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Effects of volume-controlled equal ratio ventilation with recruitment maneuver and positive end-expiratory pressure in laparoscopic sleeve gastrectomy: a prospective, randomized, controlled trial

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Background/aim: We compared the effects of volume-controlled equal ratio ventilation (VC-ERV) and volume-controlled conventional ratio ventilation (VC-CRV) on oxygenation, ventilation, respiratory mechanics, and hemodynamic status during mechanical ventilation with recruitment maneuver (RM) and positive end-expiratory pressure (PEEP) in patients undergoing laparoscopic sleeve gastrectomy.

Materials and methods: A total of 111 patients scheduled for laparoscopic sleeve gastrectomy were randomized to ventilation with inspiratory to expiratory ratio of 1:1 (Group VC-ERV) or 1:2 (Group VC-CRV) following tracheal intubation. RM (40 cmH2O, 15 s) and PEEP (10 cmH2O) were administered to all patients. Arterial blood gas samples were taken and peak airway pressure (Ppeak), mean airway pressure (Pmean), dynamic compliance (Cdyn), mean arterial pressure, heart rate, SpO2, and EtCO2 were recorded at 4 time points. Postoperative respiratory complications were recorded.

Results: Oxygenation, ventilation, Pmean levels, and hemodynamic variables were similar in both groups. VC-ERV significantly decreased Ppeak and increased Cdyn compared to VC-CRV at all time points of the operation ($P < 0.05$). No pulmonary complication was observed in any patients.

Conclusion: VC-ERV provides significantly lower Ppeak and higher Cdyn with similar oxygenation, ventilation, hemodynamic parameters, and Pmean levels when compared to VC-CRV during mechanical ventilation with RM and PEEP in laparoscopic sleeve gastrectomy.

Key words: Bariatric surgery, laparoscopy, equal ratio ventilation, recruitment maneuver, positive end-expiratory pressure

1. Introduction

Intraoperative mechanical ventilation in obese patients undergoing laparoscopic bariatric surgery is sometimes challenging because of the combined effects of restrictive lung disease, supine position, and pneumoperitoneum (1). All of these factors decrease thoracic compliance and lung volumes, leading to atelectasis, hypoxia, and increased airway pressure resulting in prolonged recovery, hospital stay, and/or intensive care unit requirement (1–5). Previous studies, which investigated different ventilation strategies for intraoperative oxygenation and respiratory mechanics, showed that the combined use of the recruitment maneuver (RM) and positive end-expiratory pressure (PEEP) gives the best results (6–13). However, PEEP administration can further increase airway pressures that already tend to be high in these cases, and patients may face the risk of barotrauma (14).

The use of equal ratio ventilation (ERV) during volume-controlled (VC) and pressure-controlled (PC) ventilation has been used to improve gas exchange and respiratory mechanics not only in restrictive lung diseases but also in surgical patients during general anesthesia (15–17). Increasing the inspiratory time leads to a decrease in the peak airway pressure (Ppeak), an increase in the mean airway pressure (Pmean), and dynamic compliance (Cdyn) (18–22). Two previous studies compared the effects of pressure-controlled equal ratio ventilation (PC-ERV) and pressure-controlled conventional ratio ventilation (PC-CRV) in laparoscopic bariatric surgery (23,24). Nevertheless, we could not find a study that compared the effects of volume-controlled equal ratio ventilation (VC-ERV) and volume-controlled conventional ratio ventilation (VC-CRV) with the combined use of RM and PEEP on intraoperative oxygenation, ventilation,

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respiratory mechanics, and hemodynamic status in patients undergoing laparoscopic bariatric surgery.

The aim of this study was to compare the effects of VC-ERV and VC-CRV on intraoperative oxygenation, ventilation, respiratory mechanics, and hemodynamic status in patients undergoing laparoscopic sleeve gastrectomy under general anesthesia with RM and PEEP.

