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Effects of Driving Pressure–Guided Ventilation During Robot-Assisted Laparoscopic Surgery in Steep Trendelenburg Position

Dik Trendelenburg Pozisyonunda Yapılan Robot Yardımlı Laparoskopik Cerrahi Sırasında Sürüş Basıncı Rehberli Ventilasyonun Etkileri

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ABSTRACT

Objective: This study aimed to evaluate the effects of driving pressure (DP)-guided personalized positive end-expiratory pressure (PEEP) ventilation compared to fixed PEEP ventilation on intraoperative respiratory mechanics, hemodynamic stability, and postoperative pulmonary function in patients undergoing robot-assisted laparoscopic surgery (RALS) in the steep Trendelenburg position.

Method: A total of 76 patients scheduled for RALS were prospectively randomized into two groups: Group S received personalized PEEP based on the lowest DP, while Group C received a fixed PEEP of 4 cmH_2O. Lung ultrasound (LUS) was utilized perioperatively to assess the degree of atelectasis. Intraoperative respiratory and hemodynamic parameters, as well as postoperative oxygenation and pulmonary complications, were evaluated and compared between groups.

Results: Seventy patients completed the study. Demographic characteristics were similar between the two groups. Group S exhibited significantly longer durations of anesthesia and pneumoperitoneum. Although intraoperative plateau pressure and peak inspiratory pressure were higher in Group S at specific time points, these values remained within safe limits. Postoperative oxygenation parameters, including peripheral oxygen saturation and arterial oxygen pressure, were significantly improved in Group S. Additionally, both intraoperative and postoperative LUS scores were significantly lower in Group S, indicating reduced pulmonary atelectasis. While the incidence of postoperative pulmonary complications was numerically lower in Group S (25.7%) compared to Group C (34.3%), this difference did not reach statistical significance. Hemodynamic stability was maintained in both groups throughout the perioperative period without the need for vasopressor support.

Conclusion: The DP-guided personalized PEEP ventilation improves postoperative oxygenation and lung aeration in patients undergoing RALS in the steep Trendelenburg position without adversely affecting intraoperative hemodynamic stability. Although the reduction in pulmonary complications did not reach statistical significance, the findings support the clinical safety and potential benefits of individualized ventilation strategies in this surgical setting.

Keywords: Robotic surgery, driving pressure, positive end expiratory pressure, lung ultrasound, mechanical ventilation

ÖZ

Amaç: Bu çalışmada, dik Trendelenburg pozisyonunda robot yardımlı laparoskopik cerrahi (RYLC) geçiren hastalarda, en düşük sürüş basıncına (DP) göre kişiselleştirilmiş pozitif ekspiratuvar son basınç (PEEP) ventilasyonu ile sabit PEEP uygulamasının intraoperatif solunumsal mekanikler, hemodinamik stabilite ve postoperatif pulmoner fonksiyonlar üzerindeki etkilerini karşılaştırmayı amaçladık.

Yöntem: Robot yardımlı laparoskopik cerrahi planlanan 76 hasta prospektif olarak iki gruba randomize edildi. Grup S, en düşük DP değerine göre belirlenen kişiselleştirilmiş PEEP ile ventile edilirken; Grup C'ye sabit 4 cmH_2O PEEP uygulandı. Perioperatif dönemde atelektazi, akciğer ultrasonografisi (ACUS) ile değerlendirildi. İntraoperatif solunumsal ve hemodinamik parametreler ile postoperatif oksijenasyon değerleri ve pulmoner komplikasyonlar karşılaştırıldı.

Bulgular: Yetmiş hasta çalışmayı tamamladı. Demografik özellikler gruplar arasında benzerdi. Grup S'de anestezi ve pnömoperitoneum süreleri anlamlı olarak daha uzundu. İntraoperatif plato ve pik inspiratuar basınçlar bazı zaman noktalarında Grup S'de daha yüksek izlendi; ancak bu değerler güvenli sınırların altında kaldı. Postoperatif periferik oksijen satürasyonu ve arteriyel oksijen basıncı düzeyleri Grup S'de anlamlı olarak daha yüksekti. Ayrıca, intraoperatif ve postoperatif ACUS skorları Grup S'de belirgin şekilde daha düşüktü, bu da daha az atelektazi ile ilişkilendirildi. Postoperatif pulmoner komplikasyonlar Grup S'de daha düşük oranda gözlense de (%25,7'ye karşı %34,3), bu fark istatistiksel olarak anlamlı değildi. Her iki grupta da perioperatif dönemde hemodinamik stabilite korunmuş, vazopresör ihtiyacı olmamıştır.

Sonuç: Dik Trendelenburg pozisyonunda gerçekleştirilen RYLC sırasında DP rehberli kişiselleştirilmiş PEEP uygulaması, intraoperatif hemodinamik stabiliteyi bozmadan postoperatif oksijenasyonu ve akciğer havalanmasını iyileştirmektedir. Pulmoner komplikasyonlarda istatistiksel anlamlı azalma gözlenmemekle birlikte, bu strateji güvenli ve potansiyel olarak faydalı görünmektedir.

