The Effects of the Alveolar Recruitment Maneuver and Positive End-Expiratory Pressure on Arterial Oxygenation During Laparoscopic Bariatric Surgery

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Abnormalities in gas exchange that occur during anesthesia are mostly caused by atelectasis, and these alterations are more pronounced in morbidly obese than in normal weight subjects. Sustained lung insufflation is capable of recruiting the collapsed areas and improving oxygenation in healthy patients of normal weight. We tested the effect of this ventilatory strategy on arterial oxygenation ($Pa{O_2}$) in patients undergoing laparoscopic bariatric surgery. After pneumoperitoneum was accomplished, the recruitment group received up to 4 sustained lung inflations with peak inspiratory pressures up to 50 cm H_2O, which was followed by ventilation with 12 cm H_2O positive end-expiratory pressure (PEEP). The patient's lungs in the control group were ventilated in a standard fashion with PEEP of 4 cm H_2O. Variables related to gas exchange, respiratory mechanics, and hemodynamics were compared between recruitment and control groups. We found that alveolar recruitment effectively increased intraoperative $Pa{O_2}$ and temporarily increased respiratory system dynamic compliance (both $P < 0.01$). The effects of alveolar recruitment on oxygenation lasted as long as the trachea was intubated, and lungs were ventilated with high PEEP, but soon after tracheal extubation, all the beneficial effects on oxygenation disappeared. The mean number of vasopressor treatments given during surgery was larger in the recruitment group compared with the control group (3.0 versus 0.8; $P = 0.04$). In conclusion, our data suggest that the use of alveolar recruitment may be an effective mode of improving intraoperative oxygenation in morbidly obese patients. Our results showed the effect to be short lived and associated with more frequent intraoperative use of vasopressors.

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Atelectasis develops after the induction of anesthesia, even in healthy subjects, and is associated with an increase in intraoperative shunt leading to impairment of gas exchange (1–3). These effects are exaggerated in morbidly obese patients (4–8). Arterial oxygenation ($Pa{O_2}$) is decreased during anesthesia to a greater extent in obese compared with normal-weight patients (8,9), and the impairment of gas exchange is directly related to the increase in body mass index (BMI). Various ventilatory strategies to improve gas exchange during general anesthesia have been proposed in morbidly obese patients (8,10–12). Visick et al. (10) suggested that by using large tidal volumes (V_T), mean lung volume shifts above closing volume, and thus, $Pa{O_2}$ increases; however, the efficacy of this strategy has not been confirmed by others (11,12). Similarly, positive end-expiratory pressure (PEEP) alone in obese patients induced only a modest increase in $Pa{O_2}$ (8). More recently, a strategy of reopening atelectatic lung areas present during anesthesia with a "recruitment maneuver" was recommended (13). Rothen et al. (14–17) demonstrated that sustained inspiratory pressure of at least 40 cm H_2O is required to fully reverse anesthesia-induced atelectasis in the healthy lungs of non-obese subjects. To prevent atelectasis from recurring, a strategy consisting of recruitment maneuvers followed by PEEP has been proposed in patients with acute lung injury (18) and in anesthetized subjects (13–17).

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The effectiveness of the recruitment maneuver has not been determined in the morbidly obese. The aim of our study was to quantitate the effects of recruitment maneuvers followed by PEEP on oxygenation, pulmonary mechanics, and hemodynamics during laparoscopic bariatric surgery. We hypothesized that this regimen would significantly increase intraoperative Pa_{O_2} and decrease respiratory system compliance without affecting hemodynamics.

Methods

After obtaining IRB approval, we conducted a prospective randomized study to quantify the effect of a lung recruitment maneuver on Pa_{O_2} during laparoscopic bariatric Roux-en-Y operations at St. Mary's Hospital, Rochester, MN between September 2004 and January 2005. We recruited ASA class 2 or 3 patients, between 25 and 65 years old, with BMI >40 kg/m^2. Patient randomization was accomplished through our Division of Biostatistics using a computerized random number generator. Group assignment was concealed in a sealed envelope until surgery began. All patients signed an informed consent form to participate in the study. None of the patients had significant preoperative pulmonary disease (forced expiratory volume in one second <50% of predicted and forced vital capacity <50% of predicted) or active asthma, and no patient was receiving home oxygen therapy. One coinvestigator (OG), blinded to group assignment, performed all postoperative outcome assessments.

