Positive End-expiratory Pressure Alone Minimizes Atelectasis Formation in Nonabdominal Surgery

A Randomized Controlled Trial

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ABSTRACT

Background: Various methods for protective ventilation are increasingly being recommended for patients undergoing general anesthesia. However, the importance of each individual component is still unclear. In particular, the perioperative use of positive end-expiratory pressure (PEEP) remains controversial. The authors tested the hypothesis that PEEP alone would be sufficient to limit atelectasis formation during nonabdominal surgery.

Methods: This was a randomized controlled evaluator-blinded study. Twenty-four healthy patients undergoing general anesthesia were randomized to receive either mechanical ventilation with PEEP 7 or 9 cm H_2O depending on body mass index (n = 12) or zero PEEP (n = 12). No recruitment maneuvers were used. The primary outcome was atelectasis area as studied by computed tomography in a transverse scan near the diaphragm, at the end of surgery, before emergence. Oxygenation was evaluated by measuring blood gases and calculating the ratio of arterial oxygen partial pressure to inspired oxygen fraction ($Pa_{O_2}/F_{I_{O_2}}$ ratio).

Results: At the end of surgery, the median (range) atelectasis area, expressed as percentage of the total lung area, was 1.8 (0.3 to 9.9) in the PEEP group and 4.6 (1.0 to 10.2) in the zero PEEP group. The difference in medians was 2.8% (95% CI, 1.7 to 5.7%; $P = 0.002$). Oxygenation and carbon dioxide elimination were maintained in the PEEP group, but both deteriorated in the zero PEEP group.

Conclusions: During nonabdominal surgery, adequate PEEP is sufficient to minimize atelectasis in healthy lungs and thereby maintain oxygenation. Thus, routine recruitment maneuvers seem unnecessary, and the authors suggest that they should only be utilized when clearly indicated.

Visual Abstract: An online visual overview is available for this article at http://links.lww.com/ALN/B728. **(ANESTHESIOLOGY 2018; 128:1117-24)**

IN recent years, the concept of intraoperative protective ventilation has drawn increased attention due to the prospects of improving outcomes after general anesthesia.[1] The term "protective ventilation" has been attributed to the use of a combination of low tidal volumes, positive end-expiratory pressure (PEEP) and recruitment maneuvers.[2] While low tidal volumes aim at reducing strain and stress in the lungs during mechanical ventilation, the common rationale for using recruitment maneuvers and/or PEEP is to avoid atelectasis formation and to maintain blood oxygenation. However, the importance of each individual component is still unclear, and this is especially true regarding the use of PEEP.[3] Furthermore, two large multicenter trials have recently given conflicting recommendations regarding its use during anesthesia.[4,5]

For many years, PEEP has been extensively used during mechanical ventilation, especially in the intensive care setting. Nevertheless, to our knowledge, some fundamental mechanisms that are relevant to general anesthesia have never been systematically studied. For example, the effect of a continuously applied PEEP on atelectasis size at the end of surgery is not known. However, in a previous study by our group, computed tomography scans at the end of surgery demonstrated surprisingly small atelectasis areas in healthy subjects being ventilated with a moderate PEEP without recruitment maneuvers during surgery.[6] Therefore, we designed this new study to test the hypothesis that PEEP alone would be sufficient to limit atelectasis formation and maintain blood oxygenation in healthy lungs during nonabdominal surgery.

What We Already Know about This Topic

- The importance of positive end-expiratory pressure on atelectasis prevention during general anesthesia remains unclear.

What This Article Tells Us That Is New

- Patients were randomly assigned to 7 to 9 cm H_2O or zero end-expiratory pressure. Atelectasis was assessed by computed tomography at the end of nonabdominal surgery while patients remained anesthetized.
- Positive end-expiratory pressure, without recruitment maneuvers, largely prevented atelectasis and maintained normal oxygenation.

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Materials and Methods

This randomized controlled evaluator-blinded trial was conducted at a single county hospital in Sweden. It was approved by the Regional Ethics Committee in Uppsala (Dnr 2015/338) and was registered with ClinicalTrials.gov on September 1, 2015 (NCT02548416, principal investigator Erland Östberg).