Anahtar sözcükler: Robotik cerrahi, sürüş basıncı, ekspiryum sonu pozitif basınç, akciğer ultrasonografisi, mekanik ventilasyon

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INTRODUCTION

In recent years, robot-assisted surgery has become increasingly prevalent across various surgical specialties offering significant advantages in the context of minimally invasive procedures. However, the combination of pneumoperitoneum and the steep Trendelenburg position, which is commonly required during robot-assisted laparoscopic surgery, may disrupt cerebrovascular, respiratory, and hemodynamic homeostasis (1). It is well established that this positioning, along with pneumoperitoneum, leads to cranial displacement of the diaphragm, impaired ventilation in the dorsal lung regions, and altered in pulmonary function, potentially contributing to postoperative pulmonary complications (2). To counteract these effects, intraoperative application of positive end-expiratory pressure (PEEP) has become common practice (3,4). Nevertheless, clinical evidence remains inconsistent: while high PEEP alone has been shown to be insufficient to improve postoperative pulmonary function, combining low tidal volumes (6 mL kg^{-1}) with moderate PEEP levels (8 cmH_2O) during robot-assisted laparoscopic prostatectomy (RALP) has been associated with better preservation of postoperative lung function (4,5).

Driving pressure (DP), which is defined as the difference between plateau pressure (Pplat) and PEEP, reflects the mechanical stress that is imposed on the lung parenchyma with each breath. In a landmark single-center study conducted in 1998, Amato et al. demonstrated that a ventilation strategy focused on maintaining low inspiratory DP (< 20 cmH_2O), in combination with low tidal volumes and elevated PEEP levels, was associated with reduced mortality in patients with acute respiratory distress syndrome (ARDS) (6). In a large-scale randomized controlled trial involving patients undergoing open abdominal surgery, individualized PEEP—determined as the level at which the lowest DP was achieved—was compared with a fixed PEEP of 5 cmH_2O. The results showed that personalized PEEP significantly improved intraoperative respiratory mechanics and reduced the incidence of postoperative pulmonary complications (7). However, the optimal PEEP level required to maintain alveolar recruitment in dorsal lung regions and the most effective PEEP adjustment method for patients undergoing pneumoperitoneum in the steep Trendelenburg position remain unclear.

Lung ultrasonography (LUS) has recently gained popularity in the perioperative setting due to its non-invasiveness, bedside applicability, and reproducibility. It is considered a reliable tool for detecting anesthesia-induced atelectasis and monitoring perioperative pulmonary changes (8-11).

Therefore, the primary aim of this study was to compare the effects of a DP-guided individualized PEEP strategy with those of fixed PEEP on postoperative LUS scores, while also evaluating its impact on arterial oxygen pressure/fraction of inspired oxygen (PaO_2/FiO_2) ratios, PaO_2 values, intraoperative pulmonary mechanics, and hemodynamic parameters during RALP performed in the steep Trendelenburg position. We hypothesized that DP-guided individualized PEEP would reduce LUS scores and improve oxygenation without causing significant hemodynamic instability.

MATERIAL and METHODS

The study was conducted following approval from the Ethics Committee of Ankara City Hospital (approval no: E2-22-1446, Date:02/03/2022) and after obtaining written informed consent from all participants. Seventy-six patients aged 18 to 70 years and classified as American Society of Anesthesiologists (ASA) physical status I–III and scheduled for robot-assisted surgery using the da Vinci® Surgical System in the steep Trendelenburg position, were included in the study. Patients classified as ASA class IV or higher, those with contraindications for PEEP application, and those with a body mass index >30 kg m^{-2} were excluded from the study. Randomization was performed using sealed envelopes prepared prior to the start of the study. Patients were divided into two groups based on envelope selection: the DP-guided ventilation group (Group S) and the fixed PEEP ventilation group (Group C). The demographic characteristics, smoking history and intensity, and preoperative laboratory findings of all participants were recorded. Patients were excluded from the study if they required conversion to open surgery, if they experienced intraoperative blood loss exceeding 1000 mL, or if they developed severe hypotension, defined as mean arterial pressure of less than 55 mmHg despite vasopressor support.

Patients who had fasted overnight and were permitted to drink clear liquids up to two hours prior to the procedure were taken to the operating theatre, where standard monitoring was initiated, including electrocardiogram, peripheral oxygen saturation (SpO_2) and non-invasive blood pressure. A 0.9% NaCl intravenous (IV) infusion was started and maintained at a rate of 4–5 mL kg^{-1} h^{-1} throughout the procedure. After monitoring, the patients received preoxygenation with FiO_2 of 80% for two minutes. Anesthesia induction was performed using IV propofol (2–2.5 mg kg^{-1}), fentanyl (1 µg kg^{-1}), and rocuronium (0.6 mg kg^{-1}), followed by endotracheal intubation after two minutes later. Once the correct placement of the tube had been confirmed, and patients were connected to the GE Aisys™ CS2 anesthesia machine.

Mechanical ventilation was administered in volume-controlled mode (VCV) with the following settings: Tidal volume (VT) 6 mL kg^{-1} (based on ideal body weight), PEEP 4 cmH_2O, inspiratory pause 30%, and inspiratory: expiratory (I:E) ratio of 1:2. The FiO_2 was adjusted to maintain SpO_2 of between 92% and 95% throughout the procedure.