Anesthetic management was standardized as follows. Anesthesia was induced with 2 mg/kg of ideal body weight (IBW) of propofol, supplemented by up to 500 μg of fentanyl, and tracheal intubation (with size 8.0 ID endotracheal tube) was facilitated with 1.5 mg/kg of IBW of succinylcholine. None of the patients required fiberoptic intubation. Anesthesia was maintained with desflurane in a mixture of oxygen and air adjusted to maintain inspiratory O_2 of 50%. Neuromuscular blockade was maintained with vecuronium, and additional opioids were given at the discretion of the primary anesthesiologist. The use of vasopressors (ephedrine or phenylephrine) was left to the discretion of the attending anesthesiologist. In addition to the ASA standard anesthesia monitors, arterial blood pressure was directly monitored with either a radial or brachial arterial line. After insertion of the arterial catheter an ultrathin sensor, a part of Paratrend 7® monitoring system (Diametrics Medical Inc., St. Paul, MN) was inserted through the arterial line catheter to continuously monitor Pa_{O_2}, Pa_{CO_2}, and pH values. The arm in which the Paratrend 7® monitoring system catheter was inserted was not used for infusion of IV fluids.

A noninvasive cardiac output monitor (NICO2™; Novametrix Medical Systems Inc., Wallingford, CT) was used to measure cardiac output by means of a differential form of the Fick equation (19). In addition, the NICO2™ monitor records mean and peak airway pressures, minute ventilation, expiratory V_T, and calculates respiratory system dynamic compliance (mL/cm H_2O) (ratio of the maximum inspiratory volume over the difference between peak inspiratory and PEEP), inspiratory airway resistance (cm $H_2O \cdot L^{-1} \cdot s^{-1}$) (calculated as ratio of driving pressure during expiration to the end-inspiratory flow; the driving pressure is the difference between the end-inspiratory pressure and the plateau pressure), and physiologic dead space to V_T ratios ($V_{DPhysiol}/V_T$) (calculated as Pa_{CO_2} − end-tidal CO_2/Pa_{CO_2}).

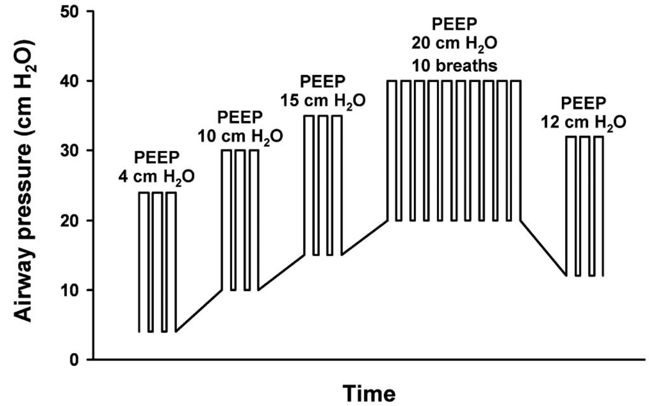

Figure 1. Mechanics of performing recruitment maneuver by using ventilator. Tidal volume was 8 mL/kg of ideal body weight (IBW), and respiratory rate was 8 breaths/min. This technique represents modification of the alveolar recruitment method described by Tusman et al. (13).

Mechanical ventilation was conducted with Datex-Ohmeda Aestiva/5 Smart Ventilator (Madison, WI). Patients were randomized to receive one of the following ventilatory regimens. In the control group (n = 10), the patient's lungs were ventilated with 50% of inspired oxygen, V_T of 8 mL/kg IBW, PEEP of 4 cm H_2O, inspiratory:expiratory ratio of 1:2, and initial ventilatory rate of 8 breaths/min. Pa_{CO_2} was continuously monitored (Paratrend 7®) and ventilation subsequently adjusted (first by increasing the respiratory rate and then the V_T in 50-mL increments if required) to maintain Pa_{CO_2} at a level of mild permissive hypercapnia between 45 and 50 mm Hg while the PEEP was maintained at 4 cm H_2O throughout the end of anesthesia. Patients' lungs in the recruitment group (n = 10) were initially ventilated with the identical respiratory variables. After the creation of pneumoperitoneum (inflation pressures of 15 mm Hg), a lung recruitment maneuver was performed as follows (Fig. 1): the V_T (8 mL/kg IBW) and inspiratory:expiratory ratio of 1:2 remained unchanged while lungs were recruited by increasing the PEEP in a stepwise fashion—first to 10 cm H_2O (3 breaths), then to 15 cm H_2O

