Anesthesiology 2009; 111:979–87 Copyright © 2009, the American Society of Anesthesiologists, Inc. Lippincott Williams & Wilkins, Inc.

Prevention of Atelectasis in Morbidly Obese Patients during General Anesthesia and Paralysis

A Computerized Tomography Study

Henrik Reinius, M.D., Lennart Jonsson, M.D.,* Sven Gustafsson, M.D., Ph.D.,† Magnus Sundbom, M.D., Ph.D.,† Olov Duvernoy, M.D., Ph.D.,‖ Paolo Pelosi, M.D., Ph.D.,‡ Göran Hedenstierna, M.D., Ph.D.,§ Filip Fredén, M.D., Ph.D.**

Background: **Morbidly obese patients show impaired pulmonary function during anesthesia and paralysis, partly due to formation of atelectasis. This study analyzed the effect of general anesthesia and three different ventilatory strategies to reduce the amount of atelectasis and improve respiratory function.**

Methods: **Thirty patients (body mass index 45 ± 4 kg/m^2) scheduled for gastric bypass surgery were prospectively randomized into three groups: (1) positive end-expiratory pressure of 10 cm H_2O (PEEP), (2) a recruitment maneuver with 55 cm H_2O for 10 s followed by zero end-expiratory pressure, (3) a recruitment maneuver followed by PEEP. Transverse lung computerized tomography scans and blood gas analysis were recorded: awake, 5 min after induction of anesthesia and paralysis at zero end-expiratory pressure, and 5 min and 20 min after intervention. In addition, spiral computerized tomography scans were performed at two occasions in 23 of the patients.**

Results: **After induction of anesthesia, atelectasis increased from 1 ± 0.5% to 11 ± 6% of total lung volume ($P < 0.0001$). End-expiratory lung volume decreased from 1,387 ± 581 ml to 697 ± 157 ml ($P = 0.0014$). A recruitment maneuver + PEEP reduced atelectasis to 3 ± 4% ($P = 0.0002$), increased end-expiratory lung volume and increased Pa_{O_2}/F_{IO_2} from 266 ± 70 mmHg to 412 ± 99 mmHg ($P < 0.0001$). PEEP alone did not reduce the amount of atelectasis or improve oxygenation. A recruitment maneuver + zero end-expiratory pressure had a transient positive effect on respiratory function. All values are presented as mean ± SD.**

Conclusions: **A recruitment maneuver followed by PEEP reduced atelectasis and improved oxygenation in morbidly obese patients, whereas PEEP or a recruitment maneuver alone did not.**

PULMONARY gas exchange and respiratory mechanics are regularly impaired during general anesthesia and paralysis. A major contributor to the impairment in gas exchange is the formation of atelectasis, which, without positive end-expiratory pressure (PEEP), is present in approximately 90% of all anesthetized subjects.[1,2]

In morbidly obese subjects compared to normal weight subjects, general anesthesia and paralysis lead to more atelectasis, severe alterations in respiratory mechanics, and an increased risk of hypoxemia.[3] The amount of atelectasis formation has been shown to correlate with body weight.[4] In addition, atelectasis is sustained into the postoperative period to a higher extent in morbidly obese patients.[5]

In normal weight subjects, a recruitment maneuver with an inspiratory pressure of 40 cm H_2O has been reported to efficiently reduce atelectasis and improve oxygenation and respiratory mechanics.[6] After a successful recruitment maneuver, atelectasis reappears very slowly if 40% O_2 is used[7]; with 100% O_2, it is necessary to apply PEEP to prevent atelectasis from rapidly reccurring.[8]

Different strategies to improve respiratory function in anesthetized obese patients have been investigated. Increases in tidal volume or respiratory rate do not improve oxygenation.[9,10] Addition of 10 cm H_2O of PEEP improves respiratory mechanics and oxygenation.[11] Recruitment maneuvers have been suggested to further improve oxygenation before application of PEEP in obese patients.[12] The effect of PEEP and recruitment maneuvers has not been evaluated with computerized tomography (CT) in morbidly obese patients. Instead of spiral computerized tomography, more indirect methods like helium dilution and analysis of pressure-volume curves have been used to study changes in lung volumes after different interventions. Neither have the independent effects of recruitment maneuvers and PEEP been investigated within this group of patients.

There is still no clear evidence of whether the positive effect in oxygenation in patients with acute lung injury or acute respiratory distress syndrome is due to the recruitment maneuver, PEEP or a combination of both.[13]

We hypothesized that a recruitment maneuver followed by PEEP would be the most efficient way to improve respiratory function by reducing atelectasis in morbidly obese patients during general anesthesia and paralysis in the supine position.

We therefore evaluated in patients with body mass index greater than 40 kg/m^2, the aeration of the lung by using CT while awake, after induction of anesthesia and paralysis, and after different ventilatory interventions: PEEP alone, a recruitment maneuver + zero end-expiratory pressure (ZEEP), and a recruitment maneuver + PEEP.

* Staff Anesthesiologist, Department of Anesthesia and Intensive Care, † Staff Surgeon, Department of Surgery, ‖ Staff Radiologist, Department of Diagnostic Radiology, § Professor, Department of Clinical Physiology, University Hospital, Uppsala, Sweden. ‡ Professor, Department of Ambient, Health and Safety, University of Insubria, Varese, Italy.

Received from the Department of Anesthesia and Intensive Care, University Hospital, Uppsala, Sweden. Submitted for publication November 9, 2008. Accepted for publication June 29, 2009. Support was provided from institutional sources at Uppsala University, Uppsala, Sweden. Equipment support was provided from Maquet, Solna, Sweden.

Address correspondence to Dr. Reinius: Department of Anesthesia and Intensive Care, University Hospital, SE-751 85 Uppsala, Sweden. henrik.reinius@surgsci.uu.se. Information on purchasing reprints may be found at www.anesthesiology.org or on the masthead page at the beginning of this issue. ANESTHESIOLOGY's articles are made freely accessible to all readers, for personal use only, 6 months from the cover date of the issue.

Copyright © by the American Society of Anesthesiologists. Unauthorized reproduction of this article is prohibited.

Materials and Methods

Thirty patients with American Society of Anesthesiologists physical status classification system grade II or III, with a body mass index greater than 40 kg/m^2, aged 25 to 54 yr, and scheduled for elective gastric bypass surgery en-Roux were enrolled in this prospective, single-blind randomized study. The study was approved by the local ethics committee at Uppsala University, Uppsala, Sweden. Informed consent was obtained from all patients.

Exclusion criteria were: (1) age below 18 yr, (2) pregnancy, (3) cardiac disease (history of ischemic heart disease and New York Heart Association [NYHA] class III or IV), (4) obstructive pulmonary disease, defined as forced expiratory volume below 80% of expected value (a spirometry was performed 1–2 days before the study).