Radial artery cannulation was performed for invasive haemodynamic monitoring, which is routinely performed in robot-assisted procedures. Anesthesia was maintained using sevoflurane and a continuous remifentanil infusion, with the minimum alveolar concentration titrated to maintain a bispectral index of between 40 and 60. Neuromuscular blockade was maintained with a continuous infusion of rocuronium at a dose of 0.15 mg kg^{-1} h^{-1}.

Following the induction of anesthesia, the patient was placed in the steep Trendelenburg position with their arms positioned parallel to their body. Pneumoperitoneum was created using CO_2 insufflation and the intra-abdominal pressure (IAP) was kept 10-15 mmHg in accordance with our institutional protocol.

In the fixed PEEP group (Group C), mechanical ventilation was administered in VCV mode with a VT of 6 mL kg^{-1} (based on ideal body weight), PEEP of 4 cmH_2O, inspiratory pause of 30%, and an I:E ratio of 1:2. In the DP–guided group (Group S), the lowest DP—calculated as Pplat minus PEEP—was used and the corresponding optimal PEEP level were determined at the same VT. A recruitment manoeuvre was performed prior to DP assessment. Subsequently, PEEP was incrementally increased from 4 to 10 cm H_2O in the steep Trendelenburg position, with a VT of 6 mL kg^{-1} and respiratory rate of 12 breaths per minute. Each PEEP level was maintained for 10 respiratory cycles, and DP was calculated during the final cycle. The lowest determined DP value was maintained throughout pneumoperitoneum.

Following pneumoperitoneum, both groups were switched from pressure-controlled volume-guaranteed (PCV-VG) mode to VCV mode. Pplat and peak inspiratory pressure (PIP) were recorded at 30th, 60th, 90th, 120th, and 150th minutes, with Pmax limited to 35 cmH_2O. During the procedure, the respiratory rate was adjusted to keep the end-tidal CO_2 level within the range of 35–45 mmHg, and the FiO_2 was adjusted to maintain the SpO_2 between 92% and 95%.

At the end of the procedure, the neuromuscular blockade was reversed with sugammadex, and the patient was extubated once adequate spontaneous respiration was confirmed. Following extubation, patients were transferred to the recovery room, where supplemental oxygen was administered only if SpO_2 fell below 92%. Postoperative analgesia was managed using 1 g of paracetamol IV and 100 mg of tramadol IV, to aim for a visual analogue scale pain score of ≤3.

Vital signs were recorded before induction, after intubation, and after Trendelenburg positioning and pneumoperitoneum, and every 15 minutes intraoperatively. Peak inspiratory pressure, Pplat, and static lung compliance (Cstat) were documented at 30th, 60th, and 90th minutes following CO_2 insufflation, as well as immediately prior to extubation. Intra-abdominal pressure was kept between 10 and 15 mmHg throughout pneumoperitoneum. Arterial blood gas values were obtained at specified intraoperative and postoperative intervals, and the PaO_2/FiO_2 ratio was calculated accordingly.

Lung USG was performed twice by the same investigator using a standard protocol: once preoperatively (before induction) and once postoperatively (at the 1st hour). According to the lung USG protocol, a total of 12 regions, including anterior, right and left lateral, and posterior thoracic areas, were systematically scanned. The intercostal spaces were evaluated, and the image showing the most significant ventilation loss was recorded for each region. Scoring was performed according to the lung US assessment system described by Monastesse et al. (8). In this system, each region was scored from 0 to 3 depending on the degree of atelectasis, with a total score ranging from 0 (no ventilation loss) to 36 (complete ventilation loss).

Patients in both groups were evaluated for postoperative pulmonary complications at 24 and 48 hours postoperatively. Vital parameters, including SpO_2, body temperature, and arterial blood gas values, were recorded during the postoperative period.

The primary outcome of the study was the postoperative LUS score, assessed at the 1st postoperative hour. Secondary outcomes included PaO_2/FiO_2 ratios, PaO_2 values, intraoperative pulmonary mechanics (driving pressure, compliance, plateau pressure, and PEEP), hemodynamic parameters mean arterial pressure (MAP) and heart rate, and the incidence of postoperative pulmonary complications.

Statistical Analysis

A priori power analysis was performed using G*Power software version 3.1.9.7 (Franz Faul, Universität Kiel, Germany) based on the primary outcome, the postoperative LUS score. The calculation assumed a significance level (α) of 0.05, a statistical power of 0.90, and an effect size (Cohen's d) of 0.78. The effect size was derived from the study by Yang et al., which investigated the effect of lung recruitment maneuvers on postoperative atelectasis using LUS in patients undergoing laparoscopic colorectal surgery in the Trendelenburg position (12). Although the surgical procedure in the present study (RALP) differed, the physiological conditions and outcome measure were sufficiently comparable to justify the estimation. This analysis indicated that at least 35 participants per group were required. To compensate for potential dropouts, an additional 10% was added, resulting in a total sample size of 76.