Table 1. Demographic and Intraoperative Characteristics, Use of Opioids, and Fluids

	Control (n = 10)	Recruitment maneuver (n = 10)	P-value
Age, yr	38 ± 11	44 ± 9	0.14
Women, n	6	8	0.63
Body mass index, kg/m^2	53 ± 11	48 ± 6	0.44
Duration of surgery, min	213 ± 91	185 ± 33	0.91
Intraoperative morphine equivalents, mg[a]	52 ± 18	46 ± 10	0.53
Intraoperative fluids, L	3.4 ± 2.7	2.9 ± 1.3	0.35
Patients who received any vasopressors, n	4	8	0.17
Vasopressor equivalents[b]	0.8 ± 1.3	3.0 ± 2.5	0.04

[a] One morphine equivalent (10 μg of fentanyl, 0.1 mg of oxymorphone, or 0.15 mg of hydromorphone) = 1 mg of morphine.
[b] Vasopressor equivalents = 1 equivalent is either 5 mg of ephedrine or 100 μg of phenylephrine.

(3 breaths), and finally to 20 cm H_2O (10 breaths). It took approximately 2 min to perform a single recruitment maneuver with an anesthesia ventilator. Provision was preestablished that if peak airway pressure at any point during the recruitment maneuver exceeded 50 cm H_2O, the next level of PEEP would be halted, and ventilation would be maintained at the preceding lower PEEP. The requirement for repeated recruitment depended on the $Pa{O_2}$ response to the preceding maneuver. If the increase in $Pa{O_2}$ during the first maneuver reached plateau (i.e., if no further increase in $Pa{O_2}$ more than the 10-s monitoring interval on Paratrend 7® was detected), only a single maneuver was performed. If the $Pa{O_2}$ showed an increasing trend after the first recruitment, a series of up to four sequential maneuvers was performed. The highest $Pa{O_2}$ value achieved during initial recruitment was established as a reference point to judge the requirement for any subsequent maneuvers. During the course of surgery, a repeat recruitment maneuver was performed whenever the $Pa{O_2}$ decreased more than 25 mm Hg less than the maximal $Pa{O_2}$ value achieved during the initial recruitment. After the recruitment maneuvers, V_T was left unchanged, and PEEP was set at 12 cm H_2O. As in the control group, ventilation was subsequently adjusted, first by increasing the respiratory rate, and then by increasing the V_T in 50-mL increments to maintain $Pa{CO_2}$ between 45 and 50 mm Hg. Hemodynamics (directly measured arterial blood pressure and heart rate) were monitored. The maneuver was to be aborted if the systolic blood pressure decreased more than 20% of the pre-recruitment value.

All measurements were made with patients positioned supine. Baseline measurements were performed at least 5 min after the induction of anesthesia but before the onset of pneumoperitoneum. A second set of measurements began 5 min after pneumoperitoneum was established and then at 30, 60, and 120 min after baseline. A final measurement was performed after pneumoperitoneum was released upon completion of surgery. The $Pa{O_2}$ and $Pa{CO_2}$ were also recorded 30 min after tracheal extubation in the recovery room. Arterial blood pressure, heart rate, and cardiac output (measured every 3 min by the NICO2™) were recorded throughout the intraoperative period.

Other intraoperative variables recorded were the use of opioids (reported as morphine equivalents) (20,21), fluids administered, and vasopressors administered (reported as vasopressor equivalents, with 5 mg of ephedrine or 100 μg of phenylephrine counted as 1 vasopressor equivalent each). Finally, medical records and clinical notes were reviewed after hospital discharge for development of the following postoperative pulmonary complications: pulmonary embolism, respiratory failure requiring mechanical ventilation or delayed tracheal extubation (>24 h after surgery), pneumonia, clinical pulmonary infection score >6, or new onset of fever and infiltrates associated with leukocytosis or leukopenia, purulent sputum or positive sputum culture, atelectasis requiring intervention (bronchoscopy), and length of hospitalization.