All patients received premedication with 1 g of acetaminophen and 15 mg of midazolam orally 30–60 min before induction of anesthesia. An anesthetist experienced in the treatment of morbidly obese patients performed the anesthesia procedure. After arrival at the CT scanner facility, cannulas were inserted in a brachial vein and the radial artery. The arterial line was used for the study protocol and inserted under local anesthesia. Before induction of anesthesia, an arterial blood gas sample with the patient breathing ambient air was collected. Monitoring included invasive arterial blood pressure, continuous electrocardiogram, and peripheral oxygen saturation (Spo_2). After induction of anesthesia and tracheal intubation, end tidal carbon dioxide concentration ($ETco_2$), airway pressures, tidal volume and respiratory rate were also monitored and recorded. An S/5 monitor (Datex-Engstrom, Helsinki, Finland) was used, and all data were collected with Datex-Ohmeda S/5 Collect (Helsinki, Finland). Data were collected 6 times per minute. The patients were positioned in the supine position on an operating table, (Maquet, Rastatt, Germany). The CT scan facility was equipped to assure safety of anesthesia procedures exactly as in the operating room, and anesthesia was always induced on the operating table to ensure highest possible safety. No adverse events occurred during induction and intubation.

Before induction of anesthesia, preoxygenation was given during 5 min by using 100% O_2 and a tight seal mask. General anesthesia was induced with intravenous propofol (1–2 mg/kg predicted body weight),[14] fentanyl (2–4 μg/kg predicted body weight), and rocuronium (0.6 mg/kg predicted body weight), followed by oral intubation. Predicted body weight was calculated as 45.4 + 0.91 (height (cm) − 152.4) for women and 49.9 + 0.91 (height (cm) − 152.4) for men.[15] For maintenance, a continuous infusion of propofol (3–6 mg/kg total body weight/h) and additional doses of fentanyl of 100 μg were given to obtain a clinically adequate depth of anesthesia. After induction, all patients were mechanically ventilated with volume-cycled ventilation by using a Servo *i* ventilator (Maquet, Solna, Sweden). Inspired oxygen fraction (Fio_2) was 0.5, and zero end-expiratory pressure was applied. Tidal volumes were set at 10 ml/kg predicted body weight with an initial respiratory frequency of 12 breaths/min. Respiratory rate was adjusted to maintain $ETco_2$ at 34 to 41 mmHg, whereas tidal volumes were not changed. Inspiratory/expiratory-ratio was 1:2, and the plateau pressure percentage was 28.5% of the inspiratory time.

All ventilatory data were recorded on a memory card connected to the ventilator. The quasistatic compliance of the respiratory system was calculated as tidal volume divided by inspiratory plateau pressure minus end-expiratory pressure at a period of no-flow at end-inspiration and end-expiration. After anesthesia and tracheal intubation patients were randomized by using sealed envelopes into one of three intervention groups:

(1) PEEP: PEEP of 10 cm H_2O; (2) RM+ZEEP: recruitment maneuver followed by ZEEP; (3) RM+PEEP: Recruitment maneuver followed by PEEP of 10 cm H_2O.

The recruitment maneuver was performed in the following way: ventilator mode was switched to pressure control, inspiratory pressure was increased to 55 cm H_2O, and an inspiratory hold was kept for 10 s. In case of a drop in systolic blood pressure by more than 20%, the recruitment maneuver would have been disrupted. In the recruitment maneuver followed by PEEP group, PEEP was applied immediately after the recruitment maneuver. Measurements were obtained: (1) before anesthesia induction, (2) 5 min after induction and tracheal intubation, and (3) 5 min, (4) 20 min, and (5) 40 min after intervention.

Computerized Tomography

As discussed by the local ethics committee at Uppsala University, Uppsala, Sweden, and according to most recent recommendations,[16] the radiation-dose permitted a maximum of two spiral CT investigations in each patient.

We aimed to do all the CT investigations at end-expiration in awake patients by asking them to exhale normally and hold their breath until the CT was completed, and in the anesthetized subjects by making an end-expiratory hold on the ventilator.

The CT scans were acquired with a Somatom Sensation 16 CT scanner (Siemens, Erlangen, Germany). Single-slice CT was performed in all 30 patients (single-slice alone or as part of a spiral CT (1) before anesthesia induction, (2) 5 min after induction and tracheal intubation, and (3) 5 min and (4) 20 min after intervention, which made it possible to follow the three groups from awake to 20 min after intervention. At end-expiration, the transversal CT cut (9-mm thickness) was positioned 1 cm above the right diaphragm, and the exposure was done with 120 kV, 135 mÅ, 0.5-s rotation time, and collimation of 0.75 mm. For practical and technical rea-

Copyright © by the American Society of Anesthesiologists. Unauthorized reproduction of this article is prohibited.

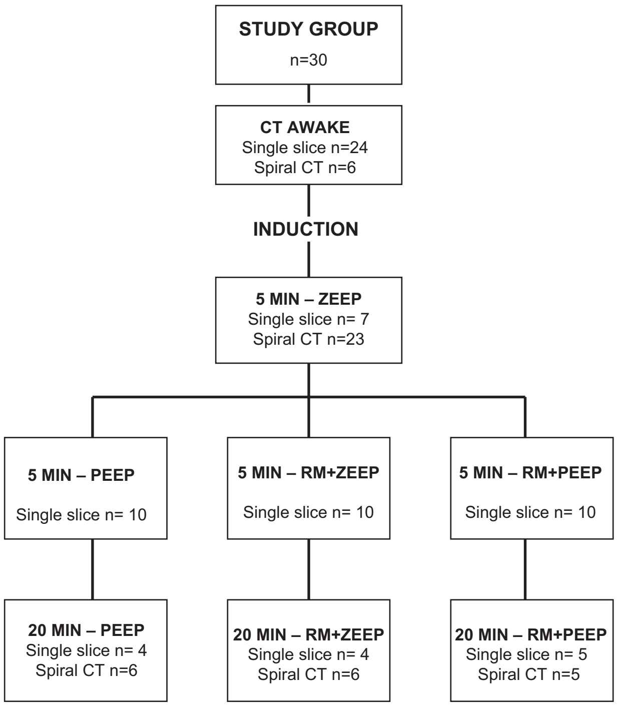

Fig. 1. Computerized tomography (CT) protocol. Spiral CT was performed at two occasions in 23 of 30 patients. Spiral CT was done before and after induction of anesthesia in 6 patients and before and 20 min after intervention in 17 patients. There were 6 patients in the PEEP and RM + ZEEP groups and 5 patients in the RM + PEEP group. Single slices were done separately and also retrieved from the spiral CT scans, so that single slices 1 cm above the diaphragm could be analyzed in all 30 patients at all four time points. CT = computerized tomography, PEEP = positive end-expiratory pressure, RM = recruitment maneuver, ZEEP = zero end-expiratory pressure.

sons, we were limited to do spiral CT in 23 of the total material of 30 patients. Six patients were randomized for a spiral CT at awake and 5 min after intubation. In 17 of the 30 patients, spiral CT scans were performed after intubation and 20 min after intervention with 5–6 patients randomized to each group (fig. 1). The spiral CT scans were acquired from a level above the apex of the lung to a level below the diaphragm (120 kV, 100 mÅ, pitch 1.1, and collimation 1.5 mm). Scanning time was approximately 4 s. To determine the borders of the lung, a frontal topogram of the chest was obtained while the patients were awake and once again after induction of anesthesia during mechanical ventilation.

