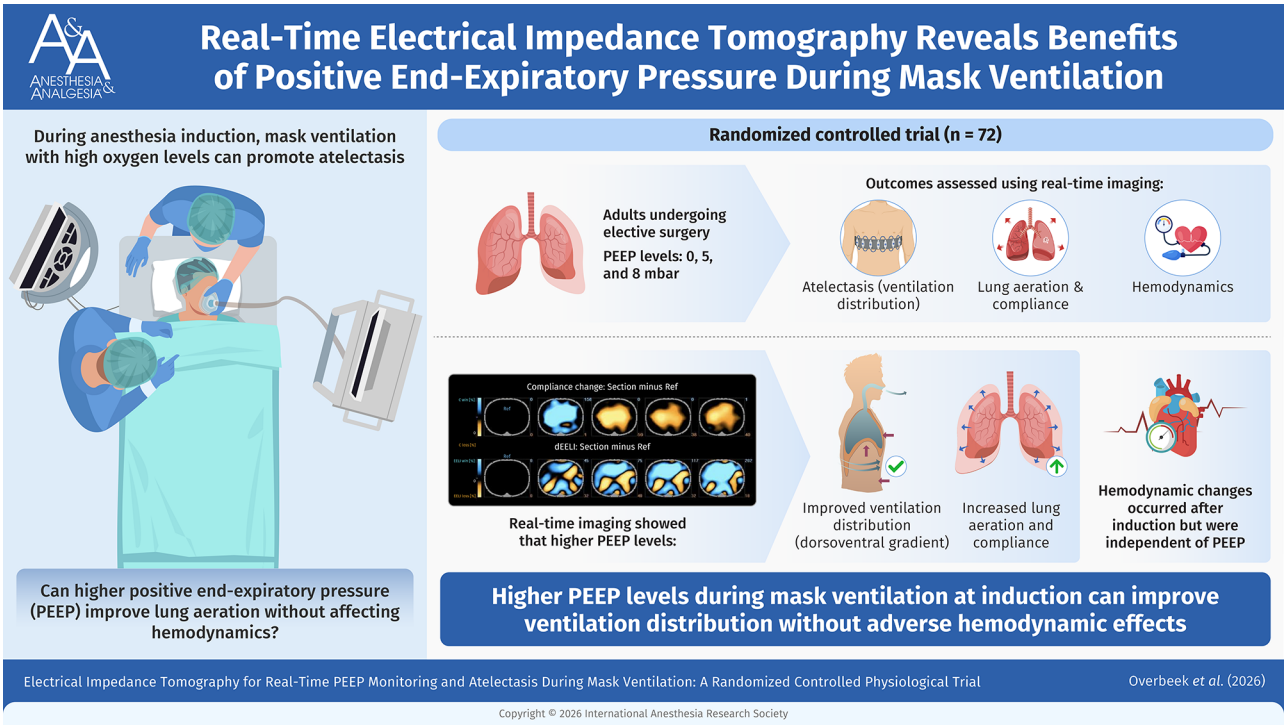
OPEN

ORIGINAL CLINICAL RESEARCH REPORT

Electrical Impedance Tomography for Real-Time PEEP Monitoring and Atelectasis During Mask Ventilation: A Randomized Controlled Physiological Trial

Remco Overbeek,[1] Anna Klug,[1] Lukas Wessendorf,[1] Annika Meyer,[1] Fabian Dusse,[1] Vasilena Sitnilska,[2] Claus Cursiefen,[2] Andrea U. Steinbicker,[1] Inéz Frerichs,[3] Petra Schiller,[4] Silke Freutel,[1] Sandra Emily Stoll[1,5]



BACKGROUND: The combination of high inspired oxygen fraction (FiO_2) and positive-pressure mask ventilation at induction can lead to atelectasis, increasing the risk of perioperative pulmonary complications. Positive end-expiratory pressure (PEEP) may reduce atelectasis, but prior studies relied on imaging performed before or after induction rather than during ongoing ventilation. We used electrical impedance tomography (EIT) as a bedside, real-time imaging tool. We hypothesized that higher PEEP levels would improve end-expiratory lung aeration and homogenize ventilation distribution without clinically relevant hemodynamic compromise.

From the [1]Department of Anaesthesiology and Intensive Care Medicine, Medical Faculty of Cologne University, University Hospital Cologne, University of Cologne, Cologne, Germany; [2]Department of Ophthalmology, Medical Faculty of Cologne University, University Hospital Cologne, University of Cologne, Cologne, Germany; [3]Department of Anaesthesiology and Intensive Care Medicine, University Medical Centre of Schleswig-Holstein Campus Kiel, Kiel, Germany; [4]Medical Faculty of Cologne University, Institute for Medical Statistics and Bioinformatics, University of Cologne, Cologne, Germany; and [5]Department of Anaesthesiology, Montefiore Medical Center, Albert Einstein College of Medicine, Bronx, New York.