The primary outcome variable was the ratio of arterial oxygen partial pressure to inspiratory oxygen concentration ($Pa{O_2}/FI{O_2}$), and other variables related to gas exchange, oxygenation, ventilation, respiratory mechanics, and hemodynamics are reported separately for patients randomized to recruitment maneuver and control. All continuous data are expressed as mean ± SD. Differences in these variables across procedure groups over time up to the end of surgery were tested using repeated-measures analysis of variance models. Age, sex, BMI, and baseline value of the variable were included as adjustor variables in all models. A procedure by time interaction was tested to determine if the nature of the treatment effect differed over time. Demographics, administration of IV fluids, morphine equivalents, vasopressor equivalents, and other outcomes were reported and compared across procedure groups using Fisher's exact tests for categorical variables and t-tests or Wilcoxon's ranked sum test for continuous variables. A P value

Table 2. Number and Timing of Recruitment Maneuvers

Patient	Initial maneuver (baseline)	Subsequent maneuver
1	4 (over 8 min)	–
2	2 (over 7 min)	–
3	4 (over 8 min)	2 at 60 min (over 5 min)
4	4 (over 11 min)	4 at 60 min (over 9 min)
5	2 (over 5 min)	–
6	1 (over 2 min)	–
7	2 (over 5 min)	–
8	2 (over 5 min)	–
9	1 (over 2 min)	2 at 45 min (over 5 min)
10	1 (over 2 min)	–

$<$0.05 was considered statistically significant. Statistical analysis was performed with the SAS statistical software package (Statistical Analysis System, SAS Institute, Cary, NC).

Results

There were no significant differences in demographic characteristics, duration of operation, or the intraoperative use of opioids or fluids between the two groups (Table 1). Recruitment was performed according to the planned protocol in all patients randomized to the recruitment group, with no patient exceeding 50 cm H_2O of inspiratory pressure. Patients in the recruitment group underwent a median of two (range, 1–8) recruitment maneuvers. In 3 of 10 patients, recruitment maneuvers were repeated later during the surgery because of a decrease in Pao_2 (Table 2).

Patients in the recruitment group had a significantly higher intraoperative Pao_2/Fio_2 (Fig. 2), even after adjusting for baseline Pao_2/Fio_2, BMI, age, and sex ($P < 0.01$). Recruitment maneuvers significantly increased respiratory system dynamic compliance (by approximately 40% at 5 min; $P < 0.05$; Fig. 2). However, compliance in these patients subsequently declined and, at 30 min after recruitment, approached the respective pre-recruitment value (Fig. 2), with lung recruitment inspiratory airway resistance modestly decreased as expected (Table 3). After the release of pneumoperitoneum (end of surgery point on Figure 2), dynamic compliance increased in both groups but was higher in the recruitment than in control patients ($P < 0.01$). $V_{DPhysiol}/V_T$ did not change after recruitment or throughout the anesthesia course in either group (Table 3). At 30 min after tracheal extubation, there was no significant difference in Pao_2/Fio_2 between the recruitment and control patients ($P = 0.57$; Table 4). The $Paco_2$ measured 30 min after extubation was significantly higher in the recruitment group (Table 4).

Mean arterial blood pressure and heart rate increased throughout the operation but were not different between the two groups (Fig. 3). Baseline cardiac