The statistical analysis was performed using IBM Statistical Package for the Social Sciences (SPSS) Statistics version 25.0

(Armonk, NY: IBM Corp.) and MedCalc version 15.8 (MedCalc Software bvba, Ostend, Belgium). In addition to descriptive statistics, the Chi-squared test was used to compare categorical variables. The normality of continuous data was assessed using the Kolmogorov-Smirnov test, as well as skewness and kurtosis values, and visual methods such as histograms, Q–Q plots, stem-and-leaf plots, and boxplots. For intergroup comparisons, the Independent Samples t-test was used for normally distributed data, and the Mann–Whitney U test was used for non-normally distributed data. Intra-group comparisons were performed using the Paired Samples t-test and repeated measures ANOVA, as appropriate. A p-value of less than 0.05 was considered statistically significant.

RESULTS

Of the 76 patients initially included in the study, 70 were ultimately analysed. Three patients in Group C and two in Group S were excluded due to conversion to open surgery during the procedure. Additionally, one patient in Group S withdrew from the study voluntarily during the postoperative period.

There were no significant differences between the groups in terms of demographic characteristics or intraoperative blood loss. However, the durations of anesthesia, surgery, the Trendelenburg positioning, and pneumoperitoneum were significantly longer in Group S than in Group C ($p<0.05$) (Table I).

Mean arterial pressure values were significantly lower in Group S than in Group C at 5, 75, and 180 minutes after pneumoperitoneum. However, no patient required vasopressor support. Heart rate values were significantly higher in Group S than in Group C at 45, 60, 90, 120, and 180 minutes after pneumoperitoneum, as well as before and after extubation ($p<0.05$) (Figures 1 and 2).

Plateau pressure was significantly higher in Group S than in Group C both 5 minutes after pneumoperitoneum (Group S: 28.9 ± 3.8 vs. Group C: 25.7 ± 2.3; p=0.005) and immediately before extubation (Group S: 16.7 ± 3.0 vs. Group C: 15.3 ± 1.9; p=0.03). Similarly, PIP was significantly higher in Group S than in Group C at 5 minutes after pneumoperitoneum (Group S: 33.9 ± 3.7 vs. Group C: 31.9 ± 3.8; p=0.035) and before extubation (Group S: 22.8 ± 3.7 vs. Group C: 20.0 ± 2.5; p=0.000). Although Cstat decreased in both groups following pneumoperitoneum, there were no statistically significant differences in Cstat values between the groups at any time point ($p>0.05$).

Although the preoperative SpO_2 values were similar between the two groups, post-extubation, post anesthesia care unit discharge, and postoperative values at 1, 24, and 48 hours were significantly higher in Group S compared to Group C ($p<0.05$) (Table II). While no significant difference in PaO_2 values was observed preoperatively, PaO_2 at the first postoperative hour was significantly higher in Group S than in Group