Accepted for publication April 8, 2026.

Copyright © 2026 The Author(s). Published by Wolters Kluwer Health, Inc. on behalf of the International Anesthesia Research Society. This is an open-access article distributed under the terms of the Creative Commons Attribution-Non Commercial-No Derivatives License 4.0 (CCBY-NC-ND), where it is permissible to download and share the work provided it is properly cited. The work cannot be changed in any way or used commercially without permission from the journal.

DOI: 10.1213/ANE.0000000000008165

Funding: None of the authors have a conflict of interest or received funding regarding this study.

Conflicts of Interest, Funding: Please see DISCLOSURES at the end of this article.

Declaration of interests: None.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's website (www.anesthesia-analgesia.org).

Trial Registration: German Clinical Trials Register/DRKS/DRKS00033334, January 17th, 2024, by Sandra Emily Stoll.

Approved by the ethics committee of the Medical Faculty of the University of Cologne (IRB 23-1133).

Availability of data and materials: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Reprints will not be available from the authors.

Corresponding Author: Remco Overbeek, Email: remco.overbeek@uk-koeln.de, Department of Anaesthesiology and Intensive Care Medicine, Medical Faculty of Cologne University, Kerpener Straße 62, Cologne 50937, Germany.

METHODS: In this prospective, randomized controlled study, 72 adult patients undergoing elective ophthalmic surgery under general anesthesia were enrolled. The effect of three different PEEP levels (0, 5 and 8 mbar) on the distribution of lung ventilation and hemodynamic parameters during mask ventilation at anesthesia induction with 100% (FiO_2) were evaluated. Patients were randomized to ascending or descending PEEP sequences to control for order effects. The primary endpoint was the occurrence and the degree of atelectasis represented by the dorsoventral ventilation gradient at each PEEP level as detected by EIT. Secondary endpoints were changes in end-expiratory lung impedance (EELI) (ratio of EELI gain to EELI loss) and changes in lung compliance (ratio of compliance gain to compliance loss) as surrogate markers for atelectasis formation. Hemodynamic parameters were monitored with noninvasive blood pressure, electrocardiography, and electrical cardiometry.

RESULTS: EIT was able to show in real-time that higher PEEP levels significantly improved the mean [SD] dorsoventral ventilation gradient (0.48 [0.21] at 0 mbar vs 0.56 [0.28] at 5 mbar vs 0.63 [0.25] at 8 mbar; p<.001), increased the ratio of gain/loss of the end-expiratory lung impedance of the whole lung (3.1 [4.8] at 0 mbar vs 6.1 [8.1] at 5 mbar (~5.1 cmH20) vs 10.5 [12.2] at 8 mbar (~8.2 cmH20); p<.001) and increased the compliance gain/loss ratio of the whole lung (2.7 [9.2] at 0 mbar vs 3.8 [10.3] at 5 mbar vs 4.3 [11.3] at 8 mbar; p=.011), independent of the sequence of PEEP (all data dimensionless). Electrical cardiometry revealed that hemodynamic parameters decreased after induction, but these changes were not associated with specific PEEP levels.

CONCLUSIONS: Using real-time bedside EIT our study demonstrates that higher PEEP levels during mask ventilation at anesthesia induction can improve ventilation distribution without adverse hemodynamic effects. (Anesth Analg 2026;XXX:00–00)

KEY POINTS

- **Question:** During anesthesia induction, do higher PEEP levels improve end-expiratory lung aeration and homogenize ventilation distribution (represented by dorsoventral gradient) without clinically relevant hemodynamic compromise?
- **Findings:** In 72 adults, higher PEEP levels (0, 5, 8 mbar) progressively improved the dorsoventral ventilation gradient and EIT-derived surrogates (↑ compliance gain/loss; ↑ EELI gain/loss) without PEEP-specific hemodynamic compromise.
- **Meaning:** Modest PEEP during mask ventilation improves ventilation distribution at induction, detectable by bedside EIT.