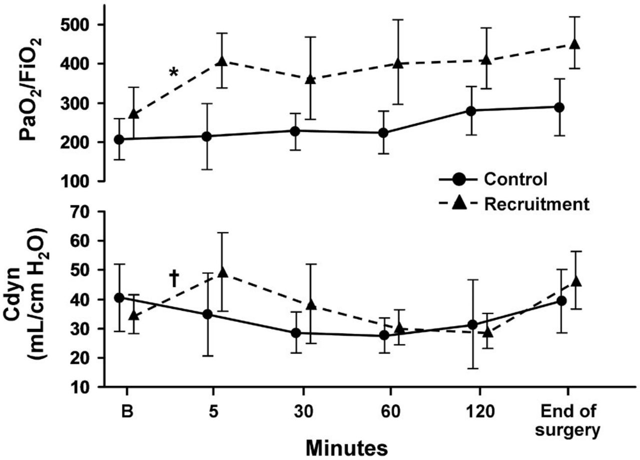

Figure 2. Arterial oxygen partial pressure as a fraction of inspiratory oxygen concentration (Pao_2/Fio_2) and dynamic respiratory system compliance (C_{dyn}) in control and recruitment groups. Pao_2/Fio_2 improved after recruitment and remained higher compared with control patients throughout the surgery when adjusted for baseline values, age, sex, and body mass index (BMI). Recruitment increased C_{dyn}; however, C_{dyn} continued to decrease during surgery, despite 12 cm H_2O of positive end-expiratory pressure (PEEP), and was not substantially different from pre-recruitment baseline by 30 min. 5 min = denotes measurement after recruitment. Symbols * and † indicate $P < 0.05$ change at 5 min compared with baseline. End of surgery measurement ranged from 129 min to 389 min.

index was larger in the recruitment group (4.6 versus 3.8 L · min^{-1} · m^2); however, after adjusting it for differences in baseline value, age, sex, and BMI, patients in the recruitment group had a smaller cardiac index during surgery compared with control patients ($P = 0.02$). In both groups, release of pneumoperitoneum at the end of surgery was associated with a modest increase in cardiac index. Patients in the recruitment group received a larger total dose of vasopressors (Table 1; $P = 0.04$).

Ventilatory requirements to maintain $Paco_2$ around 50 mm Hg were similar between the two groups (Table 2). Peak inspiratory and mean airway pressures were higher in the recruitment group ($P < 0.01$). Furthermore, throughout the surgery, no differences between the arterial and end-tidal CO_2 were observed between groups (Table 3).

The length of hospitalization and incidence of pulmonary complications were not significantly different (Table 4), although the small number of the latter events precluded meaningful statistical comparison. One patient in the recruitment group had a pulmonary embolism, and two had respiratory failure (tracheally intubated more than 24 h), whereas in the control group, one patient had respiratory failure, and one had atelectasis requiring intervention (bronchoscopy).

Discussion

This study shows that recruitment maneuvers followed by PEEP effectively increases intraoperative

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Table 3. Respiratory Variables in Control and Recruitment Groups