Study Population

Potential study subjects were contacted by phone a few days before surgery and were given initial information about the study. We included only patients who were planned for day case nonabdominal procedures. Further inclusion criteria were: age between 40 and 75 yr old, American Society of Anesthesiologists (ASA) physical status I and II, and a body mass index of less than 30 kg/m^2. Patients were excluded if they had a history of chronic obstructive pulmonary disease, ischemic heart disease, or were smokers or previous smokers with a history of more than six pack years. Upon arrival at the day case unit, a normal spirometry result was assured, and we excluded patients with a peripheral arterial oxygen saturation level (Spo_2) less than 96% while breathing air and subjects with hemoglobin levels less than 10 g/dl. We also excluded patients with known or anticipated difficult airway, as well as patients receiving interscalene or supraclavicular plexus blocks, since these blocks frequently cause paralysis of the phrenic nerve. Written informed consent was obtained from all participants.

Randomization

The randomization schedule was concealed from the investigators and generated by an independent statistician at our clinical research center. The same person prepared sequentially numbered envelopes that were sealed and opaque to maintain allocation concealment until the time of randomization.

The corresponding author enrolled the study subjects after evaluating eligibility. Patients were assigned to study groups by opening the randomization envelopes just before the start of anesthesia.

Anesthesia and Monitoring

No premedication was used. Before anesthesia induction, an arterial catheter was placed in the right radial artery under local anesthesia. It was used for repeated blood gas sampling and for monitoring blood pressure. We also used three-lead electrocardiography (Philips IntelliVue MP, Philips Medizin Systeme, Germany) and pulse oximetry (Masimo Rad-5, Masimo Corporation, USA) equipment.

All patients were preoxygenated in a 15 to 20 degrees head-up position without continuous positive airway pressure. The inspired oxygen fraction (FIO_2) was set to 1.0, and preoxygenation lasted for at least 3 min or until the end-tidal oxygen concentration (ETO_2) was greater than or equal to 90%. Induction and maintenance were performed with target-controlled infusions of propofol and remifentanil (Injectomat TIVA Agilia, Fresenius Kabi AB, Sweden). All patients were bag mask ventilated without PEEP and with an FIO_2 of 1.0. Tracheal intubation was performed 6 min after the start of preoxygenation, and was facilitated by rocuronium, 0.5 mg/kg of ideal body weight.[7] Patients were thereafter ventilated with an FIO_2 of 0.30 to 0.35 in a volume-controlled mode by a Vivo 50 (Breas Medical AB, Sweden). This ventilator was chosen because of its portability and its ability to deliver zero PEEP, as opposed to our standard anesthesia machine, which cannot deliver a PEEP less than 3 cm H_2O. In both groups, the tidal volume was set to 7 ml/kg of ideal body weight, the inspiratory to expiratory ratio at 1:2, and the respiratory rate was adjusted to maintain a normal end-tidal carbon dioxide pressure ($PETCO_2$) between 35 and 45 mmHg.

The only difference in treatment between the groups was the level of PEEP. The intervention group received a PEEP of 7 cm H_2O, or 9 cm H_2O in the case of a body mass index greater than or equal to 25 kg/m^2. The control group received zero PEEP (ZEEP). Peak inspiratory pressures (PIP) were recorded throughout the anesthetic period for an approximate calculation of dynamic compliance [C_{dyn} = tidal volume/(PIP – PEEP)]. Recruitment maneuvers were not used in any of the two groups.

Small doses of phenylephrine or ephedrine were administered as required to maintain mean arterial blood pressure above 60 mmHg. Intravenous fluids were given as maintenance only and standardized to an infusion of 200 to 250 ml/h of a balanced crystalloid solution with 2.5% glucose. All 24 patients were anesthetized by the same two investigators (E.Ö., L.E.).

Computed Tomography

The primary outcome was atelectasis area after completed surgery, before emergence. The patients were transported to the radiology department located below the operating room. Due to the use of a portable ventilator from start of anesthesia, transportation was possible without disconnecting and changing ventilator settings.