2. Materials and methods

This prospective, randomized trial was conducted according to the Declaration of Helsinki and ethical approval was provided by the Institutional Review Board and Ethics Committee (Project Number: KA15/198) on 20 August 2015. Adult patients with American Society of Anesthesiologists (ASA) physical status II–III and a body mass index (BMI) above 40 kg/m^2 scheduled for laparoscopic sleeve gastrectomy were enrolled in the study. All patients were evaluated by consultants including the cardiology, chest disease, and endocrine disease departments before surgery in order to achieve optimal perioperative medical status. Informed consent was obtained from each patient. Exclusion criteria were age outside the range of 20 to 65 years; ASA physical status >III; pregnancy; severe obstructive or restrictive pulmonary conditions (less than 70% of expected values of respiratory function tests); neuromuscular, renal, or cardiac disease; previous adverse reactions to medications used in the study protocol; and inability to provide informed consent. Demographic data such as sex, age, height, body weight, body mass index, and respiratory function test results of patients were recorded. Surgical and anesthetic management of all patients was performed by the same surgical and anesthesia teams, respectively.

In the operating room, an intravenous catheter was inserted in the arm and a crystalloid solution was administered. All patients were continuously monitored for noninvasive blood pressure (NIBP), heart rate (HR), oxygen saturation (SpO_2), end-tidal carbon dioxide ($EtCO_2$), electrocardiogram (ECG), and core body temperature. Preoxygenation was provided for at least 5 min with supplemental oxygen (3 L/min) administered via a face mask during the monitoring procedure. Standardized anesthetic induction and maintenance was used and all drug dosages were calculated according to ideal body weight. General anesthesia was induced intravenously with propofol (1.5–2.5 mg/kg) and fentanyl (2 µg/kg), and tracheal intubation was facilitated with rocuronium (0.8 mg/kg) in the 30° reverse Trendelenburg position. A 20-gauge catheter was placed in the radial artery for arterial blood gas samples. Anesthesia was maintained with 2%–3% sevoflurane in 50%:50% oxygen and nitrous oxide and intravenous fentanyl.

Following tracheal intubation, a recruitment maneuver with the application of continuous positive airway pressure (40 cmH_2O, 15 s) was performed and lungs were ventilated in VCV mode with a constant flow for inspiration (Primus anesthesia workstation, Dräger, Lübeck, Germany) with fractional inspiratory oxygen concentration (FiO_2) of 50%, tidal volume (VT) of 7 mL/kg according to ideal body weight, and positive end-expiratory pressure (PEEP) of 10 cmH_2O in all patients. Respiratory rate (RR) was set to an $EtCO_2$ between 30 and 40 mmHg. Patients were then randomly assigned to one of two ventilation protocols. Inspiratory-to-expiratory (I/E) time ratio was set as 1:1 and 1:2 in the VC-ERV and VC-CRV groups, respectively. Randomization was provided using a computer-generated randomization list including 120 patients. The attending anesthesiologist was aware of the allocated group, but the data analyst, surgeon, and patients were blinded to group allocation.

Carbon dioxide pneumoperitoneum was established with 12–14 mmHg intraabdominal pressure in the supine position and the surgical procedure was maintained in a 30° reverse Trendelenburg position throughout the surgical procedure. Respiratory parameters (VT, RR, Ppeak, Pmean, and Cdyn) and hemodynamic data [mean arterial pressure (MAP), HR, SpO_2, and $EtCO_2$] were recorded and arterial blood gas samples were taken at 4 time points (T_1 = 10 min after tracheal intubation, before pneumoperitoneum; T_2 = 10 min after the beginning of pneumoperitoneum; T_3 = 10 min before the end of pneumoperitoneum; T_4 = 10 min after the end of pneumoperitoneum).

Oxygenation was assessed by alveolo-arterial oxygen gradient (A-a O_2) and PaO_2/FiO_2 ratio. A-a O_2 was determined as the difference between calculated alveolar partial pressure of oxygen (PAO_2) and the measured arterial partial pressure of oxygen (PaO_2). PAO_2 was calculated using the formula $PAO_2 = (FiO_2)\ (PB\text{-}pH_2O) - (PaCO_2\ /\ RQ)$ in which PB means barometric pressure (760 mmHg), pH_2O means the water vapor pressure (47 mmHg) at 37 °C, and RQ means the respiratory coefficient (0.8). Dynamic compliance was calculated as "exhaled tidal volume / (PIP-PEEP)" and obtained from the monitor screen of the ventilator. The duration of pneumoperitoneum, surgical procedure, and anesthesia as well as the length of recovery and hospitalization were recorded. The anesthesiologists were allowed to change the ventilation protocol at any time point if there was any concern about patient safety. Patients were withdrawn from the study if SpO_2 decreased to <95% or if Ppeak increased to >35 cmH_2O. Postoperative complications including respiratory failure, pneumonia, and pulmonary embolism were also recorded.