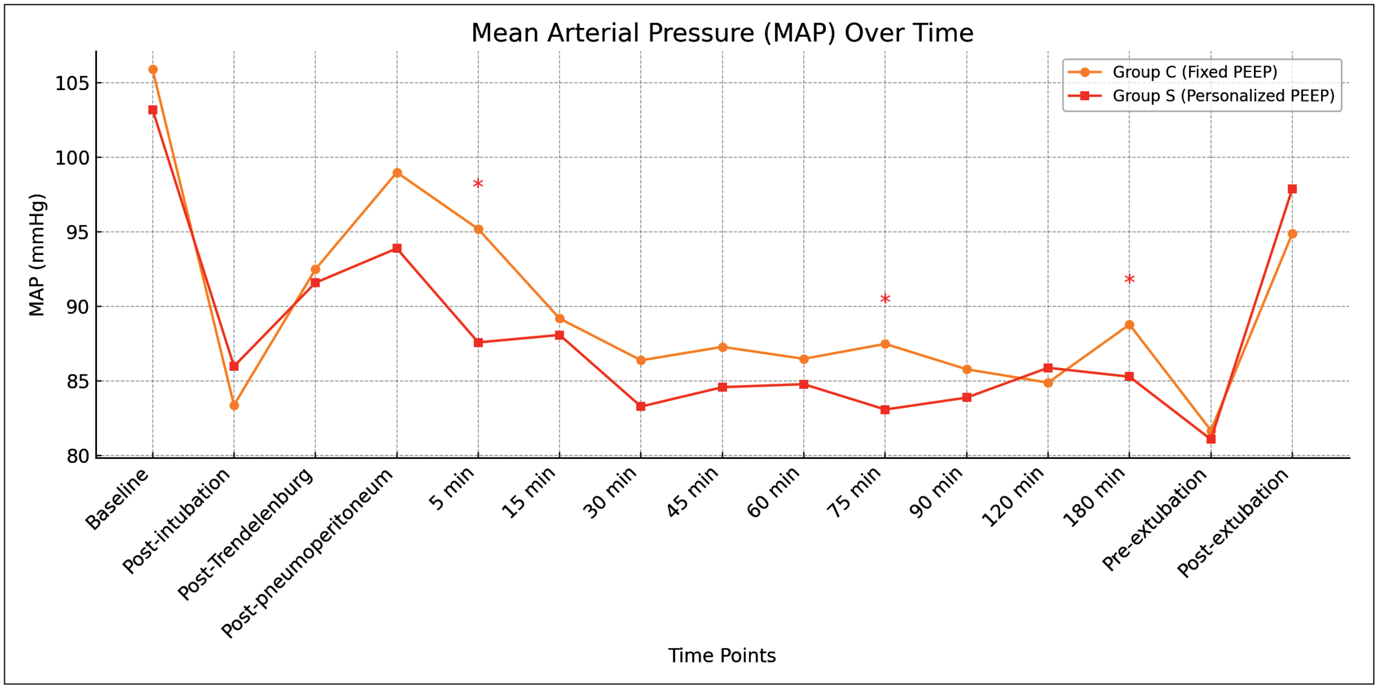

Figure 1. Mean arterial pressure (MAP) values over time. Mean arterial pressure (MAP) values at predefined intraoperative and perioperative time points in patients undergoing RALP. **Group C:** fixed PEEP group (4 cmH_2O), **Group S:** personalized PEEP group (adjusted according to driving pressure). Data are presented as group means. Red asterisks indicate time points at which a statistically significant difference was observed between groups ($p<0.05$).

C ($p<0.05$). However, the PaO_2/FiO_2 ratios calculated at the same time points showed no statistically significant differences between the groups ($p>0.05$) (Table III).

The LUS findings are summarized in Table IV in both groups, left, right, and total LUS increased significantly during the postoperative period compared to preoperative values ($p<0.05$). However, postoperative right lung and total LUS were significantly higher in Group C than in Group S ($p<0.05$) (Table IV).

Analysis of postoperative pulmonary complications revealed no statistically significant difference between the groups ($p>0.05$). Nevertheless, the overall incidence of pulmonary

Table I. Demographic and Surgical Characteristics of Patients

		Group C (n=35)	Group S (n=35)	P
Age (year)		61.5 ± 5.6 62 (50 – 71)	63.7 ± 4.6 63 (58 – 75)	0.083[b]
BMI (kg m^{-2})		26.7 ± 1.9 27.1 (22 – 29.5)	26.9 ± 1.9 26.8 (21.8 – 29.6)	0.790[b]
ASA status	I	7 (20)	12 (34.3)	0.282[a]
	II	28 (80)	23 (65.7)	
Comorbidity	None	12 (34.3)	12 (34.3)	1.000[a]
	Present	23 (65.7)	23 (65.7)	
	Single disease	18 (78.3)	22 (95.7)	*0.189*[a]
	Multiple diseases	5 (21.7)	1 (4.3)	
	HT	3 (8.6)	11 (31.4)	--
	Diabetes Mellitus	3 (8.6)	6 (17.1)	
	Asthma	4 (11.4)	1 (2.9)	
	History of COVID-19	4 (11.4)	1 (2.9)	
	HT + DM	3 (8.6)	1 (2.9)	
	Coronary Artery Disease	2 (5.7)	1 (2.9)	
	Hypothyroidism	1 (2.9)	0 (0)	
	CAD + DM	1 (2.9)	0 (0)	
	Chronic Kidney Disease	0 (0)	1 (2.9)	
	CLL + DM	1 (2.9)	0 (0)	
	COPD	0 (0)	1 (2.9)	
	History of PE	1 (2.9)	0 (0)	
Smoking	Non-smoker	28 (80)	30 (85.7)	0.751[a]
	Smoker	7 (20)	5 (14.3)	
Anesthesia Duration (minutes)		238.8 ± 40.4 240 (120 – 310)	266.1 ± 28.9 270 (200 – 310)	**0.002**[b]
Operation Duration (minutes)		206 ± 40 205 (80 – 285)	238.5 ± 33.5 235 (160 – 290)	**<0.001**[b]
Trendelenburg Duration (minutes)		193.6 ± 37 190 (75 – 255)	220.1 ± 31.9 220 (140 – 285)	**0.002**[b]
Pneumoperitoneum Duration (minutes)		187.9 ± 36.7 186 (70 – 260)	209.7 ± 33.4 210 (135 – 280)	**0.012**[b]
Estimated Blood Loss (mL)		172.9 ± 66.8 200(100 – 300)	192.9 ± 74.9 200 (100 – 300)	0.243[b]

a: Chi-square test (n (%)); **b:** Independent Samples t Test (Mean ± SD) / Median (min-max)
ASA: American Society of Anesthesiologists, **BMI:** Body mass index, **HT:** Hypertension, **DM:** Diabetes mellitus, **CAD:** Coronary artery disease, **CLL:** Chronic lymphocytic leukemia, **COPD:** Chronic obstructive pulmonary disease, **PE:** Pulmonary embolism.