	Baseline	Time (min) 5[c]	30	60	120	End[d]	P^a-value
Pa_{CO_2} (mm Hg)							
Control	47.4 ± 2.7	47.6 ± 3.0	48.8 ± 3.6	49.3 ± 3.6	49.8 ± 3.0	47.8 ± 4.0	0.80
Recruitment	47.4 ± 3.3	46.6 ± 2.4	48.7 ± 2.9	50.3 ± 3.7	48.5 ± 3.0	46.6 ± 3.4	
End-tidal CO_2 (mm Hg)							
Control	35.9 ± 3.4	36.8 ± 3.8	37.8 ± 4.7	37.6 ± 4.4	38.0 ± 4.8	39.4 ± 3.5	0.44
Recruitment	38.9 ± 5.1	37.0 ± 3.5	40.1 ± 6.0	38.2 ± 4.0	38.0 ± 5.9	38.9 ± 5.8	
pH value							
Control	7.34 ± 0.03	7.34 ± 0.03	7.33 ± 0.04	7.32 ± 0.04	7.30 ± 0.03	7.3 ± 0.04	0.59
Recruitment	7.36 ± 0.03	7.36 ± 0.04	7.34 ± 0.05	7.33 ± 0.03	7.32 ± 0.03	7.3 ± 0.04	
Respiratory rate (min^{-1})							
Control	13 ± 3	14 ± 4	15 ± 4	18 ± 3	18 ± 3	17 ± 4	0.97
Recruitment	12 ± 2	12 ± 2	14 ± 2	17 ± 4	20 ± 8	19 ± 6	
Minute volume (L/min)							
Control	8.63 ± 3.3	8.37 ± 1.8	9.65 ± 2.3	11.90 ± 1.8	13.30 ± 3.3	13.0 ± 4.4	0.02
Recruitment	7.27 ± 2.4	7.84 ± 2.3	9.39 ± 2.5	10.26 ± 2.6	13.09 ± 5.2	13.4 ± 3.4	
Tidal volume (exhaled) (mL)							
Control	571 ± 275	651 ± 176	651 ± 191	684 ± 155	734 ± 95	774 ± 292	0.39
Recruitment	591 ± 134	622 ± 128	662 ± 149	629 ± 143	665 ± 129	730 ± 99	
Tidal volume (mL)/IBW (kg)							
Control	9.0 ± 3.6	10.0 ± 1.4	10.0 ± 1.8	10.2 ± 1.4	10.5 ± 1.1	11.8 ± 2.6	0.44
Recruitment	10.0 ± 2.4	10.5 ± 2.2	11.1 ± 2.4	10.9 ± 2.2	11.6 ± 2.3	12.7 ± 1.5	
Peak airway pressure (cm H_2O)							
Control	26.9 ± 9.3	31.7 ± 13.6	34.7 ± 6.9	34.3 ± 3.4	37.3 ± 3.4	29.5 ± 4.8	<0.01
Recruitment	28.2 ± 6.7	34.0 ± 10.1	35.4 ± 7.0	39.5 ± 4.9	42.1 ± 5.2	34.9 ± 5.6	
Mean airway pressure (cm H_2O)							
Control	11.3 ± 4.6	12.6 ± 5.7	13.5 ± 4.6	14.2 ± 5.1	16.6 ± 6.1	12.7 ± 4.7	<0.01
Recruitment	10.9 ± 1.7	17.9 ± 2.5	18.4 ± 2.0	19.6 ± 1.5	20.6 ± 1.7	18.5 ± 1.3	
PEEP (cm H_2O)[b]							
Control	4.3 ± 0.8	4.1 ± 0.5	4.2 ± 0.8	4.9 ± 2.6	7.0 ± 6.4	5.6 ± 4.1	<0.01
Recruitment	4.0 ± 0.3	11.8 ± 0.3	11.8 ± 0.3	11.7 ± 0.1	11.8 ± 0.2	11.8 ± 0.2	
R_{insp}(cm $H_2O \cdot L^{-1} \cdot s^{-1}$)							
Control	13.6 ± 7.2	17.0 ± 10.6	17.5 ± 7.1	12.1 ± 2.2	11.0 ± 2.8	11.2 ± 2.3	0.14
Recruitment	16.1 ± 5.2	13.4 ± 5.4	11.6 ± 2.3	14.4 ± 5.8	13.4 ± 4.6	11.7 ± 5.5	
$V_{DPhysiol}/V_T$							
Control	0.24 ± 0.07	0.23 ± 0.08	0.22 ± 0.08	0.24 ± 0.07	0.24 ± 0.11	0.18 ± 0.08	0.08
Recruitment	0.18 ± 0.07	0.20 ± 0.09	0.18 ± 0.09	0.24 ± 0.10	0.21 ± 0.12	0.16 ± 0.13	

R_{insp} = inspiratory airway resistance; Pa_{CO_2} = partial pressure of carbon dioxide; IBW = ideal body weight; PEEP = positive end-expiratory pressure; V_DPhysiol/V_T, = physiologic dead space to tidal volume ratios.

[a] Testing for differences over time between control and recruitment maneuver adjusted for baseline value, age, sex, and body mass index (BMI).

[b] In one patient (BMI = 88 kg/m^2), the anesthesiologist considered it clinically indicated to substantially increase PEEP, which explains higher average PEEP and large standard deviation values, especially at 120 and End times in the control group.

[c] Five-minute mark is measurement after recruitment.

[d] End (of surgery) is measured before completion of surgery and after pneumoperitoneum was released.

Pa_{O_2} in patients undergoing laparoscopic bariatric surgery. The improvement in Pa_{O_2} was sustained in most patients for as long as endotracheal intubation and PEEP were maintained. However, this effect disappeared within 30 minutes of tracheal extubation. The patients in the recruitment group received more vasopressors throughout the surgery; however, the recruitment maneuvers were well tolerated, and no patient required vasopressors during performance of maneuver.