2.1. Statistical analysis

Statistical analyses were performed using SPSS 20.0 (IBM Corp., Armonk, NY, USA). The normality of the distribution was determined using the Kolmogorov–Smirnov test. The t-test was used for the assessment of normally distributed data whereas the Mann–Whitney U test was used for data that were not normally distributed. The chi-square test was used for comparison of categorical data. $P < 0.05$ was considered statistically significant. In this study, the primary outcome variable was oxygenation. Calculation of sample size was based on the primary end point of the PaO_2 results of the two groups. Based on our pilot study, the average intraoperative PaO_2 level in these patients during VCV (8 mL/kg according to ideal body weight, RR = set to an $ETCO_2$ between 35 and 45 mmHg, PEEP = 10 cmH_2O, I/E ratio = 1/2) was 170 mmHg. Assuming a PaO_2 change of about 20%, 47 patients were needed in each group with α value of 0.05, effect size of 68%, and power of 95%. Because we assessed multiple parameters, we planned to include 60 patients in each group.

3. Results

A total of 120 patients were assessed for eligibility in the study. Nine patients were excluded from the final analysis because two of them did not give consent, sleeve gastrectomy was combined with cholecystectomy in three patients, Ppeak was >35 cmH_2O in three patients, and data were lost for one patient. Consequently, data of 111 patients were analyzed (Figure 1). Patient characteristics including age, sex, weight, height, BMI, ASA status, preoperative pulmonary functions, and procedure times including the duration of pneumoperitoneum, surgery, anesthesia, recovery, and discharge were comparable between groups (Table 1).

Arterial blood gas analysis results, A-a O_2, and PaO_2/FiO_2 levels are shown in Figure 2. There was no difference between the two groups regarding PaO_2, $PaCO_2$, A-a O_2, and PaO_2/FiO_2 levels at all time points. Comparison of respiratory data revealed that there was no difference among groups with regard to mean VT and RR (Table 2). However, in the VC-ERV group, the mean Ppeak levels were significantly lower and the mean Cdyn was significantly higher at all time points compared with the VC-CRV group ($P < 0.05$). Although the mean Pmean levels were higher in the VC-ERV group at all time points, this difference was not statistically significant (Figure 3). Hemodynamic data including MAP, HR, SpO_2, and $EtCO_2$ were not different between the two groups (Figure 4). No pulmonary complications, mechanical ventilation, or intensive care unit requirements were observed in any patients.