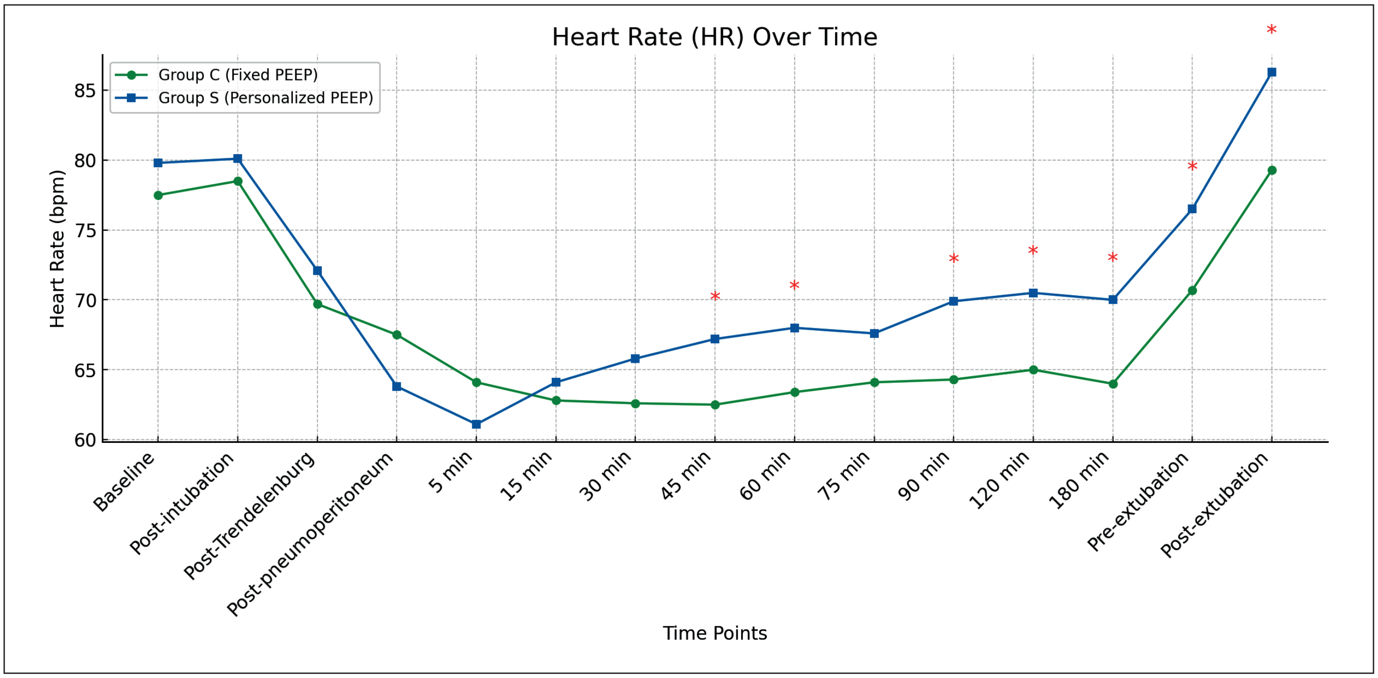

Figure 2. Heart rate (HR) values over time in patients undergoing RALP. **Group C:** fixed PEEP group (4 cmH_2O), **Group S:** personalized PEEP group (adjusted according to driving pressure). Data are shown as group means.

Table II. Perioperative Peripheral Oxygen Saturation (SpO_2) Values in Patients Undergoing Robot-Assisted Laparoscopic Surgery

SpO_2	Grup C (n=35)	Grup S (n=35)	P*
Baseline	95.6 ± 1.1 96 (94 – 98)	95.5 ± 1.2 96 (93 – 98)	0.690
Post-extubation	97.4 ± 1.3 **#** 98 (94 – 100)	98.1 ± 1.3 **#** 98 (94 – 100)	**0.034**
PACU Admission	94.7 ± 1.7 95 (92 – 98)	95.8 ± 1.8 96 (92 – 98)	**0.008**
Postoperative 1st hour	94.5 ± 1.8 94 (91 – 98)	95.9 ± 1.9 96 (92 – 99)	**0.003**
Postoperative 24th hour	93.9 ± 1.6 94 (92 – 97)	95.1 ± 1.5 95 (92 – 98)	**0.002**
Postoperative 48th hour	94.2 ± 1.1 94 (92 – 96)	95.5 ± 1.1 96 (93 – 97)	**<0.001**

***:** Independent Samples t Test (mean ± SD) / Median (min–max); **#:** Statistically significant difference compared to baseline within the same group (p<0.05). **PACU:** Post operative care unit.

complications, including pneumonia, atelectasis, pleural effusion, bronchospasm, and ARDS, was higher in Group C (34.3%) than in Group S (25.7%).

DISCUSSION

This randomized controlled study demonstrated that applying individualized PEEP adjusted according to driving pressure during RALP in the steep Trendelenburg position significantly improved postoperative oxygenation and reduced the degree of atelectasis as assessed by lung ultrasound. The PaO_2 values at the 1st postoperative hour were significantly higher and LUS scores at the same time point were significantly lower in the DP-guided group compared with the fixed PEEP group. Importantly, these benefits were achieved without clinically relevant impairment of intraoperative hemodynamics. Al-

Table III. Perioperative Arterial Oxygen Pressure (PaO_2) Values in Patients Undergoing Robot-Assisted Laparoscopic Surgery