Table 4. Postoperative Outcomes

	Control (n = 10)	Recruitment maneuver (n = 10)	P-value
Pao_2/Fio_2 (mm Hg) in recovery room	249 ± 53	202 ± 67	0.57[a]
$Paco_2$ (mm Hg) in recovery room	47 ± 5	55 ± 8	0.03[a]
Length of hospital stay, days	3.8 ± 1.1	4.5 ± 2.0	0.39
Pulmonary complications, n	2	3	1.00

Pao_2/Fio_2 = arterial oxygen partial pressure as a fraction of inspiratory oxygen concentration; $Paco_2$ = arterial carbon dioxide partial pressure.
[a] Testing for differences between control and recruitment maneuver adjusted for age, sex, body mass index, and baseline value.

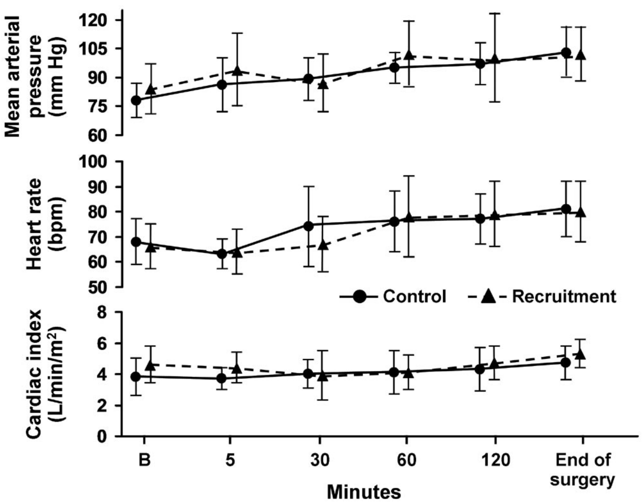

Figure 3. Mean arterial blood pressure, heart rate, and cardiac index in the control and recruitment group. There were no changes over time or between groups in mean arterial blood pressures and heart rates; however, cardiac index was lower in recruitment group after adjusting for baseline value, age, sex, and body mass index (BMI; P = 0.02). 5 min = denotes measurement after recruitment. End of surgery measurement ranged from 129 to 389 min.

In anesthetized patients undergoing laparoscopic surgery, pulmonary changes associated with increased body weight are primary factors that determine intraoperative Pao_2/Fio_2. We have previously shown that the Pao_2 was not affected by pneumoperitoneum, body position, or large V_T ventilation (9,12). Besides being ineffective, large V_T ventilation in morbidly obese patients results in high end-inspiratory (plateau) pressures (12), which may increase the risk of ventilator-induced lung injury (22,23). In a similar way, PEEP does not consistently improve Pao_2 in morbidly obese patients (8,24).

Based on previous studies of the recruitment maneuver (13–17), we conjectured that it would be a useful method to reexpand areas of lung atelectasis that develop during anesthesia in the morbidly obese. The rationale for the maneuver is based on the fact that sustained, high airway pressures are required to resolve atelectasis in experimental models, as predicted by consideration of alveolar mechanics (13–17). Thus, large V_T or PEEP alone would be insufficient to reduce atelectasis (8,11,12). Another component of this concept recognizes that although PEEP will not consistently reduce atelectasis, it may delay the redevelopment of atelectasis after a recruitment maneuver (13,18).

The recruitment method we used in this study is a modification of that described by Tusman et al. (13). To standardize the recruitment maneuver, we used anesthesia ventilator to gradually increase the levels of PEEP to open alveoli for a given number of breaths (Fig. 1). Although we did not directly measure recruited lung volume, the significant increases in Pao_2 produced by the recruitment maneuver presumably were caused by decreased atelectasis. This would also be consistent with the observed increase in dynamic respiratory system compliance and decrease in inspiratory airway resistance. Whereas high PEEP was able to maintain higher Pao_2 in the recruitment group, we are not sure that it prevented derecruitment of some parts of the lungs because the increases in dynamic respiratory system compliance were not sustained. It is possible that the dependent lung segments became progressively atelectatic because of sustained intraabdominal pressure, which caused decreases in respiratory system compliance by 30 minutes after recruitment, while at the same time, pulmonary blood flow was redistributed to expanded and ventilated nondependent areas, thus maintaining oxygenation. In any event, there does not seem to be a simple relationship between respiratory system compliance and $Paco_2$, suggesting that the beneficial effects of the recruitment maneuver on $Paco_2$ may not be simply related to resolution of atelectasis.

