ANESTHESIOLOGY

Positive End-expiratory Pressure and Distribution of Ventilation in Pneumoperitoneum Combined with Steep Trendelenburg Position

Atsuko Shono, M.D., Nozomi Katayama, M.D., Tatsuya Fujihara, M.D., Stephan H. Böhm, M.D., Andreas D. Waldmann, M.Sc., Kei Ugata, M.D., Tetsuro Nikai, M.D., Ph.D., Yoji Saito, M.D., Ph.D.

ANESTHESIOLOGY 2020; 132:476–90

EDITOR'S PERSPECTIVE

What We Already Know about This Topic

- Pneumoperitoneum and steep Trendelenburg during laparoscopic prostatectomy shift the diaphragm cephalad and cause atelectasis in the dorsal lungs
- The ability of positive end-expiratory pressure to mitigate these effects remains controversial

What This Article Tells Us That Is New

- In patients undergoing robot-assisted laparoscopic prostatectomy, 15 but not 5 cm H_2O of positive end-expiratory pressure increased ventilation in the dorsal parts of the lung, resulting in more normal lung mechanics and gas exchange
- High positive end-expiratory pressure did not improve postoperative lung function

ABSTRACT

Background: Pneumoperitoneum and a steep Trendelenburg position during robot-assisted laparoscopic prostatectomy have been demonstrated to promote a cranial shift of the diaphragm and the formation of atelectasis in the dorsal parts of the lungs. However, neither an impact of higher positive end-expiratory pressure (PEEP) on preserving the ventilation in the dorsal region nor its physiologic effects have been fully examined. The authors hypothesized that PEEP of 15 cm H_2O during robot-assisted laparoscopic prostatectomy might maintain ventilation in the dorsal parts and thus improve lung mechanics.

Methods: In this randomized controlled study, 48 patients undergoing robot-assisted laparoscopic prostatectomy were included in the analysis. Patients were assigned to the conventional PEEP (5 cm H_2O) group or the high PEEP (15 cm H_2O) group. Regional ventilation was monitored using electrical impedance tomography before and after the establishment of pneumoperitoneum and 20° Trendelenburg position during the surgery. The primary endpoint was the regional ventilation in the dorsal parts of the lungs while the secondary endpoints were lung mechanics and postoperative lung function.

Results: Compared to that in the conventional PEEP group, the fraction of regional ventilation in the most dorsal region was significantly higher in the high PEEP group during pneumoperitoneum and Trendelenburg position (mean values at 20 min after taking Trendelenburg position: conventional PEEP, 5.5 ± 3.9%; high PEEP, 9.9 ± 4.7%; difference, –4.5%; 95% CI, –7.4 to –1.6%; $P = 0.004$). Concurrently, lower driving pressure (conventional PEEP, 14.9 ± 2.5 cm H_2O; high PEEP, 11.5 ± 2.8 cm H_2O; $P < 0.001$), higher lung dynamic compliance, and better oxygenation were demonstrated in the high PEEP group. Postoperative lung function did not differ between the groups.

Conclusions: Application of a PEEP of 15 cm H_2O resulted in more homogeneous ventilation and favorable physiologic effects during robot-assisted laparoscopic prostatectomy but did not improve postoperative lung function.

(ANESTHESIOLOGY 2020; 132:476–90)

Robot-assisted laparoscopic prostatectomy is commonly used and widely accepted as a minimally invasive technique for the surgical treatment of prostate cancer.[1–3] However, it usually requires pneumoperitoneum and a steep Trendelenburg position to gain sufficient sight of the surgical field, which results in adverse effects on cardiopulmonary function.[4] It has been demonstrated that pneumoperitoneum leads to a cranial shift of the diaphragm and the formation of atelectasis in dorsal parts of the lungs[5–7]—both alter lung mechanics, increase airway pressure, and cause static elastances of the lung and chest wall while decreasing lung volume.[8–11] These side effects are accentuated by the steep Trendelenburg position.[12,13]

The changes in lung mechanics during surgery can augment the risk of stress and strain on the lungs, leading to ventilator-induced lung injury. Lung protective strategy, consisting of limited tidal volumes (V_T) and sufficient positive end-expiratory pressure (PEEP), plays a role in preventing postoperative pulmonary complications and acute respiratory distress syndrome in the operating room.[14] However, clinical research seeking better ventilatory settings to minimize the adverse effects of pneumoperitoneum and steep Trendelenburg position during robot-assisted laparoscopic prostatectomy is still controversial. In several studies, a recruitment maneuver

Submitted for publication December 26, 2018. Accepted for publication October 21, 2019. Published online first on November 21, 2019. From the Department of Anesthesiology, Shimane University, Faculty of Medicine, Izumo, Japan (A.S., N.K., T.F., K.U., T.N., Y.S.), and the Department of Anesthesiology and Intensive Care Medicine, Rostock University Medical Center, Rostock, Germany (S.H.B., A.D.W.).

 Anesthesiology 2020; 132:476–90. DOI: 10.1097/ALN.0000000000003062

accompanied by the application of PEEP has been shown to counterbalance the diaphragm's cranial shift, increase lung volume, and decrease respiratory system elastance compared with no recruitment maneuver or PEEP.[10,11] However, it has also been demonstrated that a PEEP of 10 cm H_2O was insufficient to keep the lungs free from collapse during periods of elevated intra-abdominal pressure.[15] Situations known to affect lung mechanics might require even higher PEEP levels to establish lung-protective ventilation.[16,17] Furthermore, the contribution of better intraoperative ventilatory settings to postoperative lung function, which is in general affected by persistent atelectasis and reduced lung volume after surgery, has not been fully investigated.

The purpose of our study was to investigate the effect of a PEEP of 15 cm H_2O on the distribution of ventilation lung mechanics during robot-assisted laparoscopic prostatectomy. We hypothesized that a PEEP of 15 cm H_2O is needed to achieve better ventilation of the dorsal parts of the lungs and a more favorable lung physiology than a conventional PEEP level of 5 cm H_2O. We applied two bedside monitoring techniques, electrical impedance tomography for the monitoring of regional ventilation, and esophageal pressure measurement to evaluate lung mechanics in different body positions throughout the surgery. Additionally, a lung function test was performed to reveal the impact of different PEEP during robot-assisted laparoscopic prostatectomy on postoperative lung function.

Materials and Methods

This randomized, parallel-arm, nonblinded, single-center study was registered at www.umin.ac.jp/english/ (trial registration: UMIN000022005). After receiving approval from the Ethics Committee of Shimane University, Izumo, Japan (20160115-2), we obtained written informed consent from consecutive patients scheduled for robot-assisted laparoscopic prostatectomy between September 2016 and December 2017. The inclusion criteria were age 18 yr or older and American Society of Anesthesiology Physical Status I or II. Patients with impaired lung function (chronic obstructive pulmonary disease grade greater than 3, forced expiratory volume in 1 s less than 1,000 ml) or chronic heart failure (cardiac index less than 1.8 l/m^2) were excluded from the study. Patients were randomly assigned to two groups. One was ventilated during surgery with a PEEP of 5 cm H_2O (conventional PEEP), and one with a PEEP of 15 cm H_2O (high PEEP). Randomization was performed by computer-generated random number allocation, and the allocations were sealed in an opaque envelope. The corresponding author and coauthors evaluated eligibility, obtained informed consent, and enrolled the participants. An anesthesiologist attending each participant's surgery opened the envelope and followed the procedure, in accordance with the group assignment. The corresponding author and coauthors collected and analyzed all data.

Anesthesia

Upon the arrival of patients to the operating room, standard monitoring was established. The radial artery was cannulated for continuous monitoring of blood pressure after induction of anesthesia. The arterial line was connected to a FloTrac/Vigileo system (Edwards Lifesciences, USA), which allows continuous monitoring of the cardiac index and the stroke volume variation to monitor cardiac preload and fluid responsiveness. General anesthesia was induced with 1.5 mg/kg of propofol and 3 mcg/kg of fentanyl, and tracheal intubation was facilitated with 0.6 mg/kg of rocuronium bromide. Anesthesia was maintained with a continuous infusion of propofol and remifentanil to sustain Bispectral Index values between 40 and 60. Neuromuscular blockade was monitored with train-of-four in order to maintain a train-of-four response of 0, and sugammadex was given for block reversal upon completion of surgery. After intubation, the patients were ventilated in a pressure-controlled mode of ventilation (AVEA, CareFusion, USA) with a V_T of 6 to 8 ml/kg predicted body weight and a fractional inspired oxygen tension (F_{IO_2}) of 0.4 or higher to keep oxygen saturation measured by pulse oximetry greater than 94%. Respiratory rate was adjusted to keep end-tidal pressure of carbon dioxide between 35 and 45 mmHg. All patients received infusion of crystalloid fluid to maintain the stroke volume variation less than 13% after anesthetic induction and until the Trendelenburg position was assumed. Thereafter, 3 $ml \cdot kg^{-1} \cdot h^{-1}$ of crystalloid or colloid solution (Voluven, Fresenius Kabi, Germany) were administered during the surgery. The occurrence of intraoperative hypotension (systolic blood pressure less than 90 mmHg) was managed with intravenous vasoactive drugs (a bolus of ephedrine or phenylephrine or a continuous infusion of phenylephrine). All patients were transferred to the general ward after successful extubation and adequate recovery. Pain control was started immediately after surgery using an intravenous infusion of fentanyl at a rate of 20 mcg/h with a flush of 20 mcg. A postoperative lung function test was performed by the physical therapists 24 h after patients were discharged from the operation room. Before the lung function test was performed, patients were asked to assess their pain using the Numerical Rating Scale ranging from 0 to 10 (0: no pain, 10: pain as bad as it could be, or worst pain).