PaO_2	Grup C (n=35)	Grup S (n=35)	P*
Preoperative	73.8 ± 7.7 75.4 (55.6 – 87.7)	74.1 ± 11.8 75.5 (55.4 – 102.8)	0.893
Post-intubation	150.7 ± 37.2 # 148.6 (78.5 – 237.9)	186.6 ± 66.2 # 188 (71.2 – 337.5)	**0.007**
Post-pneumoperitoneum	122.1 ± 27.6 # 118.6 (75 – 214)	140.1 ± 31.2 # 138.4 (78.5 – 195.4)	**0.013**
30th minute	114.5 ± 18.1 # 114 (81.6 – 157.7)	126.6 ± 23.8 # 127.8 (75.2 – 169.6)	**0.02**
60th minute	117 ± 18.6 # 114.7 (83.2 – 153.2)	127.8 ± 24.9 # 127.2 (83 – 195.7)	**0.044**
120th minute	121 ± 17.9 # 116.8 (95.2 – 165.2)	132 ± 27 # 131.4 (78.2 – 194.8)	0.05
Pre-extubation	190.3 ± 49.5 # 197 (81.4 – 281.6)	202.5 ± 66 # 192 (94.2 – 392.4)	0.385
Postoperative 1st hour	85.6 ± 27.4 75.8 (53.3 – 170)	104.6 ± 27.4 # 103.6 (68.9 – 154.4)	**0.005**
Postoperative 24th hour	75.9 ± 16.5 72.4 (51 – 129)	81.9 ± 19.2 79.9 (58.9 – 126.9)	0.162
Postoperative 48th hour	73 ± 7.1 72.6 (60.6 – 98.6)	72.3 ± 7.9 71.1 (55.5 – 87.8)	0.726

***:** Independent Samples t Test (mean ± SD) / Median (min–max); **#:** Statistically significant difference compared to baseline within the same group ($p<0.05$); **PaO_2:** Partial pressure of arterial oxygen.

Table IV. Perioperative Lung Ultrasound Assessment of Patients Undergoing RALP

Lung Ultrasound Score		Grup C (n=35)	Grup S (n=35)	P*
Left Lung Total	Preoperative	3.3 ± 1.3 3 (2 – 7)	3.1 ± 0.8 3 (2 – 4)	0.587
	Postoperative	6.3 ± 1.6 7 (4 – 9)	5.8 ± 1.2 6 (4 – 8)	0.108
	P**	**<0.001**	**<0.001**	
Right Lung Total	Preoperative	3.4 ± 1.5 3 (0 – 6)	3.2 ± 0.9 3 (2 – 5)	0.493
	Postoperative	6.8 ± 1.8 7 (3 – 10)	5.5 ± 1.2 5 (3 – 8)	**0.001**
	P**	**<0.001**	**<0.001**	
Total LUS	Preoperative	6.7 ± 2.5 6 (3 – 13.0)	6.3 ± 1.4 6 (4 – 9)	0.410
	Postoperative	13.1 ± 3.2 13 (7 – 19)	11.2 ± 2.2 11 (7 – 16)	0.007

:** Independent Samples t Test (mean ± SD) / Median (min–max); *:** Paired Samples t Test; **RALP:** Robot-assisted laparoscopic prostatectomy, **LUS:** Lung ultrasound score.

though the incidence of postoperative pulmonary complications was lower in the DP group, this difference did not reach statistical significance.

Postoperative pulmonary complications occur in 2–5.6% of surgical patients and may rise to 20–70% for upper abdominal and thoracic procedures (13). Numerous randomized controlled trials and meta-analyses have confirmed the effectiveness of lung-protective ventilation strategies, particularly those involving low tidal volumes and appropriate PEEP levels, in reducing postoperative pulmonary complications in abdominal surgery (14-16). D'Antini et al. reported that the optimal level of PEEP ranged from 6 to 10 cm H_2O (mean 8.9 ± 1.3 cm H_2O) in patients undergoing laparoscopic cholecystectomy in the reverse Trendelenburg position (17). In a study by Yoon et al., the optimal median PEEP determined according to DP during RALP in the steep Trendelenburg position was reported as 14 cm H_2O (interquartile range 12–18 cm H_2O) (18). In our study, the optimal PEEP level in the DP-guided PEEP adjustment group was found to be mean 8.2 ± 1.3 cm H_2O. However, this may be because we limited the maximum PEEP level used to determine the lowest DP to 10 cm H_2O to avoid hypotension. This restriction may explain the slightly lower mean PEEP values compared to previous reports.

It is well-known that the steep Trendelenburg position and pneumoperitoneum can impair pulmonary mechanics. This is caused by cranial displacement of the diaphragm, a reduction in functional residual capacity (FRC) and an increased risk of atelectasis (19). Interestingly, in our study, despite longer anaesthesia, surgery and pneumoperitoneum times in the DP-guided PEEP group, postoperative LUS were lower than in the fixed PEEP group. This suggests that personalized PEEP settings may be more effective at maintaining alveolar recruitment under challenging intraoperative conditions.