Analysis of Spiral CT

Spiral CT images were obtained to analyze aeration of the entire lung. The CT images were analyzed by using the custom-made software package MALUNA (Mannheim lung analysis tool, Maluna 2.02; Mannheim, Germany) based on the graphical programming Language G (LabView®-5.1, InaqVision®-5.0; National Instruments, Austin, TX). The lung area was delineated manually. To calculate atelectasis, a region of interest was laid out that encircled the dense part of the lung, excluding large vessels. For further analysis, the lung was divided into four categories: areas with densities ranging from −1000 to −900 Hounsfield units (HU) were classified as overaerated, from −900 to −500 HU as normally aerated, from −500 to −100 HU as poorly aerated, and from −100 to +100 HU as nonaerated (atelectasis). From the spiral CT, the end-expiratory lung volume (EELV) was calculated. Function residual capacity is determined in spontaneously breathing, resting normal subjects at the end of a normal expiration, and EELV is used to denote functional residual capacity during mechanical ventilation. In addition the fractional volumes of overaerated, normally aerated, poorly aerated, and nonaerated lung tissue were calculated, with the lungs divided into three segments: base, middle, and apex. Each segment contained 8 ± 2 consecutive slices at 9-mm slice thickness.

Analysis of Single-slice CT

Within the region of interest for atelectasis, the nonaerated lung tissue (−100 to +100 HU) was calculated and divided by the area of the region of interest containing the whole lungs.

Statistical Analysis

We assumed a difference of 50% in atelectatic area in a single CT slice between measurements of the different ventilator strategies. A sample size of 30 subjects (10 for each group) was estimated if the atelectatic area was 5% in the recruitment maneuver + PEEP group compared to 10% in the other groups with a SD of 2%.

Data are shown as mean ± SD. In all calculations, a P value <0.05 was considered significant. All the testing was two-tailed.

Comparisons between patient demographics were done by using analysis of variance (ANOVA) and Fisher exact test. Analysis of variance was also used to compare the levels of the outcome variables before intervention between the treatment groups. The analyses were done separately to evaluate the effect of induction of anesthesia and the effect of different interventions. For each outcome, the following analyses were performed. A mixed-model was set up as a two-way repeated measures design by using unstructured covariance structure. The model includes treatment group, time, and the interaction between time and treatment group as factors. Of interest was the interaction between time and treatment group because it compared the treatment effects over time. If the overall test for interaction between time and treatment group was significant, pairwise comparisons for the time and group interaction were performed to explore which treatments differed. This was done by excluding one treatment group at a time by using the same mixed model set up. Within-group effect of time was analyzed by using a one-way repeated measures mixed-model with unstructured covariance structure.

Copyright © by the American Society of Anesthesiologists. Unauthorized reproduction of this article is prohibited.

Table 1. Patient Demographics of Study Population

	PEEP (n = 10)	RM + ZEEP (n = 10)	RM + PEEP (n = 10)	*P* Value
Age, yr	40 ± 10	37 ± 10	35 ± 8	ns
Men/women, n	0/10	4/6	3/7	ns
Weight, kg	120 ± 14	130 ± 13	126 ± 9	ns
Height, m	1.64 ± 0.06	1.69 ± 0.08	1.69 ± 0.07	ns
BMI, kg/m^2	44 ± 3	45 ± 4	45 ± 5	ns
Smoking history, n	6	5	4	ns

Data are presented as mean ± SD.

BMI = body mass index, ns = nonsignificant, PEEP = positive end-expiratory pressure, RM = recruitment maneuver, ZEEP = zero end-expiratory pressure.

This model only includes time as a factor. If the effect of time was significant and the data included more than two measures over time, pairwise comparisons between time points were done comparing least squared means estimated by the mixed-model. The same one-way design was used to evaluate the effect of induction of anesthesia. Histograms of the residuals were examined visually to assess the fit of the above models. To obtain normality, the outcome values of atelectasis and EELV were log transformed.

Analyses were performed by using SAS version 9.1.3 (SAS Institute Inc., Cary, NC).

Results

Thirty patients (33 women and 7 men) were included in the study. Another two patients were excluded from the study because of forced expiratory volume percentage less than 80% of expected value. Patient characteristics were equally distributed among the three groups (table 1).

Oxygenation

A recruitment maneuver followed by PEEP caused an increase in the Pa_{O_2}/F_{IO_2} ratio ($P < 0.0001$) at 5 min, and this increase was sustained at 20 and 40 min after the recruitment maneuver ($P < 0.0001$). In contrast, PEEP alone or a recruitment maneuver followed by zero end-expiratory pressure did not cause any significant change in the Pa_{O_2}/F_{IO_2} ratio at any time point. There was no significant difference in oxygenation among the three groups before intervention (table 2), either while awake breathing ambient air or after induction of anesthesia and paralysis with F_{IO_2} of 0.5. Compared to awake, the Pa_{O_2}/F_{IO_2} ratio was reduced by approximately 40% after induction of anesthesia and paralysis ($P < 0.0001$) (fig. 2).

Hemodynamics

During the study, the mean arterial pressure was between 60 and 95 mmHg, and heart rate was between 60 and 110 beats/min. There were no significant differences in hemodynamics among the groups (table 2).