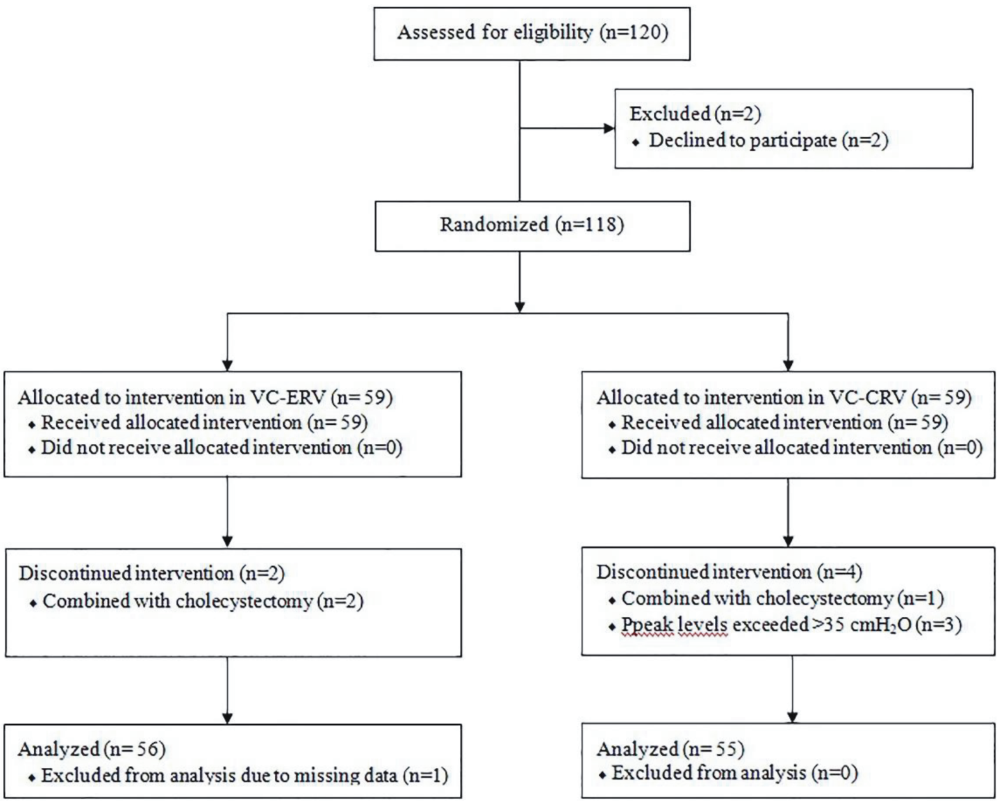
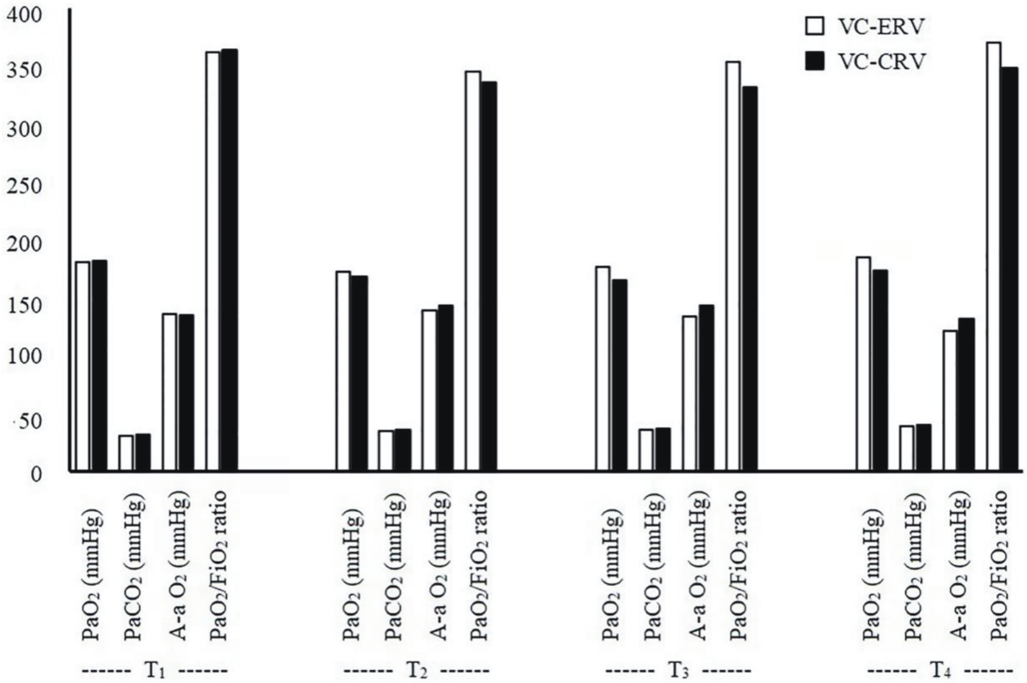
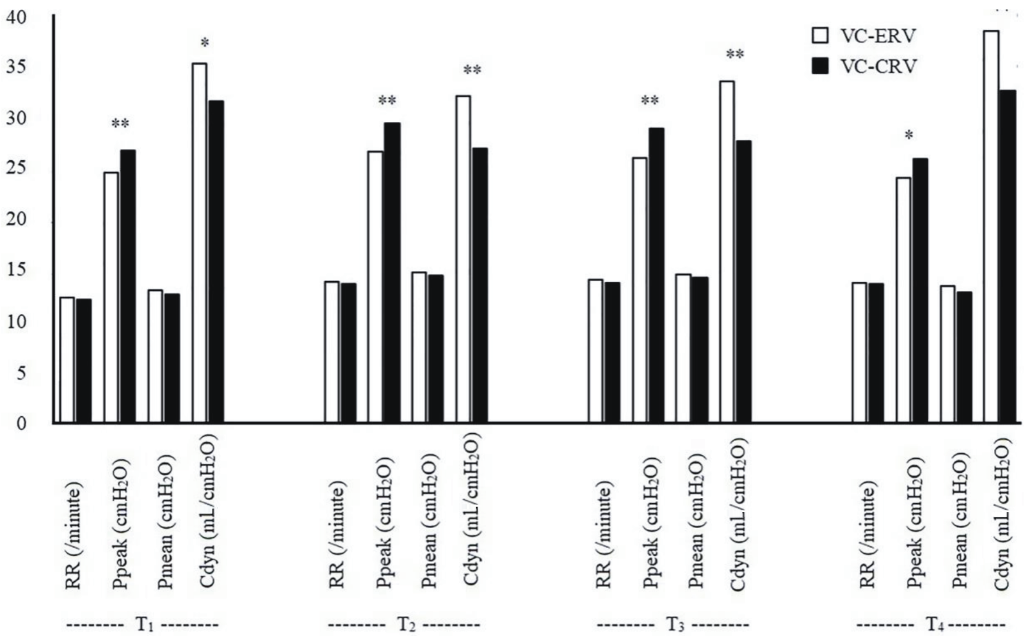