Study Protocol

The time points for data sampling are presented in figure 1. Hemodynamic and electrical impedance tomography data were measured at multiple time points. Pulmonary parameters were measured in the supine position 10 min after anesthetic induction, 10 min after recruitment maneuver (before pneumoperitoneum), in the 25° Trendelenburg position 20, 60, and 120 min after establishment of the pneumoperitoneum using an intra-abdominal pressure of 12 mmHg, in the supine position 10 min after deflation

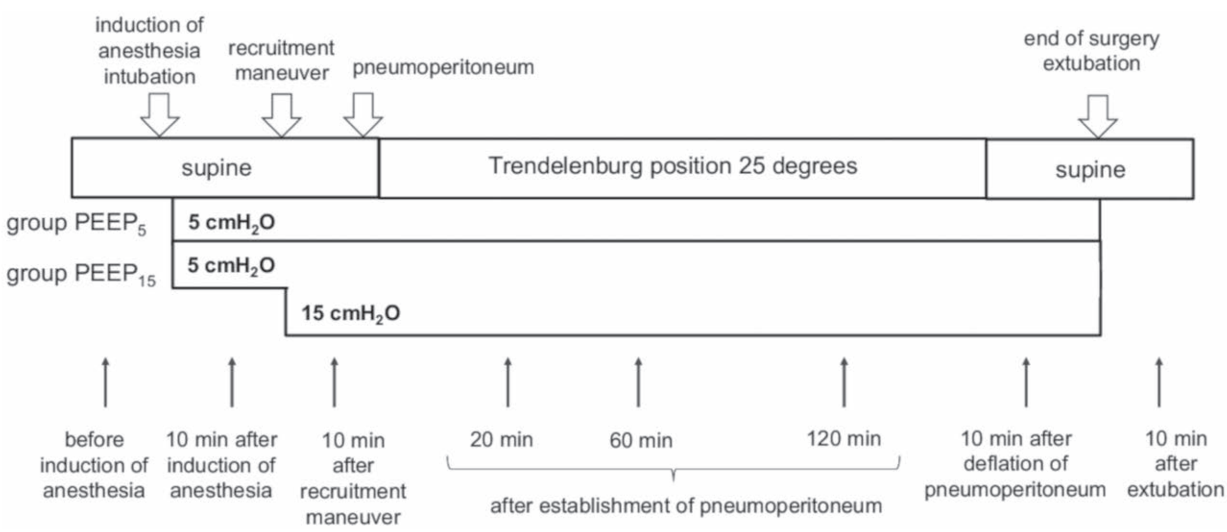

Fig. 1. Schematic diagram of study protocol and interventions for both groups. PEEP, positive end-expiratory pressure.

of the pneumoperitoneum, and 10 min after extubation. Recruitment maneuver was applied after insertion of an esophageal catheter. The peak inspiratory pressure gradient (above PEEP) was set at 20 cm H_2O, and PEEP was progressively increased every three breaths from 5 to 20 in steps of 5 cm H_2O to obtain a stepwise increase of peak inspiratory to 30, 35, and 40 cm H_2O. The final recruiting pressure of 40 cm H_2O was applied for six breaths. The recruitment was completed within 90 s. The study protocol can be accessed on request.

Measurements

Electrical Impedance Tomography. We used the commercially available Swisstom BB[2] electrical impedance tomography device (Swisstom, Switzerland) to monitor ventilation distribution. The ability and usefulness of the device in evaluating regional ventilation have previously been reported in several clinical trials.[18,19] Electrical impedance tomography can visualize regional distribution of tidal breathing by monitoring the impedance variation caused by the inspired air. The oblique belt with 32 electrodes was placed along the sixth intercostal space.[20] The data were recorded with a sampling rate of 48 Hz. The individual's sex, height, and weight were used to determine the appropriate image reconstruction matrix,[21] which consisted of 32 × 32 pixels. Four lung regions of interest were set within the lung contour in a ventral-dorsal orientation (fig. 2). The global impedance change caused by the tidal breath, which was measured as the difference between the end of inspiration and the end of the preceding expiration in all lung regions, was set at 100%. The distribution at each region of interest was expressed as percentage of the global tidal variation. The center of ventilation represents the vertical shift of the ventilation distribution along the gravitational axis. In order to define the spatiotemporal distribution of V_T within the chest, the ventral-dorsal center of ventilation was calculated and expressed as a percentage (0% representing all V_T in the most ventral nondependent regions and 100% most dorsal dependent regions; fig. 2). Due to the shape of the human chest, a value of 53% represents a uniform distribution of V_T. The dependent and nondependent silent spaces were calculated as previously described.[15,19] For each breath, poorly ventilated pixels within the region of interest showing impedance changes less than 10% of the maximal impedance change were identified. The silent spaces were categorized into dependent silent spaces and nondependent silent spaces according to the ventilation horizon determined by a virtual line perpendicular to the gravity vector through the center of ventilation. All pixels lying below this ventilation horizon defined the dependent silent spaces, whereas the areas above defined the nondependent silent spaces. The amount of silent spaces was expressed as a percentage of all pixels within the region of interest (fig. 2). The data from 10 consecutive breaths at each time point were analyzed offline using dedicated software (Ibex, Swisstom, Switzerland).

Lung Mechanics. Esophageal pressure was measured through a dedicated catheter equipped with an esophageal balloon. It was connected to a ventilator (AVEA, CareFusion, USA) that can automatically adjust the amount of air inflating the balloon. Positive pressure occlusion tests were performed to confirm the correct position of the catheter by gentle compression of the chest during the expiratory hold. The ratio of the change in esophageal pressure in relation to the change in airway pressure was confirmed to be between 0.8 and 1.2 before starting the recording. Airway pressure and

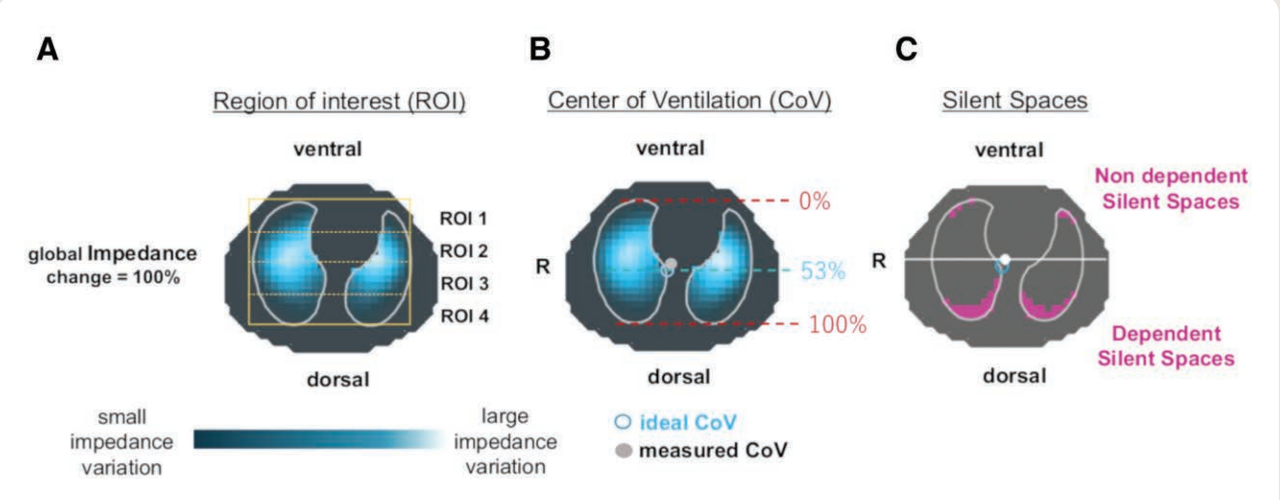

Fig. 2. (*A*) Region of interest (ROI): The impedance change during the tidal breath are shown with color scale in regional impedance map. The region of lung area is divided into 4 region of interests with equal height from ventral to dorsal. (*B*) Center of ventilation (CoV): The *gray dot* represents the center of ventilation. The *blue dot* represents an ideal center of ventilation located at 53%. (*C*) Silent spaces: The silent spaces are visualized as *purple areas* within the region of interest. The *white dot* represents measured center of ventilation, and the *white line* marks the ventilation horizon. Silent spaces above the ventilation horizon are defined as nondependent silent spaces, whereas the areas below are defined as dependent silent spaces. R, right.

esophageal pressure at end-inspiration and end-expiration were measured by applying end-inspiratory and end-expiratory holds of 3 to 5 s. End-inspiratory and end-expiratory transpulmonary pressures were calculated as the difference between the airway pressure and esophageal pressure during end-inspiratory and end-expiratory holds, respectively.

$$\text{end}-\text{inspiratory transpulmonary pressure} = \text{plateau pressure} - \text{end}-\text{inspiratory esophageal pressure}$$

$$\text{end}-\text{expiratory transpulmonary pressure} = \text{PEEP} - \text{end}-\text{expiratory esophageal pressure}$$

Driving pressure and transpulmonary driving pressure were calculated as follows:

$$\text{driving pressure} = \text{plateau pressure} - \text{PEEP}$$

$$\text{transpulmonary driving pressure} = (\text{plateau pressure} - \text{end}-\text{inspiratory esophageal pressure}) - (\text{PEEP} - \text{end}-\text{expiratory esophageal pressure})$$

Lung dynamic compliance[22] was calculated as follows:

$$\text{lung dynamic compliance} = \text{tidal volume} / \text{transpulmonary driving pressure}$$

Elastances of the respiratory system and chest wall were calculated by the elastance-derived method, computed as follows:

$$\text{elastance of the respiratory system} = \left(\text{plateau pressure} - \text{PEEP}\right) / \text{VT}$$

$$\text{elastance of chest wall} = (\text{end} - \text{inspiratory esophageal pressure} - \text{end} - \text{expiratory esophageal pressure}) / \text{VT}$$

The measurements, including the ventilation distribution (regional impedance change in region of interest 4 and center of ventilation), lung parameters and mechanics, blood gas analysis (pH, Pa_{O_2}, Pa_{CO_2}, Pa_{O_2}/F_{IO_2} ratio), hemodynamic parameters (mean blood pressure, heart rate, cardiac index, and stroke volume variation), and lung function measured by spirometry (percentage of vital capacity, forced expiratory volume in 1 s, and peak expiratory flow rate) were obtained.