Lung-protective mechanical ventilation strategies recommend maintaining a Pplat of less than 30 cm H_2O. However, increases in IAP have been shown to reduce FRC even in healthy lungs. This necessitates higher airway pressures for alveolar recruitment and consequently leading to elevated Pplat values (20). In our study, Pplat was significantly higher in the DP-guided PEEP adjustment group compared to the fixed PEEP group only at the 5^{th} minute after pneumoperitoneum and immediately before extubation. In both groups Pplat increased following Trendelenburg positioning and remained elevated throughout the operation, approaching post-intubation values after repositioning and release of pneumoperitoneum. Notably, Pplat did not exceed 35 cm H_2O at any time point in either group. A previous study comparing PEEP levels of 4 cm H_2O and 8 cm H_2O during robotic surgery, it was reported that compliance decreased after Trendelenburg positioning and remained lower in the supine position than post-intubation values, though it gradually returned to baseline (21). Similarly, in our study, Cstat decreased in both groups following pneumoperitoneum, although no significant intergroup difference was observed at any measurement time point. In a study by Fernandez-Bustamante et al., optimal PEEP determined by various methods was found to be associated with lower DP and better compliance compared to low PEEP. However, this study involved repeated intermittent recruitment manoeuvres, which could have affected compliance outcomes (22). By contrast, we applied a single recruitment manoeuvre before PEEP titration, which may explain the lack of significant differences in Cstat between groups.

While high PEEP can improve ventilation homogeneity and lung mechanics, it may also have a negative effect on hemodynamic. Shono et al. reported similar MAP values between PEEP levels but observed a higher requirement for vasopressors in the high PEEP group (4). Similarly, in the PROVHILO study, although HR was not significantly affected, hemodynamic instability and vasopressor requirement were more common in patients receiving high PEEP (23). In our study, MAP values were lower at certain time points after pneumoperitoneum in the DP-guided PEEP group than in the other group. However, this decrease did not require vasopressor support. Furthermore, the significant increase in heart rate observed at various time points in the DP-guided PEEP group indicated a physiological response to low MAP.

Some studies have reported that higher PEEP levels improve PaO_2, reducing the incidence of postoperative atelectasis and pneumonia. Shono et al. also found that high PEEP levels increased the PaO_2/FiO_2 ratio during robotic surgery (4). A correlation was demonstrated between changes in the PaO_2/FiO_2 ratio during the perioperative period and LUS. Higher LUS were reported at 1^{st} and 24^{th} hours postoperatively in patients who developed postoperative pulmonary complications (24). However, the protective role of high PEEP during surgery on postoperative pulmonary function remains controversial. Increasing PEEP can result in a decrease, no change, or even an increase in DP. In particular, high PEEP levels that fail to reduce DP may indicate impaired lung recruitment and increased mechanical stress on the alveoli (24, 25). A meta-analysis by Neto et al. compared lung-protective ventilation strategies with conventional ventilation in various surgical procedures and found that PEEP levels associated with increased DP were linked to an increased risk of postoperative pulmonary complications (14). More recently, a systematic review and meta-analysis by Sun et al. further confirmed that DP-guided PEEP titration improves respiratory mechanics and decreases the incidence of PPCs across different surgical populations (26). In laparoscopic surgery, postoperative LUS were found to be significantly lower with DP-guided personalized PEEP than with fixed PEEP (27). Like previous studies, our study found that postoperative PaO_2 values were significantly higher and LUS were lower in the group receiving DP-guided personalized PEEP than in the other group. However, the incidence of postoperative pulmonary complications did not differ between the groups.

Although the difference in postoperative pulmonary complication rates between the groups did not reach statistical significance, the observed reduction in the DP-guided PEEP group may still be clinically relevant. Even modest decreases in PPC incidence can influence patient recovery trajectories, reduce the need for additional interventions, and lower health care utilization. Furthermore, the discrepancy between unchanged PaO_2/FiO_2 ratios and the lower postoperative LUS observed in the DP group suggests that LUS may be more sensitive in detecting subclinical pulmonary changes that are not captured by conventional oxygenation indices. This finding is consistent with recent evidence reporting the utility of LUS in robotic procedures as an early marker of pulmonary impairment (28). Our results therefore reinforce the complementary value of perioperative LUS monitoring alongside traditional oxygenation parameters.

Our study has some limitations. Firstly, the PEEP level was determined according to the DP and maintained throughout the procedure without adjustment according to intraoperative physiological changes. Furthermore, inflammatory markers and advanced imaging methods were not employed, and long-term outcomes such as length of hospital stay, and late-onset pulmonary complications were not assessed. Further research investigating dynamic PEEP adjustment strategies that incorporate biochemical and clinical endpoints would provide a clearer picture of the optimal ventilation approach for robotic surgery performed in the steep Trendelenburg position.

CONCLUSION

In RALP procedures performed under pneumoperitoneum and in the steep Trendelenburg position, the application of personalized PEEP based on the lowest DP following a single recruitment manoeuvre did not significantly reduce the incidence of early postoperative pulmonary complications compared to a fixed PEEP of 4 cmH_2O. However, it was associated with reduced postoperative atelectasis as assessed by lung USG and improved perioperative oxygenation, without adversely affecting intraoperative hemodynamic stability. These findings suggest that DP-guided personalized PEEP is a safe and potentially effective ventilation strategy in this surgical population.

AUTHOR CONTRIBUTIONS

Conception or design of the work: SI
Data collection: EU
Data analysis and interpretation: EU, BN
Drafting the article: EU, BN
Critical revision of the article: SI
The author (EU, BN, SI) reviewed the results and approved the final version of the manuscript.

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