Respiratory Compliance

After induction of anesthesia, there was no significant difference in compliance among the groups (table 2). A

Table 2. Blood–gas Analysis and Hemodynamics

Group	Awake	Anesthesia	5 min	20 min	40 min	Overall Group Effect
Pa_{O_2}/F_{IO_2}						
PEEP, n = 10	432 ± 68	264 ± 96	267 ± 94	253 ± 87	263 ± 88	ns
RM + ZEEP, n = 10	410 ± 43	225 ± 77	252 ± 86	225 ± 82	217 ± 83	ns
RM + PEEP, n = 10	416 ± 48	266 ± 70	419 ± 106*	412 ± 99*	394 ± 121*	$P = 0.0065$
Pa_{CO_2}, mmHg						
PEEP, n = 10	38 ± 3	36 ± 2	34 ± 3	34 ± 3	32 ± 2	ns
RM + ZEEP, n = 10	37 ± 4	34 ± 4	33 ± 4	30 ± 11	31 ± 4	ns
RM + PEEP, n = 10	37 ± 2	33 ± 4	32 ± 4	31 ± 4	31 ± 4	ns
Compliance, ml/cm H_2O						
PEEP, n = 10		32 ± 6	43 ± 7*	43 ± 6*	47 ± 7*	$P < 0.0001$
RM + ZEEP, n = 10		37 ± 7	38 ± 7	36 ± 6	34 ± 4	$P = 0.0014$
RM + PEEP, n = 10		33 ± 8	64 ± 11*	61 ± 11*	57 ± 12*	$P < 0.0001$
MAP, mmHg						
PEEP, n = 10	103 ± 9	82 ± 9	74 ± 9	74 ± 10	nd	ns
RM + ZEEP, n = 10	94 ± 12	72 ± 6	71 ± 8	76 ± 16	nd	ns
RM + PEEP, n = 10	102 ± 19	78 ± 16	75 ± 24	77 ± 28	nd	ns
Heartrate, beats/min						
PEEP, n = 10	75 ± 8	82 ± 7	75 ± 8	72 ± 9	nd	ns
RM + ZEEP, n = 10	79 ± 15	82 ± 12	78 ± 14	77 ± 15	nd	ns
RM + PEEP, n = 10	90 ± 12	85 ± 16	92 ± 17	82 ± 18	nd	ns

Data are expressed as mean ± SD.

* $P < 0.05$ *versus* anesthesia.

Groups: PEEP = PEEP 10 cmH_2O; RM + ZEEP = recruitment maneuver and PEEP 0 cm H_2O; RM + PEEP = recruitment manuever and PEEP 10 cm H_2O. F_{IO_2} = fraction of inspired oxygen; HR = heart rate; MAP = mean arterial pressure; nd = not determined; ns = not significant; Pa_{CO_2} = arterial partial pressure of carbon dioxide; Pa_{O_2} = arterial partial pressure of oxygen; PEEP = positive end-expiratory pressure; RM = recruitment maneuver; ZEEP = zero end-expiratory pressure.

Copyright © by the American Society of Anesthesiologists. Unauthorized reproduction of this article is prohibited.

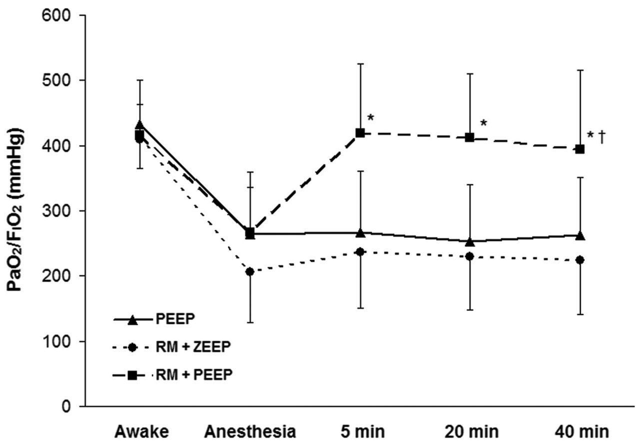

Fig. 2. Pa_{O_2}/F_{IO_2} in the three groups studied. Induction of anesthesia caused a reduction of Pa_{O_2}/F_{IO_2}. In the RM + PEEP group (n = 10), oxygenation returned to the same level as before induction of anesthesia. In the groups with RM + ZEEP (n = 10) or PEEP (n = 10), there was no significant effect on oxygenation.* $P < 0.05$ *versus* anesthesia; † $P < 0.05$ *versus* PEEP and RM + ZEEP. F_{IO_2} = fraction of inspired oxygen; Pa_{O_2} = arterial partial pressure of oxygen; PEEP = positive end expiratory pressure; RM = recruitment maneuver; ZEEP = zero end expiratory pressure.

recruitment maneuver followed by PEEP caused an increase in compliance ($P < 0.0001$). This effect was seen already at 5 min ($P < 0.0001$) and was less but still significant at 40 min ($P < 0.0001$). PEEP alone caused an increase in compliance ($P < 0.0001$). There was a small decrease in compliance in the recruitment maneuver followed by ZEEP group ($P = 0.0014$).

Spiral CT

As seen in table 3, induction of anesthesia and paralysis was accompanied by approximately 50% reduction of EELV. Twenty minutes after intervention, the EELV increased 32% in the PEEP group and 64% in the recruitment maneuver followed by PEEP group. No changes in EELV were observed after a recruitment maneuver followed by ZEEP.

In table 4, the overall changes of the fractional amount of normally aerated, poorly aerated, and nonaerated tissue, as well as their distribution at the apex, middle, and basal lung regions are reported while awake, after induction of anesthesia and paralysis, and 20 min after application of the different ventilatory strategies.

The atelectatic volume was 1 ± 0.5% before induction of anesthesia and paralysis (six patients). At 5 min after induction, the mean atelectatic volume in all 23 patients who were studied with spiral CT was 11 ± 6%, with no significant difference among the groups. The increase in atelectasis after induction of anesthesia and paralysis was most pronounced in the basal region (the part of the lung in the pleural sinuses), where it increased from 6 ± 4% to 29 ± 15% ($P < 0.0001$) (note, however, the small fraction of lung visualized in the basal CT slices), but was also present in the apical ($P = 0.0001$) and middle regions ($P < 0.0001$). Normally aerated lung-fraction decreased, but poorly aerated and overaerated fractional volumes did not change. Overaeration was always less than 1% and is, therefore, not presented.

A recruitment maneuver followed by PEEP increased the fractional amount of normally aerated tissue, decreased the amount of poorly aerated tissue mainly at the apex and middle lung regions, and caused a major reduction of nonaerated tissue (table 4). A recruitment maneuver followed by ZEEP did not substantially affect the fractional amount of normally aerated, poorly aerated, or nonaerated tissue. In the group receiving PEEP without a preceding recruitment maneuver, there was an increase in normally aerated volume ($P = 0.0004$) and a reduction of poorly aerated volume ($P = 0.0014$), whereas atelectasis remained unchanged.

Single-slice CT

Single-slice CT was made in all 30 patients at the four different time points of measurement. In figure 3, a representative CT scan done while awake, after induction of anesthesia and paralysis, and 5 and 20 min after the three different interventions (PEEP, recruitment maneuver followed by PEEP, or recruitment maneuver followed by ZEEP) is shown. As noted, atelectasis appeared after induction of anesthesia and paralysis in the most dependent lung regions. After 5 and 20 min a reduction in atelectasis is evident after recruitment maneuver followed by PEEP but not after PEEP or recruitment maneuver followed by ZEEP.