The combination of a high inspiratory oxygen fraction (FiO_2) and positive-pressure ventilation during induction and facemask ventilation can promote atelectasis formation.[1] Atelectasis occurs in 75-90% of general anesthesia cases and is associated with perioperative pulmonary complications such as pneumonia or respiratory insufficiency due to hypoxemia.[2,3] Despite the risk of absorption atelectasis, adequate preoxygenation with a high FiO_2 remains appropriate.[4] Several studies have shown that applying positive end-expiratory pressure (PEEP) during mask ventilation can prolong non-hypoxic apnea time and may reduce atelectasis formation, as assessed by studies using computed tomography (CT) or lung ultrasound. These studies are few in number though, performed in selected populations, and rely on imaging before or after induction rather than during ongoing ventilation.[5–8]

In routine clinical practice, mask ventilation is monitored only indirectly through tidal volume, peak pressure, and oxygen saturation. These parameters do not provide real-time information about regional ventilation distribution or the early development of atelectasis. Electrical impedance tomography (EIT) is a radiation-free functional imaging modality that allows an easy, bedside monitoring of the distribution of lung ventilation.[9,10] EIT has proven to be a reliable tool for detecting atelectasis, with findings consistent with CT scans.[11]

While increased PEEP levels may improve pulmonary function, positive-pressure ventilation with high PEEP levels raises intrathoracic pressure, and consequently limits venous blood return and reduces cardiac output.[12] Similar to EIT, Electrical Cardiometry™ (ICON by Osypka Medical) is a new noninvasive method to assess cardiac output.[13] Using four skin electrodes, it measures alterations in thoracic electrical bioimpedance due to changes in blood velocity during the cardiac cycle, and allows real-time calculation of parameters such as stroke volume, heart rate, and cardiac output.[14] Combining EIT and electrical cardiometry provides a unique opportunity to simultaneously assess pulmonary and hemodynamic effects of PEEP in real time during mask ventilation at anesthesia induction.

This study therefore aims to determine whether increased PEEP levels can reduce atelectasis formation, as indicated by an increased dorsoventral gradient,

changes in end-expiratory lung impedance (EELI), and changes in lung compliance during mask ventilation after the induction of general anesthesia, all assessed in real time by EIT. In addition, this trial evaluates the hemodynamic effects of this approach using noninvasive electrical cardiometry. We hypothesized that higher PEEP levels would improve end-expiratory lung aeration and homogenize ventilation distribution (represented by dorsoventral gradient) without clinically relevant hemodynamic compromise.

METHODS

This prospective, randomized, interventional study is part of the PreOxygenEIT trial and included all adult patients (≥18 years) undergoing elective ophthalmic surgery with the requirement of general anesthesia at the Department of Anesthesiology and Intensive Care Medicine at the University Hospital of Cologne, Germany. The PreOxygenEIT trial investigates whether preoxygenation can be improved using real-time feedback (via EIT), and how varying levels of PEEP during mask ventilation influence EIT derived parameters as markers for atelectasis. In the current manuscript, the research question of how varying levels of PEEP during mask ventilation influence the formation of atelectasis, will be tackled. Patients of the ophthalmologic department were chosen, as the anesthesia induction is standardized and the population of comparable range and comparable morbidity grades. The study was registered prospectively with the German Clinical Trials Register on January 17th, 2024, prior to patient enrollment (Deutsches Register Klinischer Studien/DRKS/DRKS00033334). The study followed the Declaration of Helsinki and was approved by the local ethics committee (IRB 23-1133). All patients included in this study gave written, informed consent before study inclusion. The manuscript adheres to the applicable CONSORT guidelines.

Eligibility Criteria

Adult patients aged 18 years or older scheduled for elective ophthalmic surgery requiring general anesthesia were eligible for inclusion. All patients received standardized study information and provided written informed consent prior to study enrollment. Patients were excluded if they were at increased risk of aspiration necessitating rapid sequence induction, had an anticipated difficult airway requiring awake fiberoptic intubation or immediate neuromuscular blockade, or were pregnant. Exclusion also applied when EIT monitoring was not feasible, including cases of immobilization that prevented proper belt placement (such as unstable spinal, rib, sternal, or pelvic fractures), the presence of transvenous or subcutaneous pacemakers, implantable cardioverter defibrillators, or other electronic cardiac devices potentially affected by EIT, or relevant skin lesions, drains, or catheters at the intended belt position. In addition, patients who were already intubated, under neuromuscular blockade or required neuromuscular blockade to facilitate mask ventilation or rapid intubation, or in whom facemask ventilation was deemed inadequate by the attending consultant anesthesiologist were excluded from the study.

Randomization

Patients were randomly assigned (sealed envelopes) to two treatment groups of mask ventilation during induction of general anesthesia: A) Mask ventilation with incremental PEEP values of 0, 5 and 8 mbar (1 mbar ≈ 1.02 cmH_2O) (iPEEP) or B) Mask ventilation with decremental PEEP values of 8, 5 and 0 mbar (dPEEP). Blinding of clinicians was not feasible.

EIT monitoring

EIT measurements were performed using the PulmoVista500 EIT device (Dräger Medical GmbH, Lübeck, Germany). The 16-electrode belt was placed between the 4th and 5th intercostal space and the position of the belt was maintained during all study measurements. Ventilator data were continuously recorded by the EIT device through a serial interface from the ventilator.