Figure 1. The flow diagram of patients enrolled into this study.



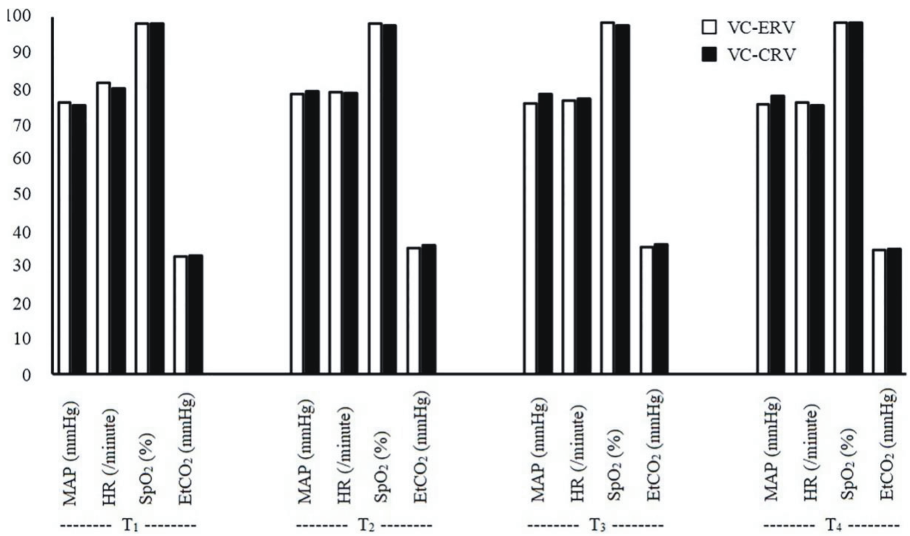
PaO_2= Arterial partial pressure of O_2, $PaCO_2$= Arterial partial pressure of CO_2, A-a O_2 = Alveolo-arterial oxygen gradient, FiO_2= Fractional inspiratory oxygen concentration, T_1= 10 min after tracheal intubation, before pneumoperitoneum, T_2= 10 min after the beginning of pneumoperitoneum, T_3= 10 min before the end of pneumoperitoneum, T_4= 10 min after the end of pneumoperitoneum.

Figure 2. Arterial blood gas analysis results, A-a O2, and PaO2/FiO2 ratio levels.



RR= Respiratory rate, Ppeak= Peak airway pressure, Pmean= Mean airway pressure, Cdyn= Dynamic compliance, T_1= 10 min after tracheal intubation, before pneumoperitoneum, T_2= 10 min after the beginning of pneumoperitoneum, T_3= 10 min before the end of pneumoperitoneum, T_4= 10 min after the end of pneumoperitoneum, * = $p<0.05$, ** = $p<0.01$.

Figure 3. Respiratory data.



MAP= Mean arterial pressure, HR= Heart rate, SpO_2= Oxygen saturation measured by pulse-oximetry, $EtCO_2$= End-tidal carbon dioxide tension, T_1= 10 min after tracheal intubation, before pneumoperitoneum, T_2= 10 min after the beginning of pneumoperitoneum, T_3= 10 min before the end of pneumoperitoneum, T_4= 10 min after the end of pneumoperitoneum.