The primary outcome of this physiologic study was the ventilation distribution in the most dorsal part of the lungs (region of interest 4) during pneumoperitoneum and a steep Trendelenburg position. The secondary outcomes were the Pa_{O_2}/F_{IO_2} ratio, lung mechanics (transpulmonary pressures, driving pressure, transpulmonary driving pressure, and lung dynamic compliance), and postoperative lung function. We also evaluated the correlation between ventilation distribution and the Pa_{O_2}/F_{IO_2} ratio and between lung mechanics during pneumoperitoneum and steep Trendelenburg position in both groups.

Statistical Analysis

The sample size was calculated according to the primary endpoint, *i.e.,* comparison of the fraction of ventilation distribution within the dorsal lung between groups.

Based on a preliminary institutional study, we determined that 22 patients would be required in each group in order to detect a 10% difference in dorsal ventilation distribution between the two groups with an alpha level of 0.05 and a SD of 10% using an independent *t* test at a power of 90%. Allowing for a 10% dropout rate during the study period, 24 patients were scheduled for enrollment in each group. After registration, the surgical approach was changed in one patient during the surgery; therefore, we excluded the data of that patient from analysis and added a new patient for enrollment. In total, 49 patients were registered, and the data of 48 patients were used for analysis.

Statistical analyses were carried out using SPSS 22 (IBM, USA). Data were tested for normal distribution using the Kolmogorov–Smirnov goodness-of-fit test and are presented as mean ± SD unless otherwise specified. Independent *t* tests or Mann–Whitney U tests for the continuous variables were used for comparison between groups. A two-way ANOVA for repeated measures was used to evaluate the effects of group, time, and the interaction on ventilation distribution, respiratory, and hemodynamic variables. A Tukey test was used for *post hoc* comparison. All tests were two-tailed, and a *P* value less than 0.05 was considered statistically significant. Correlations were tested using Pearson's product moment correlation coefficient.

Results

Study Population

Figure 3 demonstrates that the intended interventions were provided to all 49 patients. The study was conducted according to the original protocol. No adverse events associated with the study were observed. One patient was excluded from the analysis due to a change in the surgical procedure after the initiation of surgery. Electrical impedance tomography data of nine patients were found unanalyzable due to technical problems such as low signal quality or undetectable ventilation-related impedance changes. Thus, we included 39 of the 48 patients in the functional image analysis (17 in the conventional PEEP group and 22 in the high PEEP group). Patient characteristics can be found in table 1.

No significant difference existed between the two groups in terms of age, body mass index, or preoperative lung function. The fluid balance (conventional PEEP, 1,869 ± 590 ml; high PEEP, 2,215 ± 627 ml; $P = 0.030$) and total amounts of phenylephrine required to maintain systolic blood pressure greater than 90 mmHg (conventional PEEP, 0.14 ± 0.10 mg; high PEEP, 0.84 ± 0.80 mg; $P < 0.0001$) were significantly higher in the high PEEP group.

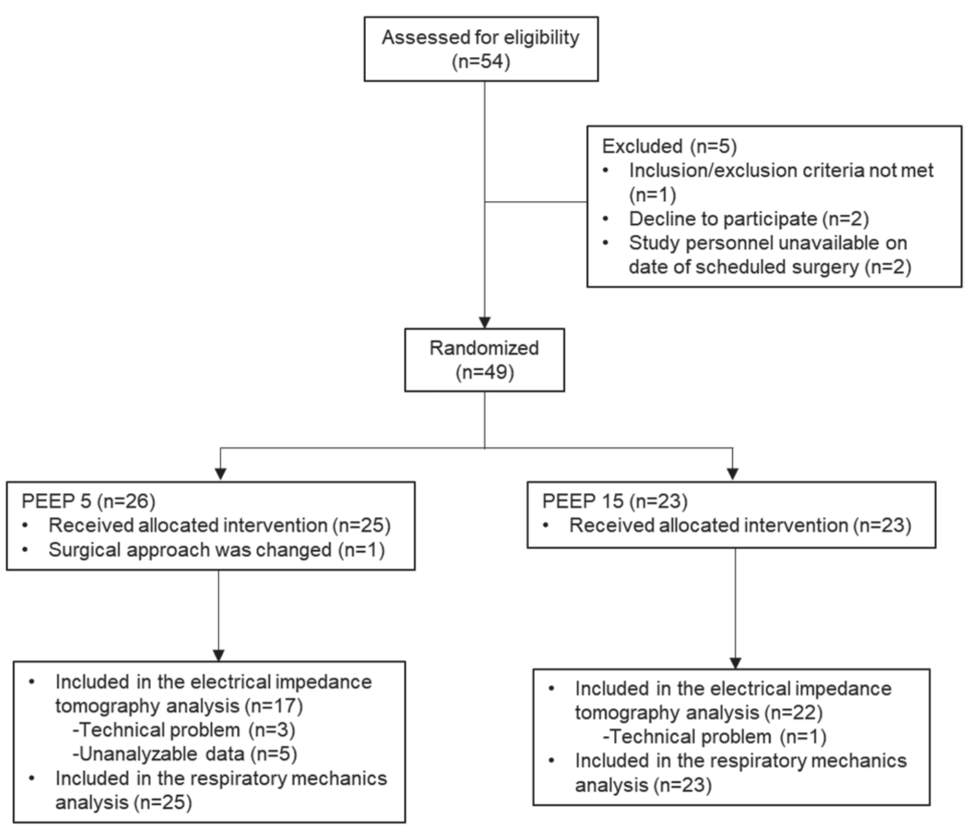

Fig. 3. Flowchart of enrollment and outcomes. PEEP, positive end-expiratory pressure.

Table 1. Patient Demographics and Characteristics

	PEEP 5 cm H_2O	PEEP 15 cm H_2O	*P* Value
No. of patients	25	23	
Age, yr	66 ± 7	67 ± 5	0.451
Body mass index, kg/m^2	23 ± 2	24 ± 2	0.111
ASA Physical Status, n (%)			0.521
I	1 (4)	0	
II	24 (96)	23 (100)	
COPD, n (%)	3 (12%)	2 (9%)	0.708
Vital capacity (%)	100 ± 12	99 ± 13	0.635
FEV1/forced vital capacity (%)	74 ± 6	77 ± 12	0.246
Time of surgery, min	392 ± 76	370 ± 61	0.884
Time of anesthesia, min	484 ± 81	473 ± 91	0.679
Fluid balance, ml	1,869 ± 590	2,215 ± 627*	0.030
Use of phenylephrine, mg	0.14 ± 0.10	0.84 ± 0.80*	< 0.001

Data are shown as mean ± SD and as percentage as appropriate. *$P < 0.05$ *versus* PEEP 5. ASA, American Society of Anesthesiologists; COPD, chronic obstructive pulmonary disease; FEV1, forced expiratory volume in 1 s; PEEP, positive end-expiratory pressure.