Single-slice CT correlates with the upper part of the middle region in the spiral CT. Results from single-slice CT were comparable to spiral CT with minimal atelectasis (0.4 ± 0.7%) in awake patients and formation of

Table 3. End-expiratory Lung Volume from Spiral Computerized Tomography

Patients group	n	Awake, ml	Anesthesia, ml	20 min, ml
Awake	6	1,387 ± 581* ($P = 0.0014$)	697 ± 157	
PEEP	6		823 ± 206	1,085 ± 304* ($P = 0.0004$)
RM + ZEEP	6		818 ± 259	805 ± 215
RM + PEEP	5		827 ± 240	1,357 ± 305* ($P < 0.0001$)

Data are presented as mean ± SD.

* Significant *versus* anesthesia.

PEEP = positive end expiratory pressure; RM = recruitment maneuver; ZEEP = zero end-expiratory pressure.

Copyright © by the American Society of Anesthesiologists. Unauthorized reproduction of this article is prohibited.

Table 4. Fractional Lung Volumes from Spiral Computerized Tomography, n = 23

Aeration	Part of Lung	Awake SB (n = 6)	Anesthesia ZEEP (n = 23)	20 min after Intervention PEEP (n = 6)	RM + ZEEP (n = 6)	RM + PEEP (n = 5)	Time *Group Interaction *P*	Pairwise Comparisons *P*
Normally aerated, %	Apex	75 ± 11*	56 ± 17	70 ± 12†	55 ± 17	80 ± 8†		
	Middle	72 ± 10*	53 ± 11	46 ± 11†	54 ± 14	74 ± 8†		
	Basal	57 ± 16*	28 ± 13	43 ± 12†	31 ± 16	47 ± 17†		
	Total	71 ± 11*	50 ± 12	64 ± 11†	50 ± 15	72 ± 9†	0.0015	0.0083
								0.3470
								< 0.0001
Poorly aerated, %	Apex	25 ± 10*	39 ± 15	27 ± 12†	43 ± 17	19 ± 6†		
	Middle	27 ± 11*	37 ± 8	29 ± 9†	42 ± 12	24 ± 6†		
	Basal	35 ± 17	44 ± 10	38 ± 10†	45 ± 7	42 ± 14		
	Total	28 ± 12*	39 ± 9	30 ± 10†	43 ± 13	25 ± 6†	0.0014	0.0020
								0.8813
								0.0012
Nonaerated, %	Apex	0.6 ± 0.5*	6 ± 5	3 ± 4	3 ± 2†	1 ± 1†		
	Middle	0.2 ± 0.3*	10 ± 7	6 ± 4	5 ± 5†	2 ± 2†		
	Basal	6 ± 4*	28 ± 15	15 ± 3	24 ± 11†	10 ± 12†		
	Total	1 ± 0.5*	11 ± 6	7 ± 3	7 ± 4†	3 ± 4†	0.032	0.0340
								0.0163
								0.3472

Data are presented as mean percent of each section (apex, middle, and basal part of the lung) with ± SD. Overaeration was always less than 1% and is, therefore, not presented. If there was a significant difference between groups over time, comparisons were made between the groups to determine which interventions differed from each other. Pairwise comparisons were made between: PEEP *vs.* RM + ZEEP, PEEP *vs.* RM + PEEP, and RM+ZEEP *vs.*RM + PEEP, respectivly.

* *P* < 0.05, awake *vs.* anesthesia; † *P* < 0.05, anesthesia *vs.* after intervention.

ns = non significant; PEEP = positive end-expiratory pressure; RM = recruitment maneuver; SB = spontaneous breathing; ZEEP = zero end-expiratory pressure.

atelectasis after induction of anesthesia and paralysis (7 ± 5%) (fig. 4). At 5 min after intervention, the group receiving a recruitment maneuver followed by PEEP had a significantly reduced mean area of atelectasis of 1 ± 1% compared to 7 ± 5% immediately after induction (*P* < 0.0001). This reduction in atelectasis was maintained at 20 min after intervention (*P* < 0.0001). In the group where a recruitment maneuver was followed by ZEEP, there was a reduction of atelectatic area at 5 min after intervention (*P* < 0.0083), but this reduction in atelectasis was not sustained at 20 min.

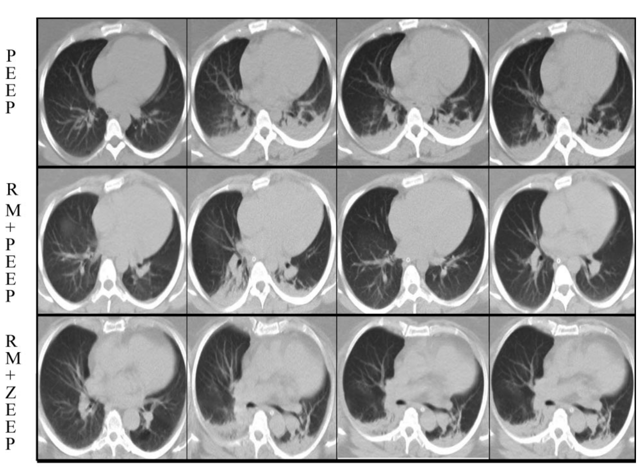

Fig. 3. Representative computerized tomography (CT). A CT scan 1 cm above the diaphragm in the three different groups at all four time points. Note the sustained effect of RM + PEEP and the transient effect of RM + ZEEP. PEEP = positive end-expiratory pressure; RM = recruitment maneuver; ZEEP = zero end-expiratory pressure.

Discussion

In morbidly obese patients, we found (1) that induction of anesthesia and paralysis dramatically reduced EELV, promoted atelectasis in dependent lung regions and caused a marked fall in arterial oxygenation and (2) that a recruitment maneuver followed by PEEP increased EELV, effectively opened up atelectatic lung areas, increased respiratory system compliance, and improved arterial oxygenation. The improvement in oxygenation after the recruitment maneuver remained stable during the study period of 40 min. PEEP or a recruitment ma-

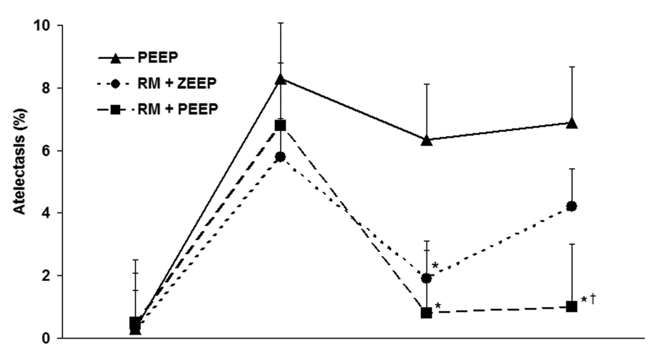

Fig. 4. Single-slice computerized tomography (CT). Percentage of atelectasis 1 cm above the diaphragm. The application of RM + PEEP (n = 10) reduced atelectasis, and this effect was sustained for 20 min. RM + ZEEP (n = 10) caused a reduction of atelectasis, but this effect could not be seen after 20 min. PEEP (n = 10) had no effect on the amount of atelectasis. * *P* < 0.05 *versus* anesthesia, † *P* < 0.05 *versus* PEEP and RM+ZEEP. PEEP = positive end-expiratory pressure; RM = recruitment maneuver; ZEEP = zero end-expiratory pressure.