Patients were placed in a supine position. Using the GE LightSpeed VCT XTe machine (GE Healthcare, USA), we obtained a frontal scout view at end-expiration to locate the diaphragm. A single-sliced transverse scan was then performed 5 to 10 mm above the right diaphragm dome, also at end-expiration. Computed tomography scan assessments were done using Sectra RIS and PACS systems (version 17.1.21, Sectra, Sweden) and measurements were done using a workstation software (AW Server 2.0 GE Healthcare, USA). In the obtained computed tomography slice, we first measured the total lung area in cm^2 by accurately delineating the contours of both lungs. Pulmonary hilus vessels were manually excluded from the lung region of interest. Second, using a separate region of interest technique, the atelectasis

region was outlined posteriorly as close to the pleura as possible but with some margin ventrally beyond the radiologic appearance of atelectasis and lung parenchyma haziness. Vascular structures larger than 3 mm in diameter were manually excluded when drawing the atelectasis region of interest. Finally, we used the histogram functional view to identify the actual atelectasis area, which was defined as −100 to +100 Hounsfield Units.[8] The calculated area was expressed in cm^2 and as the percentage of the total lung area in the basal slice. Areas of different aeration were considered secondary outcomes, and were measured with the same technique described above by setting the histogram parameters between −1,000 and −901, −900 and −501, and −500 and −101 Hounsfield Units for over-aeration, normal aeration, and poor aeration, respectively.[9,10] All computed tomography scans were assessed by the same radiologist, who was blinded to the group assignment and patient outcome.

Arterial Blood Gases and Oxygenation

A further secondary outcome was oxygenation, calculated as the ratio of the arterial oxygen partial pressure to the inspired oxygen fraction ($Pa_{O_2}/F_{I_{O_2}}$ ratio). Three samples were drawn from the arterial line with the patient in 15 to 20 degrees head-up position. The samples were collected before anesthesia induction during air breathing, midway through the surgery, and at the end of the surgery with an $F_{I_{O_2}}$ of 0.30 to 0.35. The samples were analyzed directly after sampling using the Radiometer ABL800 Flex (Radiometer Medical, Denmark).

Statistical Analysis

Based on previous data, we expected the study subjects in the control group to have atelectasis areas of at least 4.5% of the total lung area.[8] We estimated the SD to be 2 percentage points and considered a 50% reduction in atelectasis size to be clinically significant. With an alpha error of 0.05 and a power of 80%, we calculated that a sample size of 24 subjects would be sufficient. The power calculation was done with atelectasis area as being the sole primary outcome. Areas of different aeration were erroneously preregistered as additional primary outcomes, but were considered secondary outcomes throughout the study.

We did not rely on our data to be normally distributed. For both primary and secondary outcomes, we therefore used the Mann–Whitney U test for comparisons between groups. A two-sided *P* value less than 0.05 was considered significant unless Bonferroni adjustments were made. The CI for the difference in medians was derived by the percentile bootstrap method. The statistical analyses were performed using the IBM SPSS Statistics version 24 software (IBM Corporation, USA) and R version 3.4.2 (https://www.r-project.org; accessed November 2017).

Results

To achieve our sample size of 24 subjects, we assessed for eligibility a total of 105 patients between November 2015 and October 2016 (fig. 1). The two study groups were similar regarding characteristics and baseline physiologic data (table 1). All of the 24 randomized patients received the allocated treatment and were included in the analysis. No patient complications were recorded during the study.

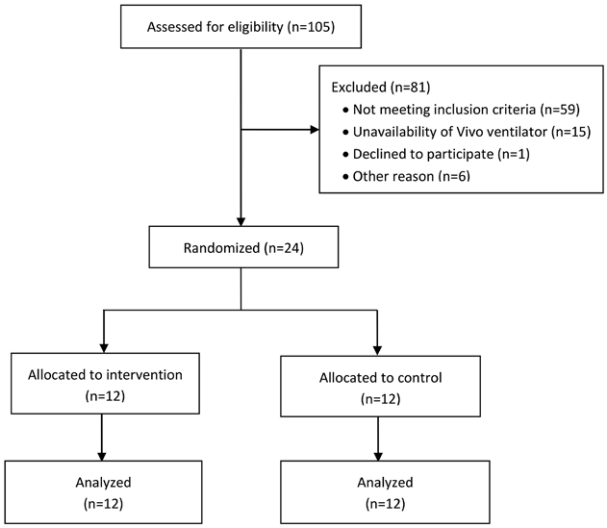

Fig. 1. Consolidated Standards of Reporting Trials diagram of the study. Of the excluded patients, 21 were for logistical reasons. For example, the authors had only one portable ventilator and could therefore only study one patient at a time, although two eligible patients might be simultaneously in different theaters (n = 15). Furthermore, patients scheduled at the end of the operation list (n = 6) could not be included since study participation would jeopardize their discharge on time from the day case unit.