Distribution of Ventilation

Significant differences between the groups evolved along the protocol in distribution of ventilation within region of interest 4 ($P < 0.0001$), center of ventilation ($P < 0.0001$), and dependent silent spaces ($P = 0.035$). Figure 4 shows representative images of electrical impedance tomography in both groups. After induction of anesthesia, the percent values of ventilation distribution in region of interest 4 and center of ventilation were significantly lower in both groups than before intubation, indicating dorsal lung collapse with a concomitant ventral shift of ventilation (fig. 5). After recruitment maneuver, a dorsal shift of ventilation was observed in the high PEEP group, but not in the conventional PEEP group, compared with after induction of anesthesia. During pneumoperitoneum and steep Trendelenburg position, ventilation in region of interest 4 was significantly higher in the high PEEP group (60 min after pneumoperitoneum and Trendelenburg position: conventional PEEP, 5.0 ± 3.5%; high PEEP, 9.5 ± 4.4%; difference, –4.5%; 95% CI, –7.2 to –1.8%; $P = 0.002$), showing a distribution of ventilation comparable with that after induction of anesthesia (table 2, fig. 5). In contrast, patients in the conventional PEEP group had a significantly lower center of ventilation than those in the high PEEP group, *i.e.,* a notable ventral shift in ventilation occurred during surgery (60 min after pneumoperitoneum and Trendelenburg position: conventional PEEP, 46 ± 5%; high PEEP, 49 ± 4%; difference, –3.2%; 95% CI, –6.2 to –0.3%; $P = 0.032$). After release of the pneumoperitoneum and return to the supine position, dorsal ventilation and center of ventilation recovered in both groups, reaching values similar to those just before the Trendelenburg

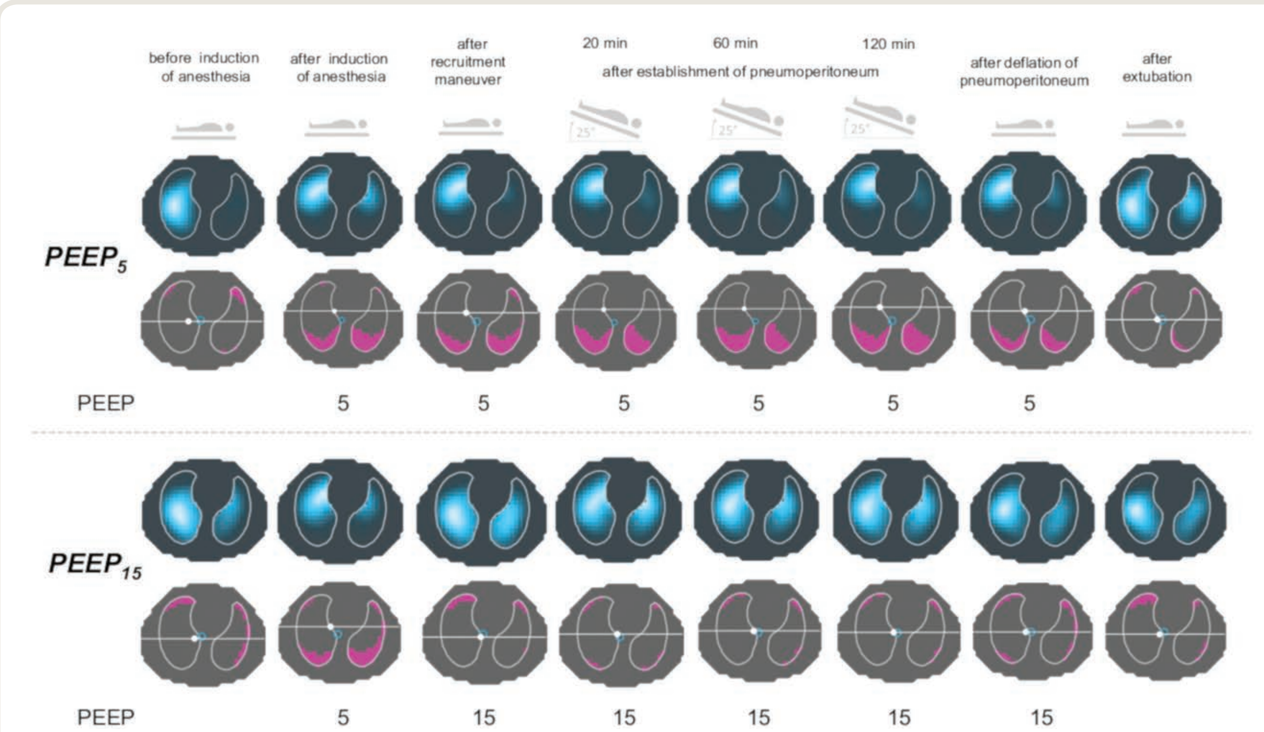

Fig. 4. The representative images of regional impedance maps (*upper row*) and silent spaces (*lower row*) at all time points are shown in each group. The corresponding levels of positive end-expiratory pressure (PEEP) at each time point are indicated at the *bottom*.

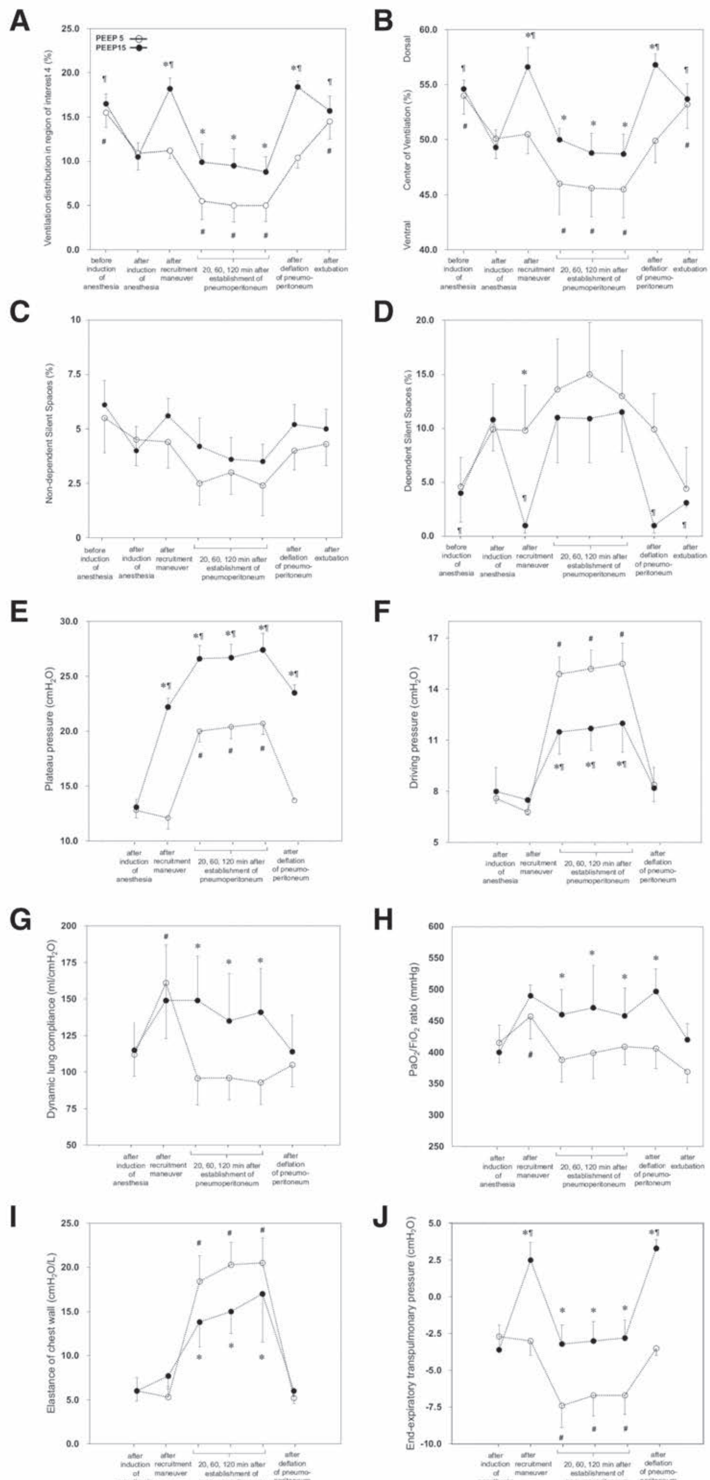

Fig. 5. Changes in ventilation distribution (*A*), center of ventilation (*B*), nondependent silent spaces (*C*), dependent silent spaces (*D*), plateau pressure (*E*), driving pressure (*F*), dynamic lung compliance (*G*), Pao_2/Fio_2 ratio (*H*), elastance of chest wall (*I*), and end-expiratory transpulmonary pressure (*J*), presented as mean ± SD. *Dashed lines* represent interpolation lines; *open circles*, conventional positive end-expiratory pressure (PEEP); *solid circles*, high PEEP. Pao_2/Fio_2 ratio, arterial partial pressure of oxygen/inspired fraction of oxygen. *$P < 0.05$ *versus* conventional PEEP. #$P < 0.05$ *versus* after the induction of anesthesia in the conventional PEEP group.¶$P < 0.05$ *versus* after the induction of anesthesia in the high PEEP group.

Table 2. Electrical Impedance Tomography and Respiratory Parameters during Mechanical Ventilation