Copyright © by the American Society of Anesthesiologists. Unauthorized reproduction of this article is prohibited.

neuver alone did not substantially improve respiratory function.

The prevalence of obesity continues to rise, both in the United States[17] and globally.[18] It has recently been reported that gastric bypass surgery is effective not only for weight reduction but also reduces clinical complications of obesity and even mortality.[19] Thus it seems likely that there will be more obese patients undergoing surgery in the future.[20] Atelectasis formation during induction of anesthesia and paralysis, surgery, and also postoperatively[5] may promote perioperative and postoperative hypoxemia and also postoperative pneumonia.[21] Previously, Eichenberger *et al.* have demonstrated that 8% of the lungs in obese patients were atelectatic 1 h after extubation and that the atelectasis remained 24 h later.[5]

In the current study, spiral CT was done in a majority of the patients, which made it possible to calculate EELV at different time points. In addition, the fractional volumes of overaerated, normally aerated, poorly aerated, and nonaerated lung tissue have been calculated, with the lungs divided in three different regions from base to apex. The radiation-dose permitted a maximum of two spiral CT scans in each patient. Single-slice CT could be performed in all patients at four time points and made it possible to follow the three groups from awake to 20 min after intervention. Great differences in the cross-sectional area regarding aeration can be observed from apex to basal parts of the lung. The level of the single-slice CT corresponds to the upper middle section of the spiral CT, hence the higher fraction of atelectasis in spiral CT scans because they include the juxta-diaphragmatic lung regions that contain a large fraction of atelectasis. Previous studies have shown significant correlation in fractional aeration in single-slice CT compared to spiral CT. However, single-slice CT seems less accurate in estimating the changes in aeration of the lung when compared to spiral CT.[22,23] All CT investigations were done at end-expiration; therefore, the results were optimized for comparison between awake and anesthetized patients.

We found that these patients while awake in supine position showed a low EELV, although gas-exchange variables were within normal range. This is in fair agreement with previous reports in awake morbidly obese patients.[24,25] Negative effects of anesthesia and paralysis on respiratory function were demonstrated by a reduction of an already low EELV, increased atelectasis formation in the dependent lung regions, and a marked fall in Pa_{O_2}/F_{IO_2} ratio. After induction of anesthesia and paralysis, we found an average EELV of approximately 800 ml, confirming previous EELV measurements in morbidly obese patients obtained by helium dilution technique during anesthesia, and paralysis in the absence of PEEP.[11,25,26]

We found that anesthesia and paralysis decreased the fractional amount of normally aerated tissue from 71% to 50% and increased the fractional amount of poorly aerated from 28% to 39% and nonaerated tissue from 1% to 11%. This is in line with previous results in which obese patients were investigated with single-slice CT before and after induction of anesthesia and paralysis, reporting 10% atelectasis.[27] In contrast, previous studies in normal weight subjects have reported approximately 3% atelectasis when performing spiral CT during anesthesia and ZEEP.[28]

The recruitment maneuver of 55 cm H_2O for 10 seconds reduced atelectasis, as seen in the group with recruitment maneuver followed by PEEP. In most patients, this pressure was sufficient to abolish atelectasis; in some cases, however, there were still some atelectasis remaining. We also observed a marked increase in EELV, a reduction in poorly aerated tissue associated with an increase in normally aerated tissue, improved respiratory compliance and oxygenation. Our results are in agreement with previous studies in which application of PEEP preceded by a recruitment maneuver was more effective than PEEP alone.[12,29] In addition, it has been shown in normal weight subjects that a single insufflation of 40 cm H_2O for 8 s was sufficient to open atelectatic areas.[30] However, it is likely that, for a comparable airway pressure, the transpulmonary pressure, which is the real alveolar distending pressure, is lower in the anesthetized morbidly obese than in normal weight subjects. This is caused by increased chest wall elastance[11,31] and higher intraabdominal pressure[3] as illustrated by a return of EELV to almost preanesthesia values in obese patients when the abdominal wall was opened.[25] Thus, we estimated that a pressure of 55 cm H_2O for 10 s during the recruitment maneuver would optimize the beneficial effect of the recruitment maneuver while minimizing possible negative effects, in terms of barotrauma and hemodynamic compromise.

Excessive pressures during the recruitment maneuver may cause transient hemodynamic instability with severe side effects, especially in hypovolemic subjects.[32] We consider the safety of the recruitment maneuver to be of great importance, also because the outcome benefits in morbidity and mortality are still to be clearly shown.[13] Care was therefore taken to make sure the patients were clinically normovolemic and hemodynamically stable before the extended insufflations. The recruitment maneuver used only had a mild, short-lasting effect on blood pressure, despite the high pressures used. None of the patients showed clinical signs of pneumothorax or suffered from severe respiratory failure requiring prolonged mechanical ventilation or postoperative reintubation.

PEEP alone increased the normally aerated lung fraction. This was combined with a reduction of poorly aerated lung tissue while atelectasis remained unchanged. The increase in normally aerated lung tissue was not accompanied by an increase in Pa_{O_2}.This might

Copyright © by the American Society of Anesthesiologists. Unauthorized reproduction of this article is prohibited.

be explained by a redistribution of blood to nonventilated regions or by a decrease in cardiac output.[10] In a previous study[11] in postoperative mechanically ventilated obese patients (mean body mass index 51) after abdominal surgery, PEEP of 10 cm H_2O caused an increase in Pa_{O_2}, respiratory compliance, and EELV. This was in contrast to nonobese patients in whom PEEP had no beneficial effects.