The atelectasis area, calculated as the percentage of the total lung area, had a median (range) of 1.8 (0.3 to 9.9) in the PEEP group and 4.6 (1.0 to 10.2) in the ZEEP group, with a difference in medians of 2.8% (95% CI, 1.7 to 5.7%; $P = 0.002$; figs. 2 and 3). The areas described above expressed in cm^2 had a median (range) value of 4.0 (0.8 to 15.1) in the PEEP group and 9.6 (2.2 to 16.8) in the ZEEP group, with a difference in medians of 5.6 cm^2 (95% CI, 1.5 to 10.2 cm^2; $P = 0.007$).

The PEEP group exhibited smaller areas of poor aeration compared to the ZEEP group, but there was no significant difference between the two groups in over-aerated lung tissue (table 2). The PEEP group maintained the preoperative oxygenation levels until the end of surgery, while the ZEEP group exhibited a decrease in $Pa_{O_2}/F_{I_{O_2}}$ ratio (fig. 4). There was a significant difference between the two groups when comparing the change in oxygenation levels between when the patients were awake and when they were at the end of the surgery ($P = 0.03$; table 3). Furthermore, the ZEEP group demonstrated a lower dynamic compliance than the PEEP group (table 2), as well as higher levels of arterial carbon dioxide partial pressure (Pa_{CO_2}; table 3). There was no difference between the two groups regarding the need for vasoactive drugs to maintain hemodynamic stability.

Table 1. Patient Characteristics and Baseline Data

Characteristic	PEEP Group (n = 12)	ZEEP Group (n = 12)
Male/female, n	6/6	9/3
Age, yr	54 (42–73)	57 (42–73)
BMI, kg/m^2	26 (22–29)	24 (21–28)
IBW, kg	67 (52–83)	72 (53–78)
ASA physical status, I/II	6/6	8/4
Hemoglobin, g/dl	14.1 (11.3–15.7)	13.9 (12.5–16.1)
Type of surgery, n		
Inguinal hernia	6	6
Upper extremity	5	5
Arthroscopy, knee	1	1

Values are numbers or the median (range).

ASA = American Society of Anesthesiologists; BMI = body mass index; IBW = ideal body weight; PEEP = positive end-expiratory pressure; ZEEP = zero positive end-expiratory pressure.

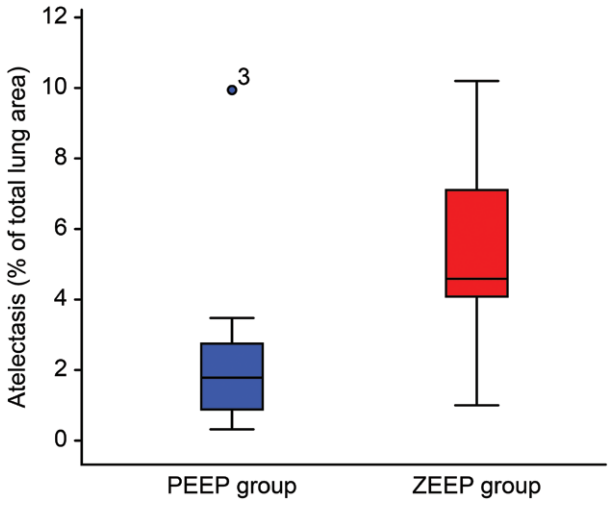

Fig. 2. Atelectasis areas in the positive end-expiratory pressure (PEEP) group and the zero positive end-expiratory pressure (ZEEP) group as expressed by percentages of total lung area. The data are presented as the median, interquartile range (*box*), and range (*whiskers*), except for one observation that was considered an outlier (subject no. 3 in the PEEP group), $P = 0.002$. Computed tomography scans to study atelectasis sizes were performed 5 to 10 mm above the right diaphragm dome at the end of surgery.