		Before Induction of Anesthesia	After Induction of Anesthesia	After Recruitment Maneuver before Pneumoperitoneum	20 min after Application of Pneumoperitoneum and Trendelenburg Position	60 min after Application of Pneumoperitoneum and Trendelenburg Position	120 min after Application of Pneumoperitoneum and Trendelenburg Position	After Deflation of Pneumoperitoneum	After Extubation	*P* Value: Time	*P* Value: Group	*P* Value: Interaction
Ventilation distribution in region of interest 4 (%)												
	PEEP 5	15.5 ± 3.4†	10.9 ± 3.7	11.2 ± 3.8	5.5 ± 3.9†	5.0 ± 3.5†	5.1 ± 3.5†	10.4 ± 4.1	14.5 ± 3.8†	< 0.001	< 0.001	< 0.001
	PEEP 15	16.4 ± 2.4‡	10.5 ± 3.5	18.2 ± 2.6‡	9.9 ± 4.7*	9.5 ± 4.4*	8.8 ± 3.8*	18.4 ± 3.0‡	15.7 ± 3.8‡			
Center of ventilation (%)												
	PEEP 5	54.0 ± 3.3†	50.1 ± 3.6	50.5 ± 3.5	46.0 ± 5.3†	45.6 ± 4.8†	45.5 ± 4.8†	49.9 ± 3.9	53.2 ± 4.1†	< 0.001	0.006	< 0.001
	PEEP 15	54.6 ± 1.9‡	49.3 ± 3.5	56.6 ± 2.2‡	50.0 ± 4.4*	48.8 ± 4.1*	48.7 ± 4.2*	56.8 ± 2.3‡	53.7 ± 3.0‡			
Tidal volume/predictive body weight (ml/kg)												
	PEEP 5	—	7.2 ± 0.8	7.3 ± 0.7	7.2 ± 0.6	7.2 ± 0.5	7.2 ± 0.6	7.4 ± 0.6	—	< 0.001	0.944	0.147
	PEEP 15	—	6.9 ± 0.7	6.8 ± 0.7	6.9 ± 0.8	6.7 ± 0.8	6.8 ± 0.9	7.1 ± 0.8	—			
FIO_2												
	PEEP 5	—	0.39 ± 0.02	0.39 ± 0.02	0.40 ± 0.02	0.39 ± 0.02	0.39 ± 0.02	0.39 ± 0.03	—	0.011	0.109	0.046
	PEEP 15	—	0.39 ± 0.02	0.39 ± 0.02	0.38 ± 0.04*	0.37 ± 0.04	0.38 ± 0.04	0.37 ± 0.04	—			
Respiratory rate (/min)												
	PEEP 5	—	12 ± 1	12 ± 1	12 ± 1	13 ± 2	13 ± 2	13 ± 2	—	< 0.001	0.654	0.131
	PEEP 15	—	12 ± 1	11 ± 1	12 ± 2	13 ± 2	14 ± 2	14 ± 2	—			
Plateau pressure (cm H_2O)												
	PEEP 5	—	12.8 ± 1.9	12.1 ± 1.7	20.0 ± 5.9†	20.4 ± 2.5†	20.7 ± 2.6†	13.7 ± 2.3	—	< 0.001	0.010	< 0.001
	PEEP 15	—	13.1 ± 1.6	22.2 ± 2.8‡	26.6 ± 2.8‡	26.7 ± 2.7‡	27.4 ± 3.6‡	23.5 ± 1.7‡	—			
PEEP (cm H_2O)												
	PEEP 5	—	5.2 ± 0.3	5.7 ± 2.0	5.5 ± 2.1	5.5 ± 2.0	5.6 ± 2.2	5.7 ± 2.0	—	< 0.001	< 0.001	< 0.001
	PEEP 15	—	5.1 ± 0.1	15.2 ± 0.4*	15.1 ± 0.4*	15.1 ± 0.5*	15.2 ± 0.9*	15.2 ± 0.4*	—			
Driving pressure (cm H_2O)												
	PEEP 5	—	7.6 ± 2.0	6.9 ± 1.9	14.9 ± 2.5†	15.2 ± 1.2†	15.5 ± 2.8†	8.4 ± 2.4	—	< 0.001	0.010	< 0.001
	PEEP 15	—	8.0 ± 1.7	7.5 ± 2.0	11.5 ± 2.8‡	11.7 ± 2.8‡	12.0 ± 3.7‡	8.1 ± 1.9	—			
Dynamic compliance (ml/cm H_2O)												
	PEEP 5	—	63.6 ± 12.6	72.9 ± 20.5†	31.9 ± 6.0†	31.7 ± 8.5†	30.9 ± 6.8†	60.1 ± 14.5	—	< 0.001	0.599	< 0.001
	PEEP 15	—	57.6 ± 14.7	55.0 ± 45.0*	40.7 ± 12.0*	38.9 ± 10.5‡	40.0 ± 14.9*	58.3 ± 13.3	—			
End-inspiratory transpulmonary pressure (cm H_2O)												
	PEEP 5	—	1.8 ± 2.9	0.9 ± 2.6	–1.6 ± 1.9†	–1.3 ± 1.9†	–1.0 ± 1.6†	1.6 ± 1.6	—	< 0.001	< 0.001	< 0.001
	PEEP 15	—	0.8 ± 3.5	6.3 ± 3.2‡	0.4 ± 3.4*	0.9 ± 3.4*	1.0 ± 3.3*	8.0 ± 2.8‡	—			
End-expiratory transpulmonary pressure (cm H_2O)												
	PEEP 5	—	–2.8 ± 2.5	–2.9 ± 2.3	–7.3 ± 3.5†	–6.7 ± 3.2†	–6.7 ± 3.2†	–3.3 ± 2.3	—	< 0.001	< 0.001	< 0.001
	PEEP 15	—	–3.6 ± 4.1	2.5 ± 2.8‡	–3.7 ± 3.4*	–3.0 ± 3.1*	–2.9 ± 2.8*	3.3 ± 2.8‡	—			

(*Continued*)

Table 2. (Continued)

		Before Induction of Anesthesia	After Induction of Anesthesia	After Recruitment Maneuver before Pneumoperitoneum	20 min after Application of Pneumoperitoneum and Trendelenburg Position	60 min after Application of Pneumoperitoneum and Trendelenburg Position	120 min after Application of Pneumoperitoneum and Trendelenburg Position	After Deflation of Pneumoperitoneum	After Extubation	*P* Value: Time	*P* Value: Group	*P* Value: Interaction
Transpulmonary driving pressure (cm H_2O)	PEEP 5	—	4.9 ± 2.1	3.8 ± 1.9	5.7 ± 2.6†	5.5 ± 2.4	5.7 ± 2.4	4.9 ± 1.6	—	0.009	0.025	0.001
	PEEP 15	—	4.5 ± 1.9	3.8 ± 1.7	3.6 ± 1.8*	3.9 ± 1.8*	3.9 ± 2.1*	4.6 ± 1.8	—			
Lung dynamic compliance (ml/cm H_2O)	PEEP 5	—	112 ± 35	159 ± 88†	107 ± 87	96 ± 32	93 ± 36	106 ± 34	—	0.002	0.033	0.005
	PEEP 15	—	115 ± 50	149 ± 90	149 ± 70*	135 ± 75*	140 ± 66*	117 ± 57	—			
Chest wall elastance (cm H_2O/l)	PEEP 5	—	6.0 ± 3.5	5.4 ± 2.0	18.4 ± 7.0†	20.3 ± 6.1†	20.5 ± 6.9†	5.2 ± 2.3	—	< 0.001	0.120	0.012
	PEEP 15	—	6.0 ± 2.7	7.7 ± 6.0	13.8 ± 6.5*	15.0 ± 5.8*	14.4 ± 5.1*	6.0 ± 3.1	—			

Data are shown as mean ± SD. **P* < 0.05 *versus* positive end-expiratory pressure (PEEP) 5 cm H_2O. †*P* < 0.05 *versus* after induction of anesthesia in PEEP 5 cm H_2O. ‡P < 0.05 *versus* after induction of anesthesia in PEEP 15 cm H_2O.

position. When patients returned to spontaneous breathing, the center of ventilation shifted back to the dependent lung in the conventional PEEP group.

In line with the trend of the distribution in region of interest 4 and center of ventilation, the dependent silent spaces increased during pneumoperitoneum and steep Trendelenburg position, whereas nondependent silent spaces remained constant over the course of the study period in both groups (fig. 5).

Respiratory Parameters and Mechanics

The following parameters showed significant differences between the groups over the study period: airway pressure at end-inspiration (P < 0.0001), driving pressure (P < 0.0001), transpulmonary pressure at end-expiration (P < 0.0001), dynamic lung compliance (P = 0.005), chest wall elastance (P = 0.012), and Pao_2/Fio_2 ratio (P = 0.047; table 2, fig. 5). Airway pressure at end-inspiration was higher in the high PEEP group during pneumoperitoneum and steep Trendelenburg position; however, the driving pressures were significantly lower in the high PEEP group than in the conventional PEEP group, with mean values less than 14 cm H_2O (60 min after pneumoperitoneum and Trendelenburg position: conventional PEEP, 15.2 ± 1.2 cm H_2O; high PEEP, 11.7 ± 2.8 cm H_2O; difference, 3.6 cm H_2O; 95% CI, 2.0 to 5.2 cm H_2O; P < 0.0001). While transpulmonary pressures at end-expiration were significantly higher but remained below zero, transpulmonary driving pressures were lower in the high PEEP group during pneumoperitoneum and steep Trendelenburg position. Dynamic lung compliance was maintained higher in the high PEEP group and did not change over the course of the examination. Chest wall elastance increased after the initiation of the pneumoperitoneum in both groups; however, it was significantly higher in the conventional PEEP group (60 min after pneumoperitoneum and Trendelenburg position: conventional PEEP, 20.3 ± 6.1 cm H_2O/l; high PEEP, 15.0 ± 5.8 cm H_2O/l; difference, 5.3 cm H_2O/l; 95% CI, 1.8 to 8.7 cm H_2O/l; P = 0.004). The Pao_2/Fio_2 ratios were significantly higher in the high PEEP group starting after recruitment maneuver until the end of surgery (table 3, fig. 5).

Correlations among Ventilation Distribution, Lung Mechanics, and Pao_2/Fio_2 Ratio

The ventilation within the most dorsal region (region of interest 4) correlated with transpulmonary pressure at end-expiration in each group (conventional PEEP, R = 0.58, P < 0.01; high PEEP, R = 0.69, P < 0.01), and was also correlated with driving pressure (conventional PEEP, R = –0.54, P < 0.01; high PEEP, R = –0.55, P < 0.01) and Pao_2/Fio_2 ratio (conventional PEEP, R = 0.53, P < 0.01; high PEEP, R = 0.54, P < 0.01; fig. 6).