In a recent study[33] of morbidly obese patients using impedance tomography, the optimal level of PEEP (defined as the pressure level where no recruitment or derecruitment occurred) was 15 cm H_2O. Despite the use of an optimal level of PEEP, these patients still improved in oxygenation after a recruitment maneuver. Thus there possibly were recruitable lung regions even at the PEEP level of 15 cm H_2O. It is possible that the level of PEEP used in the current study was not enough to maximize the beneficial effects on the respiratory function. However, a PEEP of 10 cm H_2O was sufficient to maintain a substantial improvement in respiratory function. This is most probably explained by the preceding recruitment maneuver, thus applying PEEP to an open lung. In addition, PEEP higher than 10 cm H_2O may be associated with marked derangements in hemodynamics, especially in morbidly obese patients.[34]

When a recruitment maneuver was applied without PEEP, the effect was short lasting. Twenty minutes after the recruitment maneuver, no beneficial effects remained. This is in contrast to what has been observed in normal weight patients in whom a recruitment maneuver followed by ZEEP reduced atelectasis significantly for at least 20 min if F_{IO_2} was kept at 0.4.[35] This observation suggests that the application of PEEP in morbidly obese patients is needed to keep the lung open and improve respiratory function after an effective recruitment maneuver.

Our study has limitations that need to be addressed for interpretation of the results. (1) The number of patients included in the study is limited, and the results should be interpreted with this in mind. However, the sample size was enough to detect the large differences that occurred in the respiratory and morphological variables. (2) We used fixed levels of inspiratory pressures for recruitment maneuver and PEEP. (3) We used fixed tidal volumes of 10 ml/kg predicted body weight; therefore, different effects of higher or lower tidal volumes cannot be excluded. (4) We studied our patients in the supine position; however, beach chair position has been shown to effectively improve respiratory mechanics and oxygenation in obese patients during anesthesia, especially in combination with PEEP.[36] (5) We used conventional volume-controlled ventilation, and recent studies have shown promising results with improved gas-exchange and respiratory mechanics while using biologically variable ventilation.[37] (6) The majority of the patients included in the study were female, the most common population of patients undergoing bariatric surgery.[20] (7) We did not study children, although obesity in children is a growing problem and poses great challenges in airway and ventilatory treatment with increased risk of desaturation and airway management problems.[38] (8) We did not evaluate hemodynamics in detail in these patients undergoing conventional bariatric surgery. (9) We minimized the number of CT scans for each patient as requested by the ethical committee at Uppsala University, Sweden, and in line with good clinical and research practice.[16] (10) The anesthesia was induced with 100% O_2, which promotes formation of atelectasis; however, this is a standard procedure in patients with high risk of difficult intubation and hypoxemia at the time of induction of anesthesia.[39,40] (11) We chose to perform the recruitment maneuver in pressure control to optimize its effects. Not all ventilators used in anesthesia are made to enable such a maneuver. However, these techniques are very common in ventilators used in intensive care units, and we believe that future technical development is needed to improve anesthesia ventilators. (12) The changes in lung volumes were most likely caused by induction of anesthesia and paralysis, but another possible explanation is that during spontaneous breathing the patient did not comprehend the instructions given, thus failing to make an end-expiratory breath-hold. However we believe this to be unlikely; careful instructions were given, and each patient was observed to make a breath-hold during the CT scanning.

In conclusion, this study has demonstrated that anesthesia in morbidly obese patients induces atelectasis formation and impairment in oxygenation. A recruitment maneuver followed by PEEP was sufficient to reduce the amount of atelectasis and improve oxygenation for a prolonged period of time. Conversely, PEEP or recruitment maneuver alone was not effective to reach a sustained improvement of respiratory function.

The authors thank Niclas Eriksson, M.Sc., Statistician, Uppsala Clinical Research Center, University Hospital, Uppsala, Sweden, for performing the statistical analysis.

References

1. Gunnarsson L, Strandberg A, Brismar B, Tokics L, Lundquist H, Hedenstierna G: Atelectasis and gas exchange impairment during enflurane/nitrous oxide anaesthesia. Acta Anaesthesiol Scand 1989; 33:629–37

2. Brismar B, Hedenstierna G, Lundquist H, Strandberg A, Svensson L, Tokics L: Pulmonary densities during anesthesia with muscular relaxation–a proposal of atelectasis. Anesthesiology 1985; 62:422–8

3. Pelosi P, Croci M, Ravagnan I, Cerisara M, Vicardi P, Lissoni A, Gattinoni L: Respiratory system mechanics in sedated, paralyzed, morbidly obese patients. J Appl Physiol 1997; 82:811–8

4. Strandberg A, Tokics L, Brismar B, Lundquist H, Hedenstierna G: Constitutional factors promoting development of atelectasis during anaesthesia. Acta Anaesthesiol Scand 1987; 31:21–4

5. Eichenberger A, Proietti S, Wicky S, Frascarolo P, Suter M, Spahn DR, Magnusson L: Morbid obesity and postoperative pulmonary atelectasis: An underestimated problem. Anesth Analg 2002; 95:1788–92

6. Rothen HU, Sporre B, Engberg G, Wegenius G, Hedenstierna G: Re-expansion of atelectasis during general anaesthesia: A computed tomography study. Br J Anaesth 1993; 71:788–95

Copyright © by the American Society of Anesthesiologists. Unauthorized reproduction of this article is prohibited.

7. Rothen HU, Sporre B, Engberg G, Wegenius G, Hedenstierna G: Reexpansion of atelectasis during general anaesthesia may have a prolonged effect. Acta Anaesthesiol Scand 1995; 39:118–25

8. Neumann P, Rothen HU, Berglund JE, Valtysson J, Magnusson A, Hedenstierna G: Positive end-expiratory pressure prevents atelectasis during general anaesthesia even in the presence of a high inspired oxygen concentration. Acta Anaesthesiol Scand 1999; 43:295–301

9. Bardoczky GI, Yernault JC, Houben JJ, d'Hollander AA: Large tidal volume ventilation does not improve oxygenation in morbidly obese patients during anesthesia. Anesth Analg 1995; 81:385–8

10. Sprung J, Whalley DG, Falcone T, Wilks W, Navratil JE, Bourke DL: The effects of tidal volume and respiratory rate on oxygenation and respiratory mechanics during laparoscopy in morbidly obese patients. Anesth Analg 2003; 97:268–74

11. Pelosi P, Ravagnan I, Giurati G, Panigada M, Bottino N, Tredici S, Eccher G, Gattinoni L: Positive end-expiratory pressure improves respiratory function in obese but not in normal subjects during anesthesia and paralysis. ANESTHESIOLOGY 1999; 91:1221–31

12. Chalhoub V, Yazigi A, Sleilaty G, Haddad F, Noun R, Madi-Jebara S, Yazbeck P: Effect of vital capacity manoeuvres on arterial oxygenation in morbidly obese patients undergoing open bariatric surgery. Eur J Anaesthesiol 2007; 24:283–8