Discussion

The main finding in this study was that PEEP, as a single intervention, resulted in minimal atelectasis in healthy lungs during nonabdominal surgery. The group ventilated with a moderate PEEP, exhibited a median atelectasis area of only 1.8% at the end of surgery without the use of recruitment maneuvers. This group also maintained oxygenation during anesthesia. There is reason to believe when the atelectasis is this small, there is a negligible contribution to the risk of postoperative pulmonary complications, especially in a low-risk population such as the one studied here. On the other hand, a ventilation profile combining low tidal volume with ZEEP seemed to promote atelectasis formation as well as impaired oxygenation, reduced carbon dioxide excretion, and decreased pulmonary compliance.

Ventilation

In some previous studies on protective ventilation, it has been difficult to draw conclusions regarding the importance of each individual component (*i.e.*, tidal volume size, PEEP, and recruitment maneuvers). The strength of this study is that we chose to simplify the investigation, comparing only PEEP with ZEEP.

We applied PEEP immediately after intubation, and the early application may have prevented or reduced any atelectasis formation. Definite preventive effects have been shown in previous works after the use of continuous positive airway pressure/PEEP during preoxygenation and induction,[11,12] or after a recruitment maneuver during anesthesia.[13] A preventive effect in our study could thus be explained by assuming that atelectasis is an evolving process from the start of induction, but not yet completed at the time of intubation.[14] Second, a true recruitment effect of PEEP during the anesthesia is also possible. Such a mechanism has previously been observed soon after the application of a PEEP of 10 cm H_2O, unadjusted for weight.[15,16] However, the present study also shows a persisting effect of PEEP for 60 to 120 min during ventilation with low tidal volumes and without additional recruitment maneuvers.

In recent years, there has been an increased interest in driving pressure (defined as plateau airway pressure minus PEEP) as an important variable for predicting negative consequences of mechanical ventilation.[17,18] Unfortunately, the portable ventilator used in this study did not display the plateau pressures necessary for calculating the driving pressure. Instead, we calculated the dynamic compliance, which was distinctively lower in the ZEEP group, $P = 0.001$ (table 2). The fact that application of a moderate PEEP results in better compliance has been previously shown[19,20] and is explained by an increased end-expiratory lung volume that will lift tidal breathing to a more favorable part of the pressure-volume curve. On the other hand, during ventilation with low PEEP or ZEEP, the decreased compliance may be a result of intratidal recruitment/derecruitment of alveoli and thus atelectrauma, as suggested by Mols *et al.*[21] and Wirth *et al.*[22]

Another finding in this study was that the ZEEP group exhibited larger areas of poor aeration, potentially creating regions with low ventilation/perfusion ratios. Altogether, there seem to be several reasons to believe that ZEEP is associated with an unfavorable ventilation profile, especially in combination with low tidal volumes. These physiologic circumstances regarding ventilation patterns might be part of an underlying explanation to the findings by Levin *et al.*,[23] who reported that ventilation with minimal PEEP is associated with increased mortality.

Oxygenation and Analysis of Blood Gases

The PEEP group exhibited maintained oxygenation throughout anesthesia, while the ZEEP group's oxygenation