Table 3. Gas Exchange Parameters and Hemodynamic Data

		Before Induction of Anesthesia	After Induction of Anesthesia	After Recruitment Maneuver before Pneumoperitoneum	20 min after Application of Pneumoperitoneum and Trendelenburg Position	60 min after Application of Pneumoperitoneum and Trendelenburg Position	120 min after Application of Pneumoperitoneum and Trendelenburg Position	After Deflation of Pneumoperitoneum	After Extubation	*P* Value		
										Time	Group	Interaction
Pa_{O_2}/ F_{IO_2} ratio												
	PEEP 5	—	415 ± 78	457 ± 84†	388 ± 85	399 ± 99	409 ± 70	406 ± 77	369 ± 92	< 0.001	0.065	0.014
	PEEP 15	—	400 ± 99	490 ± 61	460 ± 92*	471 ± 154*	458 ± 99*	497 ± 81*	420 ± 118			
Pa_{CO_2} (mmHg)												
	PEEP 5	—	36 ± 3	37 ± 4	44 ± 6†	46 ± 5†	46 ± 5†	45 ± 5†	46 ± 4	< 0.001	0.465	0.698
	PEEP 15	—	36 ± 4	38 ± 4	45 ± 5‡	48 ± 5‡	49 ± 4‡	48 ± 7‡	45 ± 4			
Mean blood pressure (mmHg)												
	PEEP 5	101 ± 12	68 ± 10	80 ± 14†	82 ± 15†	76 ± 12	72 ± 10	74 ± 12	100 ± 15	< 0.001	0.024	0.189
	PEEP 15	95 ± 10	70 ± 10	72 ± 11	73 ± 11	73 ± 9	69 ± 7	69 ± 8	92 ± 11			
HR (min-1)												
	PEEP 5	70 ± 16	61 ± 11	58 ± 12	59 ± 13	59 ± 14	59 ± 13	61 ± 12	74 ± 16	< 0.001	0.295	0.533
	PEEP 15	73 ± 13	63 ± 8	63 ± 8	61 ± 8	62 ± 9	62 ± 8	67 ± 10	77 ± 11			
Cadiac Index (L/m2)												
	PEEP 5	—	2.1 ± 0.4	2.3 ± 0.3	2.4 ± 0.4	2.3 ± 0.4	2.2 ± 0.3	2.6 ± 0.7†	—	0.001	0.682	0.001
	PEEP 15	—	2.4 ± 0.4	1.9 ± 0.4*‡	2.4 ± 0.6	2.4 ± 0.8	2.3 ± 0.5	2.3 ± 0.4	—			
Stroke volume variation (%)												
	PEEP 5	—	12 ± 4	8 ± 3†	12 ± 4	14 ± 4	16 ± 4	8 ± 2†	—	< 0.001	0.07	< 0.001
	PEEP 15	—	10 ± 3	13 ± 4	13 ± 4	14 ± 4‡	15 ± 5‡	13 ± 5‡	—			

Data are shown as mean ± SD. *$P < 0.05$ *versus* positive end-expiratory pressure (PEEP) 5 cm H_2O. †$P < 0.05$ *versus* after induction of anesthesia in PEEP 5 cm H_2O. ¶$P < 0.05$ *versus* after induction of anesthesia in PEEP 15 cm H_2O. Pa_{O_2}/F_{IO_2} ratio, arterial partial pressure of oxygen/inspired fraction of oxygen.

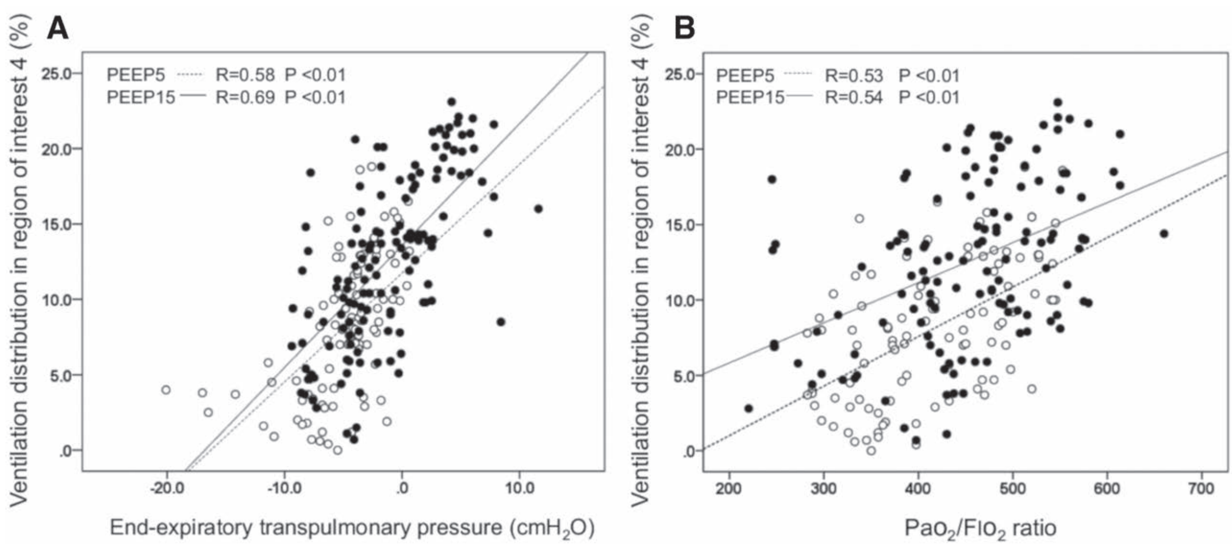

Fig. 6. Correlation between ventilation distribution in region of interest 4 (most dorsal region) and end-expiratory transpulmonary pressure (*A*), and Pao_2/FIO_2 ratio (*B*) during mechanical ventilation. Data were collected from at 10 min after the induction of anesthesia to 10 min after the deflation of pneumoperitoneum in both groups. *Open circles*, conventional positive end-expiratory pressure (PEEP); *solid circles*, high PEEP.

Hemodynamics

No significant differences between the groups were observed in mean blood pressure ($P = 0.095$; table 3); however, significant differences between the groups were observed in cardiac index ($P < 0.0001$) and stroke volume variation ($P < 0.0001$). After recruitment maneuver, cardiac index was significantly lower in the high PEEP group; however, it was consistently above 2.1 l/m^2 during pneumoperitoneum and steep Trendelenburg position, with no difference between the groups. The mean stroke volume variation was below 12% before recruitment maneuver in both groups, increasing to greater than 15% during pneumoperitoneum and steep Trendelenburg position and returning to the values at after recruitment maneuver in both groups after deflation.

Postoperative Lung Function

Patients with severe postoperative pain at deep breathing or those who refused the test were excluded from the lung function study. In total, 19 and 21 patients in the conventional PEEP and high PEEP groups were included, respectively. The mean Numerical Rating Scale values before the test were 4 and 3 for the conventional PEEP and high PEEP groups, respectively. The mean vital capacity percentage reduced by about 30% from the preoperative values in both groups, showing significant differences before and after surgery in each group (table 4). There were no significant differences between the groups in terms of postoperative lung function.

Discussion

In the current study, the impact of pneumoperitoneum and steep Trendelenburg position on ventilation within the dorsal parts of the lungs was significant in both the conventional PEEP and high PEEP groups. However, the treatment effect was greater and resulted in more favorable physiologic effects and better oxygenation during surgery when PEEP 15 cm H_2O was applied than when PEEP 5 cm H_2O was applied. Lower driving pressure and higher lung dynamic compliance were demonstrated in the high PEEP group during pneumoperitoneum and steep Trendelenburg position.

Several studies have investigated the effect of PEEP on regional ventilation using electrical impedance tomography during laparoscopic surgery.[15,23,24] Karsten *et al.* examined the effect of recruitment maneuver and the subsequent application of 10 cm H_2O PEEP on regional ventilation by monitoring center of ventilation. They reported that a more favorable distribution to the dorsal parts of the lungs was found with recruitment maneuver and subsequent 10 cm H_2O PEEP than in patients ventilated without PEEP; however, the mean center of ventilation was still located at ventral region, indicating a ventral shift of ventilation.[23] Ukere *et al.* also examined the center of ventilation and silent spaces in patients undergoing robot-assisted laparoscopic prostatectomy.[15] They found that an increase of PEEP from 5 to 10 cm H_2O could not prevent a shift in center of ventilation toward the ventral lung region and an increase in the dependent silent spaces after establishment of pneumoperitoneum and a 30° head-down tilt position. The results from their research imply that

Table 4. Lung Function before and after Surgery

	Preoperative Lung Function				Postoperative Lung Function			
	% Vital Capacity (%)	FEV1/Forced Vital Capacity (%)	Peak Expiratory Flow (l/s)	% Predicted Peak Expiratory Flow (%)	% Vital Capacity (%)	FEV1/Forced Vital Capacity (%)	Peak Expiratory Flow (l/s)	% Predicted Peak Expiratory Flow (%)
PEEP 5 (n = 19)	103 ± 10	74 ± 7	8.6 ± 1.3	93 ± 16	70 ± 14*	78 ± 7	5.3 ± 1.4*	57 ± 16*
PEEP 15 (n = 21)	100 ± 13	77 ± 13	7.7 ± 1.3	85 ± 16	73 ± 16*	76 ± 8	4.4 ± 1.9*	49 ± 20*

