arterial systolic blood pressure, *BMI* body mass index, *$EtCO_2$* end-tidal carbon dioxide, *SpO_2* peripheral capillary oxygen saturation surgeries. This indicates that laparoscopic hepatectomy itself can be a risk factor for CO_2 embolism.

In terms of hepatectomy subtype, four of eight patients (50.0%) with positive responses underwent non-anatomical minor resection, indicating that there is a risk of CO_2 embolism even with minor hepatectomy, in which the hepatic vein is not extensively exposed. On the other hand, it is unclear how the AirSeal® played a role in the positive responses because we did not compare the data from a conventional insufflation system. However, two studies [2, 21] demonstrated that CO_2 elimination was significantly reduced with the AirSeal® versus conventional insufflation system. CO_2 elimination rates are reportedly directly related to CO_2 absorption rates when the patient remains metabolically constant [2]. Moreover, Miyano et al. [3] reported that stable pneumoperitoneum was established with lower IPP using the AirSeal® compared with conventional pneumoperitoneum during pediatric laparoscopic appendectomy. The incidence of CO_2 embolism is higher at a higher IPP [16, 22, 23]. Considering these facts, use of the AirSeal® was not necessarily associated with rapid CO_2 absorption or a drop in all three parameters reflecting possible CO_2 embolism.

In this study, inhaled anesthetics (desflurane or sevoflurane) were used during the surgery. Recently, Hong et al. [24] reported that inhaled anesthetics lengthen the duration of CO_2 embolism episodes and worsened hemodynamic parameters compared to intravenous anesthetics (propofol). They speculated that the impairment of the pulmonary filtration capacity by inhaled anesthetics inhabited the passage of bubbles across the lungs by reducing the pulmonary vascular tone. However, there is still no definite consensus of which anesthetic drug is more likely to induce CO_2 embolism.

The present study does have some limitations. First, it was a retrospective analysis with a relatively small sample size. Second, the $EtCO_2$ data were retrospectively collected at 1 min intervals, which would have failed to detect a rapid change in $EtCO_2$ within 1 min. Finally, minor adjustments in IPP, respiratory minute volume, and PEEP during surgery, which could have affected $EtCO_2$, were omitted. Also, we did not consider central venous pressure (CVP) in this study. Decreasing the CVP is a simple and effective way to reduce blood loss during liver surgery [13, 25]; however, the risk of CO2 embolism increases when the CVP is lower than the IPP [26, 27].

Conclusion

In conclusion, although the $EtCO_2$ of laparoscopic hepatectomy was comparable to that of the other three types of surgeries in the whole and pneumoperitoneum periods using the AirSeal®, laparoscopic hepatectomy showed high tendency toward positive responses, which is suggestive of CO_2 embolism. Thus, a secure and careful approach is mandatory for laparoscopic hepatectomy using the AirSeal® insufflation system.

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Declarations

Conflict of interest The authors declare no conflicts of interest or financial ties.

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