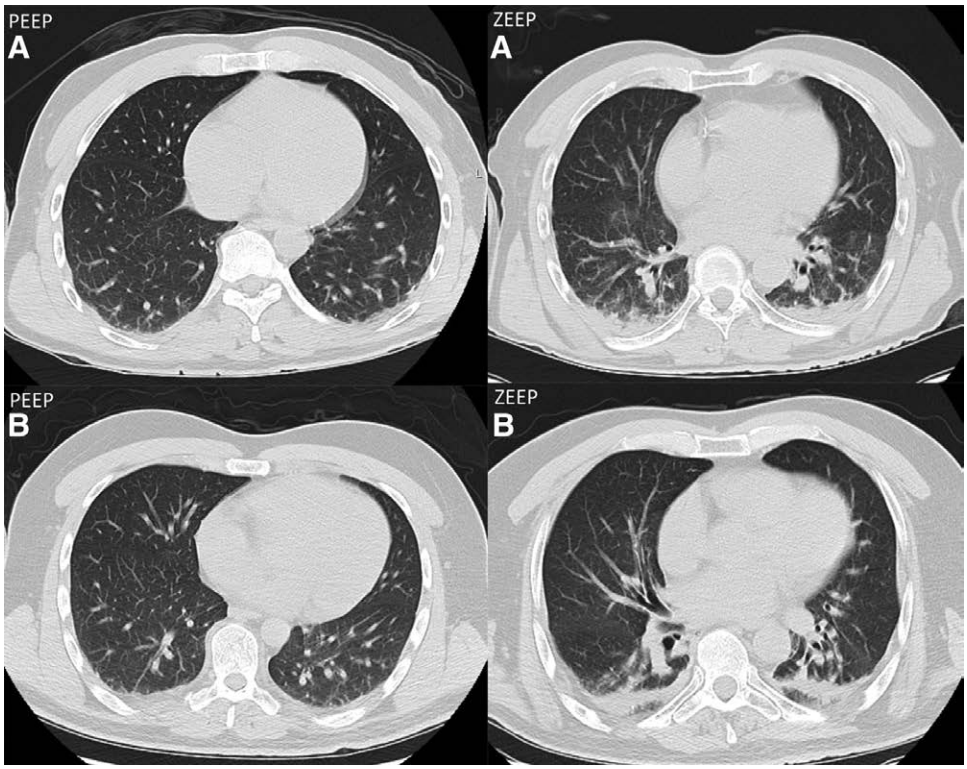

Fig. 3. Examples of computed tomography scans. The images were chosen to illustrate atelectasis areas close to the values of the median (*A*) and the third quartile (*B*) in the two groups, respectively. Positive end-expiratory pressure (PEEP) A: 2.2%; zero positive end-expiratory pressure (ZEEP) A: 4.5%; PEEP B: 2.4%; ZEEP B: 6.4%. All areas are expressed as the percentage of total lung area. The computed tomography scans were obtained at end expiration, 5 to 10 mm above the right diaphragm dome and after completed surgery, before emergence.

Table 2. Ventilatory and Other Data from the Two Study Groups at the End of Surgery

	PEEP Group (n = 12)	ZEEP Group (n = 12)	*P* Value
PEEP			
0 cm $H_2$0, n	0	12	—
7 cm $H_2$0, n	5	0	—
9 cm $H_2$0, n	7	0	—
Tidal volume, ml	470 (380–600)	500 (380–550)	0.71
Tidal volume, ml/kg IBW	7.1 (7.0–7.3)	7.0 (6.9–7.4)	0.35
PIP, cm H_2O	18 (15–22)	13 (10–17)	< 0.001
C_{dyn}, ml/cm $H_2$0	51 (29–71)	34 (26–50)	0.001
Time at CT, min	104 (68–124)	96 (66–114)	0.44
Over-aeration, %	10.4 (2.4–23.1)	4.9 (1.3–23.8)	0.09
Normal aeration, %	76.6 (63.8–86.5)	70.6 (57.7–81.9)	0.22
Poor aeration, %	7.9 (4.5–11.4)	11.9 (5.6–13.9)	0.03*

Values are numbers or the median (range). t_0 = start of preoxygenation. Areas of aeration are expressed as percentage of total lung area.

*The difference in medians was 4.0% (95% CI, –0.6 to 5.6%; *P* = 0.03).

C_{dyn} = dynamic compliance, calculated as tidal volume/(PIP – PEEP); CT = computed tomography; IBW = ideal body weight; PEEP = positive end-expiratory pressure; PIP = peak inspiratory pressure; ZEEP = zero positive end-expiratory pressure.

level deteriorated (fig. 4). For most patients in the ZEEP group, the impairment occurred after the second blood gas sample. The fact that this group still preserved oxygenation levels 40 min after preoxygenation was unexpected, since atelectasis usually begins to develop sooner. Nonetheless, at the time of CT scanning, there was a significant difference between the groups when comparing the change in oxygenation levels from the awake state (table 3).

The elevated levels of $Paco_2$ and $Petco_2$ during anesthesia in the ZEEP group (table 3) occurred despite increased ventilation, thus indicating impaired carbon dioxide excretion in this group. Right-to-left shunting of carbon dioxide due to the greater atelectic and poorly ventilated areas in this group should cause retention of carbon dioxide, as should any increase in alveolar dead space. The contribution by either mechanism cannot be determined from the available data.