Data are shown as mean ± SD. *$P < 0.05$ *versus* preoperative lung function. FEV_1, forced expiratory volume in 1 s; PEEP, positive end-expiratory pressure.

a PEEP 10 cm H_2O was not sufficient to prevent the loss of efficient dorsal ventilation caused by pneumoperitoneum and steep Trendelenburg position. In the current study, we employed a higher PEEP of 15 cm H_2O in nonobese patients after recruitment maneuver and compared its effects with a standard level of PEEP of 5 cm H_2O in a control group. We found that recruitment maneuver followed by higher PEEP favored a more homogeneous ventilation distribution by recruiting dorsal lung regions and keeping those lung regions open. A higher PEEP might be required to counterbalance a cranial shift of the diaphragm and prevent lung collapse in dorsal parts of the lungs during pneumoperitoneum and steep Trendelenburg position. In fact, corresponding increase in transpulmonary pressure at end-expiration was found in the high PEEP group, which indicates that a higher transpulmonary pressure could preserve dorsal aeration at end-expiration and thus better dorsal ventilation. However, the fact that dependent silent spaces remained during Trendelenburg position and pneumoperitoneum might indicate that even a PEEP as high as 15 cm H_2O was still insufficient to keep transpulmonary pressures above zero, a physiologic condition required to keep the lungs fully open.[22]

Restored dorsal lung aeration facilitated by higher PEEP is likely to have exhibited the beneficial physiologic effects in the current study. It has been demonstrated that driving pressure, which is the surrogate for cyclic lung strain, depends on respiratory system compliance, and is affected by functional lung size.[25] The reduction in the volume of lung available for tidal ventilation leads to lowered respiratory system compliance and an increase in driving pressure. In the current study, the ventilation of a fixed tidal volume to a less collapsed or more open lung of higher functional size required less driving pressure and transpulmonary driving pressure, as indicated by a higher lung dynamic compliance in the high PEEP group. Additionally, the elastance of the chest wall was lower at PEEP 15 cm H_2O than at 5 cm H_2O, which might be attributed to the effect of PEEP on counterbalancing the diaphragm's cranial shift and preventing the deformation of the chest wall's shape.[9,10] Given these beneficial physiologic effects, it is suggested that lung protective ventilation aiming at reducing stress and strain could be achieved by the application of sufficiently high PEEP to counteract elevated intra-abdominal pressures.

The pneumoperitoneum in combination with a steep Trendelenburg position increased chest wall elastance in our study. Pelosi *et al.* examined the relationship between chest wall elastance and intra-abdominal pressure in anaesthetized patients and patients with injured lungs.[26] They reported that when the intra-abdominal pressure was less than 12 mmHg, chest wall elastance remained normal, at approximately 10 cm H_2O/l; however, if the intra-abdominal pressure exceeded 20 mmHg, chest wall elastance and pleural pressure significantly increased beyond normal. Although the intra-abdominal pressure used in the current study was 12 mmHg, the mean esophageal pressures at end-inspiration were higher than 20 cm H_2O in both groups, indicating that an additional intra-abdominal pressure effect might have been superimposed by the steep Trendelenburg position. As a result, the inspiratory plateau pressure increased significantly, showing an extremely high mean pressure of 27 cm H_2O and a maximum of 32 cm H_2O in the high PEEP group. However, the transpulmonary driving pressure remained within 10 cm H_2O at any time during the surgery. In a previous experimental study using an intra-abdominal hypertension model, Kubiak *et al.* reported that sequential increments in intra-abdominal pressure caused a linear increase in plateau pressure, whereas transpulmonary pressures did not increase with intra-abdominal pressure.[27] These results indicate that judging stress to the lungs or its risk by the absolute value of airway pressure alone is impossible in conditions with increased chest wall elastance.

In the current study, dependent silent spaces were lower, indicating reduction of atelectasis during surgery in the high PEEP group.[15,19] This favorable effect of PEEP disappeared after extubation, resulting in comparable values between the groups; this might have led to equivalent oxygenation and lung function. Similar results were also reported in the previous study conducted by Nestler *et al.*[28] The benefit of individual PEEP settings in their study, in which homogeneous ventilation and higher end-expiratory lung volume were achieved, did not last beyond surgery. In our study, lung function 24 h after surgery was equally impaired in both groups. The impact of persistent atelectasis or intraoperative fluid balance on postoperative lung function was not assessed in the current study. Of note, in the current physiologic study, our aim was not to test the superiority of intraoperative high PEEP with respect to relevant postoperative clinical parameters in patients with noninjured lungs. All we intended to do was to describe and compare preoperative with postoperative lung function in patients undergoing two different ventilation protocols. Further studies are needed to define the impact of intraoperative lung protective ventilation on postoperative pulmonary outcomes.

Although the higher PEEP could provide a more homogenous distribution of ventilation and more favorable lung mechanics, the hemodynamics were negatively affected by a higher PEEP. The cardiac index during the surgery did not differ significantly between the arms; however, the dose of vasopressors required to keep blood pressure within the desired range was significantly higher in the high PEEP group. It was demonstrated that pneumoperitoneum using carbon dioxide reduces left ventricular preload[29] and is exacerbated by simultaneous use of PEEP.[30,31] In our study, significantly higher esophageal pressures were detected and more fluid volumes were administered in the high PEEP group, indicating a more pronounced reduction in venous return. The measured parameters remained within the clinically acceptable range; however, the advantage of obtaining more homogenous ventilation with higher PEEP levels must be balanced against the risk of hemodynamic side effects. The application of high PEEP is recommended when avoidance of deterioration in gas exchange is prioritized, especially in patients with impaired cardiac function.

Our study had several limitations. First, in this physiologic study, we included a small number of patients and evaluated them only short-term during the postoperative period. In addition, we studied relatively healthy and nonobese patients with normal lung function. Therefore, our findings need further confirmation before they can be extrapolated to patients with risk factors for atelectasis formation and postoperative hypoxemia. Second, electrical impedance tomography measures ventilation distribution in a limited cross-sectional section of the lung[32,33] and depends primarily on the position of the belt.[34] We placed the belt just above the diaphragm, a region particularly susceptible to the development of lung collapse. However, the establishment of pneumoperitoneum and steep Trendelenburg position might have accelerated not only the ventral but also a cranial shift of overall ventilation, which might not have been picked up fully by the caudal belt even though its position remained fixed with regard to the thorax.[35] The data of five patients in the conventional PEEP group had to be excluded from the study due to the collection of unanalyzable impedance data during surgery, indicating that monitoring might have been precluded by the direct movement of the diaphragm into the measurement plane. Third, the volume of fluid administered might have influenced the impedance values due to a change in pulmonary bioimpedance caused by increased intrathoracic fluid content.[36,37] In our study, mean positive fluid intake was 1,869 ml in the conventional group and 2,215 ml in the high PEEP group, which might have changed the absolute values of impedance. However, ventilation distribution was calculated as relative changes of impedance rather than absolute values, which likely minimized the influence of the positive fluid balance on the evaluation of ventilation in clinical practice.

Conclusions

In conclusion, we demonstrated the physiologic effects of applying high and low PEEP after recruitment to reverse pneumoperitoneum-induced alveolar collapse in patients undergoing robot-assisted laparoscopic prostatectomy in a steep Trendelenburg position. Alveolar recruitment in conjunction with 15 but not 5 cm H_2O of PEEP applied before the onset of pneumoperitoneum increased ventilation within dorsal gravity-dependent parts of the lung, which resulted in more normal lung mechanics and gas exchange. However, the high PEEP strategy did not improve postoperative lung function.

Acknowledgments

The authors would like to thank Gerardo Tusman, M.D., Department of Anesthesiology, Hospital Privado de Comunidad, Mar del Plata, Argentina, for his guidance and insights during the review process.

Research Support

Support was provided solely from institutional and/or departmental sources.

Competing Interests

The authors declare no competing interests.

Reproducible Science

Full protocol available at: atsuko929shono@yahoo.co.jp. Raw data available at: atsuko929shono@yahoo.co.jp.

Correspondence

Address correspondence to Dr. Shono: Department of Anesthesiology, Shimane University Hospital, Enya 89-1, Izumo, Shimane, Japan. atsuko929shono@yahoo.co.jp. 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.