Because the effects of recruitment on $Paco_2$ in our patients dissipated immediately after tracheal extubation, it is possible that techniques such as continuous positive airway pressure (CPAP) or bilevel positive pressure, applied by mask immediately after tracheal extubation, could help to maintain the alveolar expansion. CPAP and bilevel positive pressure are two effective respiratory modalities that may prevent tracheal intubation and decrease length of hospitalization in patients with acute respiratory failure (25,26). In a recent study of surgical patients who developed hypoxia in the recovery room, administration of CPAP had a dramatic positive impact on postoperative outcomes (27). Future studies are required in this area because it is not known if the same beneficial effect could be extended to bariatric patients.

In the present study, we maintained $Paco_2$ at the level of mild hypercapnia in all patients. The rationale for this strategy was avoiding aggressive ventilation to bring the $Paco_2$ closer to 40 mm Hg, which could have added mechanical stress to already stretched lungs in the recruitment group. Ventilatory requirements to maintain the comparable levels of hypercapnia were similar in the two groups; therefore, recruitment with its effect on increasing the surface for gas exchange did not affect the efficiency of ventilation. In the control and recruitment groups at baseline, the $V_{DPhysiol}/V_T$ ratio accounted for 24% and 18% of each normal breath, respectively. The $V_{DPhysiol}/V_T$ remained unchanged throughout the course of the anesthesia, a finding described by others (28,29).

Throughout surgery, patients in the recruitment group had higher peak and mean airway pressures, which presumably caused hypotension requiring treatments. Of note, the use of vasopressors was not standardized by our study protocol but were administered as part of routine anesthesia management. The recruitment maneuvers were well tolerated, and no patient required treatment with vasopressors during their performance. This may reflect the fact that morbidly obese patients have lower respiratory system compliance, higher resistance (6,9,12), and, contrary to wide belief, normal chest wall compliance (6,28,30). These changes in respiratory system mechanics may result in a decrease in the transpulmonary pressure achieved for a given airway opening pressure, which may not only decrease the effectiveness of the recruitment maneuver, but also may decrease the likelihood of adverse hemodynamic effects.

The association between obesity and increased cardiac output is a well-established fact (31), also illustrated by the findings in the present study. Cardiac output measured by NICO2™ has never been reported in the bariatric population. Because the NICO2™ technique depends on CO_2 equilibrium, CO_2 insufflation (laparoscopy) can theoretically affect the accuracy; however, a recent study demonstrated that NICO2™ cardiac output correlates well with those measured by the thermodilution technique during laparoscopy (32).

The recruitment group had higher $Paco_2$ values and a trend to have lower Pao_2 values after surgery. The lack of significance in the postoperative Pao_2 data may be due to the small numbers studied. However, these findings raise an important question: Does the recruitment therapy interfere with postoperative pulmonary function? A larger number of patients will be required to answer this question. Furthermore, besides having an immediate effect on $Paco_2$, the recruitment maneuver may theoretically have longer-lasting benefits. For example, in an animal model, prolonged atelectasis during anesthesia may cause lung injury, and alveolar recruitment could prevent this injury (33). Our study was not powered to detect important differences in postoperative pulmonary complications, so we cannot comment on any sustained effect, other than to note that there were no striking differences between groups. The relatively frequent rate of significant pulmonary complications overall (25%) highlights the risks encountered in this morbidly obese population.

In conclusion, a recruitment maneuver followed by PEEP effectively improves intraoperative $Paco_2$ in morbidly obese patients throughout the course of operation, but it promptly dissipates after tracheal extubation. Further studies are required to examine if immediate postextubation use of lung expansion strategies (CPAP) could improve pulmonary outcomes in bariatric patients.

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