Figure 4. Hemodynamic data.

Table 1. Demographic characteristics of the patients, preoperative pulmonary functions, procedure times, and postoperative pulmonary complications.

	Group VC-ERV (n = 56)	Group VC-CRV (n = 55)	P
Demographic data			
Age (years)	38.0 ± 13.2	40.1 ± 12.7	0.390
Sex (female/male)	42/14	45/10	0.383
Weight (kg)	124.2 ± 20.4	120.5 ±20.1	0.339
Height (cm)	166.3 ± 10.3	163.4 ± 8.7	0.114
BMI (kg/m^2)	44.8 ± 5.1	45.1 ± 6.5	0.764
ASA status (II/III)	3/53	3/52	0.982
OSAS	3	1	0.317
Smoking	16	22	0.205
Preoperative pulmonary function tests			
FEV_1 (L)	3.0 ± 0.8	2.8 ± 0.7	0.339
FVC (L)	3.6 ± 1.0	3.4 ± 0.8	0.213
FEV_1/FVC	82.9 ± 6.1	82.5 ± 12.2	0.814
Procedure times (minutes)			
Duration of pneumoperitoneum	74.1 ± 16.3	74.9 ± 16.2	0.790
Duration of operation	95.1 ± 16.5	96.7 ± 23.3	0.680
Duration of anesthesia	115.6 ± 18.1	116.3 ± 24.2	0.866
Recovery and discharge times			
Recovery time (minutes)	26.9 ± 4.4	26.7 ± 5.1	0.842
Discharge time (days)	4.0 ± 0.0	3.9 ± 0.1	0.153
Postoperative pulmonary complications	-	-	-

Variables are mean ± standard deviation (SD) or numbers. BMI = Body mass index, ASA = American Society of Anesthesiologists, OSAS = Obstructive sleep apnea syndrome), FEV_1 = Forced expiratory volume after 1 s, FVC = Forced vital capacity.

Table 2. Respiratory data of the patients.

	Group VC-ERV (n = 56)	Group VC-CRV (n =55)	P
V_T [L (T_1)]	486.4 ± 79.7	501.8 ± 53.3	0.237
V_T [L (T_2)]	492.1 ± 79.7	492.7 ± 63.9	0.967
V_T [L (T_3)]	495.7 ± 78.2	493.1 ± 64.0	0.853
V_T [L (T_4)]	495.7 ± 77.9	493.5 ± 63.6	0.870
RR [/minute (T_1)]	12.3 ± 0.8	12.1 ± 0.6	0.185
RR [/minute (T_2)]	13.9 ± 1.1	13.7 ± 1.1	0.292
RR [/minute (T_3)]	14.1 ± 1.0	13.8 ± 1.3	0.221
RR [/minute (T_4)]	13.8 ± 1.1	13.7 ± 1.3	0.746
Ppeak [cmH_2O (T_1)]	24.6 ± 2.9	26.7 ± 3.6	0.001
Ppeak [cmH_2O (T_2)]	26.6 ± 3.9	29.4 ± 4.3	0.001
Ppeak [cmH_2O (T_3)]	26.0 ± 3.9	28.9 ± 4.2	0.000
Ppeak [cmH_2O (T_4)]	24.1 ± 3.5	25.9 ± 3.3	0.007
Pmean [cmH_2O (T_1)]	13.0 ± 1.4	12.6 ± 1.1	0.128
Pmean [cmH_2O (T_2)]	14.8 ± 1.6	14.5 ± 1.3	0.310
Pmean [cmH_2O (T_3)]	14.6 ± 1.5	14.3 ± 1.2	0.240
Pmean [cmH_2O (T_4)]	13.5 ± 1.6	12.8 ± 1.5	0.104
Cdyn [mL/cmH_2O (T_1)]	35.3 ± 9.0	31.6 ± 8.2	0.028
Cdyn [mL/cmH_2O (T_2)]	32.1 ± 9.3	26.9 ± 7.8	0.002
Cdyn [mL/cmH_2O (T_3)]	33.5 ± 9.4	27.6 ± 8.2	0.001
Cdyn [mL/cmH_2O (T_4)]	38.5 ± 12.8	32.6 ± 8.8	0.006

Variables are mean ± standard deviation (SD). V_T = Tidal volume, RR = Respiratory rate, Ppeak = Peak airway pressure, Pmean = Mean airway pressure, Cdyn = Dynamic compliance, T_1 = 10 min after tracheal intubation and before pneumoperitoneum, T_2 = 10 min after the beginning of pneumoperitoneum, T_3 = 10 min before the end of pneumoperitoneum, T_4 = 10 min after the end of pneumoperitoneum.