References

1. Trinh QD, Sammon J, Sun M, Ravi P, Ghani KR, Bianchi M, Jeong W, Shariat SF, Hansen J, Schmitges J, Jeldres C, Rogers CG, Peabody JO, Montorsi F,

Menon M, Karakiewicz PI: Perioperative outcomes of robot-assisted radical prostatectomy compared with open radical prostatectomy: Results from the nationwide inpatient sample. Eur Urol 2012; 61:679–85
2. Novara G, Ficarra V, Rosen RC, Artibani W, Costello A, Eastham JA, Graefen M, Guazzoni G, Shariat SF, Stolzenburg JU, Van Poppel H, Zattoni F, Montorsi F, Mottrie A, Wilson TG: Systematic review and meta-analysis of perioperative outcomes and complications after robot-assisted radical prostatectomy. Eur Urol 2012; 62:431–52
3. Liss MA, Skarecky D, Morales B, Osann K, Eichel L, Ahlering TE: Preventing perioperative complications of robotic-assisted radical prostatectomy. Urology 2013; 81:319–23
4. Awad H, Walker CM, Shaikh M, Dimitrova GT, Abaza R, O'Hara J: Anesthetic considerations for robotic prostatectomy: A review of the literature. J Clin Anesth 2012; 24:494–504
5. Sánchez-Margallo FM, Moyano-Cuevas JL, Latorre R, Maestre J, Correa L, Pagador JB, Sánchez-Peralta LF, Sánchez-Margallo JA, Usón-Gargallo J: Anatomical changes due to pneumoperitoneum analyzed by MRI: An experimental study in pigs. Surg Radiol Anat 2011; 33:389–96
6. Andersson LE, Bååth M, Thörne A, Aspelin P, Odeberg-Wernerman S: Effect of carbon dioxide pneumoperitoneum on development of atelectasis during anesthesia, examined by spiral computed tomography. Anesthesiology 2005; 102:293–9
7. Strang CM, Hachenberg T, Fredén F, Hedenstierna G: Development of atelectasis and arterial to end-tidal PCO2-difference in a porcine model of pneumoperitoneum. Br J Anaesth 2009; 103:298–303
8. Pelosi P, Foti G, Cereda M, Vicardi P, Gattinoni L: Effects of carbon dioxide insufflation for laparoscopic cholecystectomy on the respiratory system. Anaesthesia 1996; 51:744–9
9. 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
10. Cinnella G, Grasso S, Spadaro S, Rauseo M, Mirabella L, Salatto P, De Capraris A, Nappi L, Greco P, Dambrosio M: Effects of recruitment maneuver and positive end-expiratory pressure on respiratory mechanics and transpulmonary pressure during laparoscopic surgery. Anesthesiology 2013; 118:114–22
11. Futier E, Constantin JM, Pelosi P, Chanques G, Kwiatkoskwi F, Jaber S, Bazin JE: Intraoperative recruitment maneuver reverses detrimental pneumoperitoneum-induced respiratory effects in healthy weight and obese patients undergoing laparoscopy. Anesthesiology 2010; 113:1310–9
12. Suh MK, Seong KW, Jung SH, Kim SS: The effect of pneumoperitoneum and Trendelenburg position on respiratory mechanics during pelviscopic surgery. Korean J Anesthesiol 2010; 59:329–34
13. Rubini A, Del Monte D, Catena V: Effects of the pneumoperitoneum and Trendelenburg position on respiratory mechanics in the rats by the end-inflation occlusion method. Ann Thorac Med 2012; 7:205–9
14. Serpa Neto A, Hemmes SN, Barbas CS, Beiderlinden M, Biehl M, Binnekade JM, Canet J, Fernandez-Bustamante A, Futier E, Gajic O, Hedenstierna G, Hollmann MW, Jaber S, Kozian A, Licker M, Lin WQ, Maslow AD, Memtsoudis SG, Reis Miranda D, Moine P, Ng T, Paparella D, Putensen C, Ranieri M, Scavonetto F, Schilling T, Schmid W, Selmo G, Severgnini P, Sprung J, Sundar S, Talmor D, Treschan T, Unzueta C, Weingarten TN, Wolthuis EK, Wrigge H, Gama de Abreu M, Pelosi P, Schultz MJ; PROVE Network Investigators: Protective *versus* conventional ventilation for surgery: A systematic review and individual patient data meta-analysis. Anesthesiology 2015; 123:66–78
15. Ukere A, März A, Wodack KH, Trepte CJ, Haese A, Waldmann AD, Böhm SH, Reuter DA: Perioperative assessment of regional ventilation during changing body positions and ventilation conditions by electrical impedance tomography. Br J Anaesth 2016; 117:228–35
16. Böhm SH, Maisch S, von Sandersleben A, Thamm O, Passoni I, Martinez Arca J, Tusman G: The effects of lung recruitment on the Phase III slope of volumetric capnography in morbidly obese patients. Anesth Analg 2009; 109:151–9
17. Bohm SH, Thamm OC, von Sandersleben A, Bangert K, Langwieler TE, Tusman G, Strate TG, Standl TG: Alveolar recruitment strategy and high positive end-expiratory pressure levels do not affect hemodynamics in morbidly obese intravascular volume-loaded patients. Anesth Analg 2009; 109:160–3
18. Wiegel M, Hammermüller S, Wrigge H, Reske AW: Electrical impedance tomography visualizes impaired ventilation due to hemidiaphragmatic paresis after interscalene brachial plexus block. Anesthesiology 2016; 125:807
19. Spadaro S, Mauri T, Böhm SH, Scaramuzzo G, Turrini C, Waldmann AD, Ragazzi R, Pesenti A, Volta CA: Variation of poorly ventilated lung units (silent spaces) measured by electrical impedance tomography to dynamically assess recruitment. Crit Care 2018; 22:26
20. Waldmann AD, Wodack KH, März A, Ukere A, Trepte CJ, Böhm SH, Reuter DA: Performance of novel patient interface for electrical impedance tomography applications. J Med Biol Eng. 2017; 37: 561–6
21. Thürk F, Boehme S, Mudrak D, Kampusch S, Wielandner A, Prosch H, Braun C, Toemboel FPR, Hofmanninger J, Kaniusas E: Effects of individualized

electrical impedance tomography and image reconstruction settings upon the assessment of regional ventilation distribution: Comparison to 4-dimensional computed tomography in a porcine model. PLoS One 2017; 12:e0182215
22. Ferrando C, Tusman G, Suarez-Sipmann F, León I, Pozo N, Carbonell J, Puig J, Pastor E, Gracia E, Gutiérrez A, Aguilar G, Belda FJ, Soro M: Individualized lung recruitment maneuver guided by pulse-oximetry in anesthetized patients undergoing laparoscopy: A feasibility study. Acta Anaesthesiol Scand 2018; 62:608–19
23. Karsten J, Luepschen H, Grossherr M, Bruch HP, Leonhardt S, Gehring H, Meier T: Effect of PEEP on regional ventilation during laparoscopic surgery monitored by electrical impedance tomography. Acta Anaesthesiol Scand 2011; 55:878–86
24. He X, Jiang J, Liu Y, Xu H, Zhou S, Yang S, Shi X, Yuan H: Electrical impedance tomography-guided PEEP titration in patients undergoing laparoscopic abdominal surgery. Medicine (Baltimore) 2016; 95:e3306
25. Amato MB, Meade MO, Slutsky AS, Brochard L, Costa EL, Schoenfeld DA, Stewart TE, Briel M, Talmor D, Mercat A, Richard JC, Carvalho CR, Brower RG: Driving pressure and survival in the acute respiratory distress syndrome. N Engl J Med 2015; 372:747–55
26. Pelosi P, Luecke T, Rocco PR: Chest wall mechanics and abdominal pressure during general anaesthesia in normal and obese individuals and in acute lung injury. Curr Opin Crit Care 2011; 17:72–9
27. Kubiak BD, Gatto LA, Jimenez EJ, Silva-Parra H, Snyder KP, Vieau CJ, Barba J, Nasseri-Nik N, Falk JL, Nieman GF: Plateau and transpulmonary pressure with elevated intra-abdominal pressure or atelectasis. J Surg Res 2010; 159:e17–24
28. Nestler C, Simon P, Petroff D, Hammermüller S, Kamrath D, Wolf S, Dietrich A, Camilo LM, Beda A, Carvalho AR, Giannella-Neto A, Reske AW, Wrigge H: Individualized positive end-expiratory pressure in obese patients during general anaesthesia: A randomized controlled clinical trial using electrical impedance tomography. Br J Anaesth 2017; 119:1194–205
29. Marathe US, Lilly RE, Silvestry SC, Schauer PR, Davis JW, Pappas TN, Glower DD: Alterations in hemodynamics and left ventricular contractility during carbon dioxide pneumoperitoneum. Surg Endosc 1996; 10:974–8
30. Moffa SM, Quinn JV, Slotman GJ: Hemodynamic effects of carbon dioxide pneumoperitoneum during mechanical ventilation and positive end-expiratory pressure. J Trauma 1993; 35:613–7; discussion 617–8
31. Kraut EJ, Anderson JT, Safwat A, Barbosa R, Wolfe BM: Impairment of cardiac performance by laparoscopy in patients receiving positive end-expiratory pressure. Arch Surg 1999; 134:76–80
32. 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
33. Lindgren S, Odenstedt H, Olegård C, Söndergaard S, Lundin S, Stenqvist O: Regional lung derecruitment after endotracheal suction during volume- or pressure-controlled ventilation: A study using electric impedance tomography. Intensive Care Med 2007; 33:172–80
34. Karsten J, Stueber T, Voigt N, Teschner E, Heinze H: Influence of different electrode belt positions on electrical impedance tomography imaging of regional ventilation: A prospective observational study. Crit Care 2016; 20:3
35. Bikker IG, Preis C, Egal M, Bakker J, Gommers D: Electrical impedance tomography measured at two thoracic levels can visualize the ventilation distribution changes at the bedside during a decremental positive end-expiratory lung pressure trial. Crit Care 2011; 15:R193
36. Becher T, Wendler A, Eimer C, Weiler N, Frerichs I: Effect of intravenous fluid administration on end-expiratory lung impedance in critically ill adult patients. 19th International Conference on Biomedical Applications of Electrical Impedance Tomography (EIT2018) Edinburgh 2018 June; p 25
37. Becher T, Wendler A, Eimer C, Weiler N, Frerichs I: Changes in electrical impedance tomography findings of ICU patients during rapid infusion of a fluid bolus: A prospective observational study. Am J Respir Crit Care Med 2019; 199:1572–5