Hemodynamics

In a previous study, we observed a possible positive correlation between hypotension and atelectasis formation.[6] We therefore used invasive blood pressure monitoring to gain meticulous control over any hemodynamic changes. Furthermore, the application of PEEP during anesthesia has been associated with an increased need for hemodynamic support, but the PEEP level was higher (12 cm H_2O) and with no individual adjustment.[5] In the present study, PEEP was lower and was adjusted to body mass index. With these precautions, and in our setting with healthy patients undergoing low-risk surgery, we could

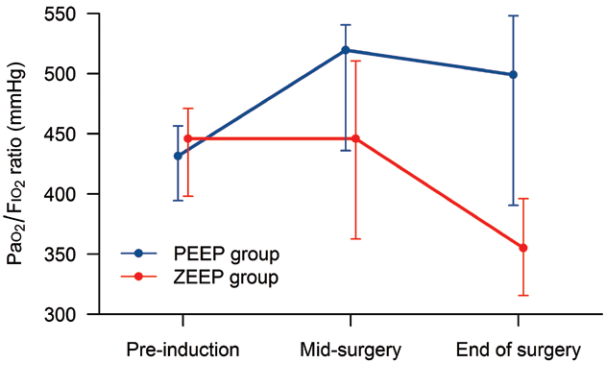

Fig. 4. Changes in median ratio of arterial oxygen partial pressure to inspired oxygen fraction ($Pa_{O_2}/F_{I_{O_2}}$) over time for the positive end-expiratory pressure (PEEP) group and the zero positive end-expiratory pressure (ZEEP) group (P = 0.03 at the end of surgery, Mann–Whitney U test). *Error bars* indicate interquartile range. The blood gas sample at preinduction was taken with all subjects breathing room air. The blood gas samples at midsurgery and at the end of surgery were taken during anesthesia ($F_{I_{O_2}}$ 0.30 to 0.35), 40 min after start of preoxygenation and at the time of computed tomography scanning, respectively.

not see any negative effect on hemodynamics. Accordingly, there was no difference between our study groups regarding the need for vasoactive drugs to maintain blood pressure.

Outliers

One patient in the PEEP group was intubated 1 min later than the mean for the others due to a prolonged induction time. A possible reason for this was a decreased cardiac output related to the combined effects of anesthesia induction and intake of several antihypertensive drugs (including one angiotensin-converting enzyme inhibitor) on the day of surgery. The resulting hypotension might lead to a greater portion of pulmonary blood flow being distributed to more dependent regions of the lungs, thus facilitating the formation of absorption atelectasis in susceptible lung units. The patient later presented with larger atelectasis (9.9%) than any other subject in the PEEP group. Additionally, on the first blood gas, this patient had a low $Pa_{O_2}/F_{I_{O_2}}$ ratio of 360 mmHg, indicating that considerable airway closure and ventilation/perfusion mismatch was occurring already in the preanesthesia awake state. Thorough preoxygenation probably made this patient particularly susceptible to atelectasis formation during the subsequent anesthesia. Although being identified as an outlier, the data from this patient were retained in the final analysis.

On the other hand, one physiologically fit patient in the ZEEP group was nearly free of atelectasis, with an estimated area of only 1.0%. Therefore, these two extremes add