4. Discussion

The present study showed that VC-ERV significantly decreased Ppeak and increased Cdyn compared to VC-CRV in patients undergoing laparoscopic sleeve gastrectomy. Pmean levels, oxygenation, ventilation, and hemodynamic variables were similar in both groups.

Intraoperative mechanical ventilation in bariatric surgery is challenging because of the combined effects of obesity, supine position, and pneumoperitoneum (1). Obesity increases chest wall resistance and decreases respiratory system compliance related to excessive adipose tissue in the chest wall and increased pulmonary blood volume (2). Lung volumes, primarily functional residual capacity, are decreased to levels below the closing capacity, causing ventilation-perfusion mismatch and hypoxemia. Additionally, oxygen consumption and carbon dioxide production are increased in obese patients due to the metabolism of increased adipose tissue (3). Moreover, these changes are more pronounced under general anesthesia in the supine position because increased intraabdominal pressure restricts diaphragmatic movement and lung expansion (4). In laparoscopic bariatric surgery, CO_2 pneumoperitoneum increases the need for minute ventilation due to systemic absorption of CO_2 and further decreases lung volumes and respiratory system compliance, leading to high Ppeak and $PaCO_2$. The resulting increase in intrapleural pressure leads to increased airway pressure and places the patient at risk of barotrauma (5,6). Therefore, a proper ventilatory setting is a fundamental aspect of appropriate patient management in bariatric anesthesia. Intraoperatively, particular focus should be directed to ensure optimal oxygenation/ventilation and to prevent the development of atelectasis that may lead to postoperative respiratory insufficiency and intensive care requirement

(7). Clinical trials that investigated the effects of different ventilation strategies in bariatric anesthesia reported that lung protective ventilation with low tidal volumes according to ideal body weight and RM with PEEP of 10 cmH_2O administration gives the best results (7–13). On the other hand, administration of PEEP of 10 cmH_2O during pneumoperitoneum in laparoscopic bariatric surgery may increase Ppeak above 30 cmH_2O, exposing patients to the risk of barotrauma because it is also recommended that peak airway pressure be kept below 30 cmH_2O during laparoscopic bariatric surgery (14).

ERV has been used for many years as an alternative ventilation strategy in ICU patients with restrictive pulmonary diseases and surgical patients during general anesthesia to improve oxygenation at lower than conventional Ppeak levels (15,16). Prolonged inspiratory time increases mean airway pressure, maintains alveoli in an inflated state, reduces intrapulmonary shunt, improves ventilation-perfusion mismatch, and decreases dead-space ventilation (17). The potential mechanisms of better oxygenation are higher mean airway pressure, intrinsic PEEP generated by decreased expiratory time, and enough time for gas change effectively provided by increased inspiratory time (18,19). However, the effect of prolonged inspiratory time on arterial oxygenation during general anesthesia remains controversial because its beneficial effects are important when a significant amount of recruitable lung units exist (20). In laparoscopic bariatric surgery, pneumoperitoneum in an obese patient causes a cephalad shift of the diaphragm and closure of small airways, considerably increasing the number of recruitable lung units. The collapsed alveoli may require a prolonged inspiratory time to reopen (21,22). Therefore, ERV might be a useful ventilation strategy for morbidly obese patients undergoing laparoscopic bariatric strategy.