13. Fan E, Wilcox ME, Brower RG, Stewart TE, Mehta S, Lapinsky SE, Meade MO, Ferguson ND: Recruitment maneuvers for acute lung injury: A systematic review. Am J Respir Crit Care Med 2008; 178:1156–63

14. Ogunnaike BO, Jones SB, Jones DB, Provost D, Whitten CW: Anesthetic considerations for bariatric surgery. Anesth Analg 2002; 95:1793–805

15. The Acute Respiratory Distress Syndrome Network: Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. N Engl J Med 2000; 342:1301–8

16. Berrington de Gonzalez A, Darby S: Risk of cancer from diagnostic X-rays: Estimates for the UK and 14 other countries. Lancet 2004; 363:345–51

17. Ogden CL, Carroll MD, Curtin LR, McDowell MA, Tabak CJ, Flegal KM: Prevalence of overweight and obesity in the United States, 1999–2004. Jama 2006; 295:1549–55

18. Hossain P, Kawar B, El Nahas M: Obesity and diabetes in the developing world–A growing challenge. N Engl J Med 2007; 356:213–5

19. Adams TD, Gress RE, Smith SC, Halverson RC, Simper SC, Rosamond WD, Lamonte MJ, Stroup AM, Hunt SC: Long-term mortality after gastric bypass surgery. N Engl J Med 2007; 357:753–61

20. Santry HP, Gillen DL, Lauderdale DS: Trends in bariatric surgical procedures. JAMA 2005; 294:1909–17

21. van Kaam AH, Lachmann RA, Herting E, De Jaegere A, van Iwaarden F, Noorduyn LA, Kok JH, Haitsma JJ, Lachmann B: Reducing atelectasis attenuates bacterial growth and translocation in experimental pneumonia. Am J Respir Crit Care Med 2004; 169:1046–53

22. Henzler D, Mahnken AH, Wildberger JE, Rossaint R, Gunther RW, Kuhlen R: Multislice spiral computed tomography to determine the effects of a recruitment maneuver in experimental lung injury. Eur Radiol 2006; 16:1351–9

23. Malbouisson LM, Muller JC, Constantin JM, Lu Q, Puybasset L, Rouby JJ: Computed tomography assessment of positive end-expiratory pressure-induced alveolar recruitment in patients with acute respiratory distress syndrome. Am J Respir Crit Care Med 2001; 163:1444–50

24. Jones RL, Nzekwu MM: The effects of body mass index on lung volumes. Chest 2006; 130:827–33

25. Damia G, Mascheroni D, Croci M, Tarenzi L: Perioperative changes in functional residual capacity in morbidly obese patients. Br J Anaesth 1988; 60:574–8

26. Pelosi P, Croci M, Ravagnan I, Tredici S, Pedoto A, Lissoni A, Gattinoni L: The effects of body mass on lung volumes, respiratory mechanics, and gas exchange during general anesthesia. Anesth Analg 1998; 87:654–60

27. Coussa M, Proietti S, Schnyder P, Frascarolo P, Suter M, Spahn DR, Magnusson L: Prevention of atelectasis formation during the induction of general anesthesia in morbidly obese patients. Anesth Analg 2004; 98:1491–5

28. Reber A, Bein T, Hogman M, Khan ZP, Nilsson S, Hedenstierna G: Lung aeration and pulmonary gas exchange during lumbar epidural anaesthesia and in the lithotomy position in elderly patients. Anaesthesia 1998; 53:854–61

29. Tusman G, Bohm SH, Melkun F, Nador CR, Staltari D, Rodriguez A, Turchetto E: [Effects of the alveolar recruitment manoeuver and PEEP on arterial oxygenation in anesthetized obese patients]. Rev Esp Anestesiol Reanim 2002; 49:177–83

30. Rothen HU, Neumann P, Berglund JE, Valtysson J, Magnusson A, Hedenstierna G: Dynamics of re-expansion of atelectasis during general anaesthesia. Br J Anaesth 1999; 82:551–6

31. Pelosi P, Croci M, Ravagnan I, Vicardi P, Gattinoni L: Total respiratory system, lung, and chest wall mechanics in sedated-paralyzed postoperative morbidly obese patients. Chest 1996; 109:144–51

32. Nielsen J, Nilsson M, Freden F, Hultman J, Alstrom U, Kjaergaard J, Hedenstierna G, Larsson A: Central hemodynamics during lung recruitment maneuvers at hypovolemia, normovolemia and hypervolemia. A study by echocardiography and continuous pulmonary artery flow measurements in lung-injured pigs. Intensive Care Med 2006; 32:585–94

33. Erlandsson K, Odenstedt H, Lundin S, Stenqvist O: Positive end-expiratory pressure optimization using electric impedance tomography in morbidly obese patients during laparoscopic gastric bypass surgery. Acta Anaesthesiol Scand 2006; 50:833–9

34. Perilli V, Sollazzi L, Modesti C, Annetta MG, Sacco T, Bocci MG, Tacchino RM, Proietti R: Comparison of positive end-expiratory pressure with reverse Trendelenburg position in morbidly obese patients undergoing bariatric surgery: effects on hemodynamics and pulmonary gas exchange. Obes Surg 2003; 13: 605–9

35. Rothen HU, Sporre B, Engberg G, Wegenius G, Hogman M, Hedenstierna G: Influence of gas composition on recurrence of atelectasis after a reexpansion maneuver during general anesthesia. ANESTHESIOLOGY 1995; 82:832–42

36. Valenza F, Vagginelli F, Tiby A, Francesconi S, Ronzoni G, Guglielmi M, Zappa M, Lattuada E, Gattinoni L: Effects of the beach chair position, positive end-expiratory pressure, and pneumoperitoneum on respiratory function in morbidly obese patients during anesthesia and paralysis. ANESTHESIOLOGY 2007; 107:725–32

37. McMullen MC, Girling LG, Graham MR, Mutch WA: Biologically variable ventilation improves oxygenation and respiratory mechanics during one-lung ventilation. ANESTHESIOLOGY 2006; 105:91–7

38. Tait AR, Voepel-Lewis T, Burke C, Kostrzewa A, Lewis I: Incidence and risk factors for perioperative adverse respiratory events in children who are obese. ANESTHESIOLOGY 2008; 108:375–80

39. Juvin P, Lavaut E, Dupont H, Lefevre P, Demetriou M, Dumoulin JL, Desmonts JM: Difficult tracheal intubation is more common in obese than in lean patients. Anesth Analg 2003; 97:595–600

40. Berthoud MC, Peacock JE, Reilly CS: Effectiveness of preoxygenation in morbidly obese patients. Br J Anaesth 1991; 67:464–6

Copyright © by the American Society of Anesthesiologists. Unauthorized reproduction of this article is prohibited.