Table 3. Oxygenation and Arterial Carbon Dioxide Levels in the Two Study Groups

	PEEP Group (n = 12)	ZEEP Group (n = 12)	*P* Value
Preinduction			
$F_{I_{O_2}}$	0.21	0.21	—
Pa_{O_2}, mmHg	91 (76–114)	94 (79–104)	—
Pa_{CO_2}, mmHg	38 (34–43)	38 (32–44)	—
$Pa_{O_2}/F_{I_{O_2}}$ ratio, mmHg	432 (360–543)	446 (375–496)	—
Midsurgery			
$F_{I_{O_2}}$	0.32 (0.31–0.34)	0.32 (0.30–0.34)	0.93*
Pa_{O_2}, mmHg	164 (84–186)	143 (81–183)	0.22*
Pa_{CO_2}, mmHg	37 (33–46)	44 (38–51)	< 0.001*
P_{ETCO_2}, mmHg	35 (30–41)	44 (38–50)	< 0.001*
$Pa_{O_2}/F_{I_{O_2}}$ ratio, mmHg	520 (263–568)	446 (238–572)	0.27*
Respiratory frequency, breaths/min	10 (9–11)	12 (10–14)	< 0.001*
Minute ventilation, l/min	4.7 (3.5–5.5)	5.7 (4.5–7.7)	0.014*
End of surgery			
$F_{I_{O_2}}$	0.33 (0.30–0.40)	0.33 (0.30–0.49)	0.63*
Pa_{O_2}, mmHg	160 (79–196)	118 (71–202)	0.16*
Pa_{CO_2}, mmHg	41 (35–46)	48 (41–52)	< 0.001*
P_{ETCO_2}, mmHg	36 (34–43)	44 (38–52)	< 0.001*
$Pa_{O_2}/F_{I_{O_2}}$ ratio, mmHg	500 (239–576)	355 (197–567)	0.06*
Change in $Pa_{O_2}/F_{I_{O_2}}$ ratio during anesthesia, mmHg	+33 (–122 to +119)	–73 (–250 to +60)	0.03†
Respiratory frequency, breaths/min	10 (9–11)	13 (10–14)	< 0.001*
Minute ventilation, l/min	4.7 (3.5–5.5)	5.8 (4.5–7.7)	0.002*
Time between 2nd and 3rd blood gas, min	64 (28–84)	56 (26–74)	0.43

Values are the median (range). The blood gas sample at preinduction was taken with all study subjects breathing room air. The blood gas samples at midsurgery and end of surgery were taken during anesthesia, 40 min after start of preoxygenation and at the time of computed tomography scanning, respectively. One study subject in each group was noted to have a higher than intended $F_{I_{O_2}}$ at end of surgery. P_{ETCO_2} is the dry value displayed by the Vivo ventilator.

*The limit for significance is 0.025 after Bonferroni correction for repeated inferences.†The difference in medians was 106 mmHg (95% CI, 16 to 195 mmHg; P = 0.03).

$F_{I_{O_2}}$ = inspired oxygen fraction; Pa_{O_2} = arterial oxygen partial pressure; Pa_{CO_2} = arterial carbon dioxide partial pressure; $Pa_{O_2}/F_{I_{O_2}}$ ratio = ratio of the arterial oxygen partial pressure to the inspired oxygen fraction; PEEP = positive end-expiratory pressure; P_{ETCO_2} = end-tidal carbon dioxide pressure; ZEEP = zero positive end-expiratory pressure.

to the growing knowledge that we ideally should seek more sophisticated ways to preoperatively identify patients already at risk.[24] Individual patient characteristics, as well as specific events during anesthesia, are important concerns when deciding on the optimal PEEP level and whether or not to use recruitment maneuvers.

Study Limitations

The results of our study with a small sample of healthy patients undergoing low-risk surgery cannot easily be extrapolated to other patient groups or other types of surgery. Although PEEP successfully limited atelectasis in nonabdominal surgery, there certainly are indications for recruitment maneuvers in situations where PEEP alone is unable to prevent or reverse alveolar collapse.

With atelectasis area sizes as small as a few percent of the total lung area, the degree of observer errors when examining the computed tomography scans are likely increased. This is a concern especially when the posterior border of the atelectasis area is outlined manually. To exclude any interobserver error, we used the same radiologist for all calculations.

Another limitation concerns calculating the area of atelectasis in a single basal computed tomography slice. This will underestimate the extent of collapsed lung, since atelectasis has a higher tissue density than aerated lung tissue. It is estimated that the actual area of collapsed lung can be four times greater at the same computed tomography image level.[8]

Our primary endpoint was atelectasis size at the end of surgery. Although avoiding atelectasis intraoperatively is probably beneficial, there is another challenge ahead, which is awakening the patients in a safe manner and delivering them to the recovery unit, ideally with an open lung.

Conclusions

For the majority of healthy patients undergoing nonabdominal surgery, adequate PEEP seems both necessary and sufficient to minimize atelectasis formation and maintain oxygenation. Therefore, we suggest that recruitment maneuvers should only be utilized when there is a clear indication. Our findings are consistent with previous observations that a combination of low tidal volumes and ZEEP is associated with several unfavorable ventilatory consequences and thus should be avoided.

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Competing Interests

The authors declare no competing interests.

Reproducible Science

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