To our knowledge, this is the first study investigating the effect of ERV on oxygenation, ventilation, respiratory mechanics, and hemodynamic status in patients undergoing laparoscopic bariatric surgery under VC ventilation with RM and PEEP of 10 cmH_2O in the reverse Trendelenburg position. Two previous studies investigated the effects of ERV in laparoscopic bariatric surgery in the reverse Trendelenburg position and reported that ERV significantly improved oxygenation, decreased Ppeak, and increased Pmean and Cdyn without significant differences in ventilation and hemodynamic parameters (23,24). Our study showed that ERV significantly increased Cdyn and reduced Ppeak, as seen in previous studies, but Pmean levels, oxygenation, ventilation, and hemodynamic parameters were unchanged compared with CRV. The differences between Pmean levels and oxygenation in our study and previous studies can be explained by different ventilation strategies and study designs used. In the prior studies, PCV was used without RM. Additionally, in a randomized crossover trial, Mousa et al. (23) did not use PEEP, whereas in a nonrandomized single-group study Jo et al. (24) used a PEEP level of 5 cmH_2O. Moreover, the time period of the application of each ratio was 20 or 30 min and data collection for each ratio was found to be established only once in both trials (23,24). Studies that investigated the effects of different ventilation strategies in bariatric anesthesia did not show significant differences between PC and VC ventilation (25–27). Similarly, increasing VT to >1 L or RR up to 20/min had no beneficial effect on oxygenation during laparoscopy in morbidly obese patients (28). Considering the advantage of ensuring constant tidal volume, we used VC ventilation in our study. This may be an explanation for improved CO_2 removal by prolonged inspiratory time in our study. In this study, we used VC ventilation with FiO_2 of 50% with PEEP of 10 cmH_2O and TV of 7 mL/kg according to ideal body weight. RR was set to an $EtCO_2$ between 30 and 40 mmHg and changes in ventilation settings were made to keep Ppeak below 30 cmH_2O in all patients. Adequate oxygenation and ventilation were established in both groups with the use of RM and PEEP of 10 cmH_2O.

There are several possible adverse effects of increasing the inspiratory time during mechanical ventilation. First, increasing the inspiratory time results in a significant increase in Pmean, which may impede venous return, leading to a decrease in cardiac output (CO). Kim et al. (29) showed that central venous oxygen saturation was significantly reduced during one-lung ventilation with VC-ERV when compared with VC-CRV in thoracoscopic lung lobectomy in the lateral decubitus position. However, Kim et al. (30) reported that there was no significant difference in CO between VC-ERV and VC-CRV in robot-assisted laparoscopic radical prostatectomy in the Trendelenburg position. The inconsistency between the results of different studies may be related to differences in patient characteristics of the enrolled patients, types of surgeries, and patient positions. Additionally, the clinical implication or the extent of reduction in CO is unclear and these effects are reported with an I:E ratio higher than 2:1. The results of our study did not show significant differences in hemodynamic parameters between VC-ERV and VC-CRV groups, although we did not directly measure CO. These results are in accordance with the previous studies that reported that hemodynamic parameters were not influenced by PC-ERV and PC-CRV in laparoscopic bariatric surgery in the reverse Trendelenburg position. No episodes of hemodynamic deterioration occurred during surgery, suggesting that VC-ERV with RM and PEEP of 10 cmH_2O was well tolerated in bariatric surgery. Secondly, decreasing the expiratory time may lead to excessive end-expiratory gas being trapped in lung units, leading to auto-PEEP that may further impede venous return and increase the risk of barotrauma (29,30). In our study, although auto-PEEP was not measured, as it requires an end-expiratory hold and measurement of the equilibrium pressure in the circuit, we monitored the flow-time curve to detect the presence of the intrinsic PEEP. Additionally, our results did not show signs of auto-PEEP or dynamic hyperinflation including decline in VT, increase in Ppeak, or hemodynamic derangement. These results are in agreement with other studies that showed no signs of auto-PEEP or hemodynamic deterioration during ERV. Lastly, we evaluated the effects of VC-ERV during laparoscopic sleeve gastrectomy and did not collect data in the postoperative period. However, the effects of VC-ERV on the postoperative the status of patients is an important issue. Therefore, further studies are needed to investigate the postoperative effects of VC-ERV in bariatric surgery.

In conclusion, both VC-ERV and VC-CRV provide similarly adequate oxygenation, ventilation, and stable hemodynamic status during mechanical ventilation with RM and PEEP in laparoscopic sleeve gastrectomy in the reverse Trendelenburg position. VC-ERV has favorable effects such as lower Ppeak and higher Cdyn levels without adverse respiratory and hemodynamic effects in these patients.

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Variables are mean ± standard deviation (SD) or numbers. BMI = Body mass index, ASA = American Society of Anesthesiologists, OSAS = Obstructive sleep apnea syndrome), FEV_1 = Forced expiratory volume after 1 s, FVC = Forced vital capacity.

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