Primary endpoint. The primary endpoint of the study is the occurrence and the degree of atelectasis. This endpoint was assessed with surrogate markers measured with EIT at three different PEEP levels. Primary surrogate marker was the ventilation distribution in the four lung regions of interest and the resulting dorsoventral gradient (dimensionless) of the ventilation distribution.

Secondary endpoints. Changes in EELI compared to baseline (the ratio of EELI gain to EELI loss) and changes in lung compliance compared to baseline (the ratio of compliance gain to compliance loss) were also assessed as indirect markers of atelectasis formation at three different PEEP levels (all data dimensionless). Additionally, the regional ventilation delay (%) was assessed.

Hemodynamic monitoring

Assessed hemodynamic parameters included noninvasive blood pressure (mmHg) and ECG-monitoring (3 electrodes) as well as electrical cardiometry (ICON® by Osypka Medical). For electrical cardiometry, two electrodes were placed on the left base of the neck and two on the left inferior side of the thorax at the level of the xiphoid process. The interelectrode gap of the lower electrodes was at least 15

cm to enable best possible accuracy.[15] Electrode positioning was not changed during measurement and did not interfere with the EIT of the lung. Assessed parameters by the electrical cardiometry were cardiac index (l/min/m^2), stroke volume (ml) and stroke volume variation (%) at three different PEEP levels.

Pulmonary monitoring

In addition to the EIT data we measured peak inspiratory pressure (mbar) and oxygen saturation (SpO_2) in % at each phase during the induction period. End-tidal CO_2 (capnometry) was continuously measured.

Study procedure

After study inclusion and randomization, patients were placed on the operating room table in supine position with the head in neutral position and an elevated upper body. Table elevation was standardized to 20° by automated OR table settings as per protocol of the surgical team. Standard monitors for general anesthesia were applied, including ECG, noninvasive blood pressure measurement, pulse oximetry, and capnography. Electrical cardiometry and EIT were established. Next, the patients included in the study were monitored at room air for 2 minutes to assess their baseline breathing (baseline monitoring), followed by preoxygenation. Preoxygenation via a sealed plastic mask was carried out with a flow rate of 10 L/min of 100% O_2 for three minutes regardless of patients' end-tidal O_2 (EtO_2) levels at the end of preoxygenation for standardization of the preoxygenation process. After preoxygenation, patients were randomized to receive either iPEEP or dPEEP levels during mask ventilation. Induction of general anesthesia was achieved by an intravenous bolus injection of propofol (2–3 mg/kg) and a remifentanil infusion (0.3 µg/kg/min). A standardized norepinephrine infusion was applied at 0.03 µg/kg/min to avoid induction-associated hypotension. Mask ventilation was performed by the anesthesiologist using either the two-handed C-E grip (The thumbs and index fingers of both hands form a "C" shape on each side of the mask) or the V-E grip (The thumbs form a "V" shape over the mask). All patients received volume-controlled ventilation (6 mL/kg predicted body weight) with a respiratory rate of 12 breaths per minute and an inspiratory-to-expiratory ratio of 1:2, administered via the Leon ventilator (Löwenstein Medical SE & Co. KG, Bad Ems). Patients were ventilated with each PEEP level for two minutes, measurements were taken at the end of each cycle. PEEP levels were set and recorded in mbar as displayed by the ventilator device (1 mbar ≈ 1.02 cmH_2O). During this procedure, the EIT monitoring was visible to the anesthetist. The patient was ventilated by an anesthesia registrar, but a senior consultant was always present and assisted in cases of difficult mask ventilation. Mask leak was continuously monitored using the ventilator's displayed leak fraction. A leak of up to 20% was tolerated, provided that stable capnography, consistent tidal volumes, and reproducible peak inspiratory pressures were maintained. The decision regarding adequacy of mask ventilation and acceptance of leak within this threshold was made by the attending consultant anesthesiologist. If the leak exceeded this threshold or adequate ventilation could not be ensured despite mask repositioning, the patient was excluded from further study measurements. Moreover, patients were excluded from the study if muscle paralysis was required to promote mask ventilation or to facilitate rapid intubation. Once the electrical cardiometry and EIT monitoring were completed at the three different PEEP levels, routine care was applied including the placement of a supraglottic airway or an endotracheal tube.

The data analysis was performed with a pseudonymized dataset by investigators who were not involved in the clinical management.

Sample size

Analysis of the PEEP effect during preoperative mask ventilation shows large differences in atelectasis development, with highly heterogeneous effect sizes, ranging from d=0.22 to d=2.47 when measured by CT scans or lung ultrasonography.[6,8,16] The influence on lung impedance as a sign of atelectasis formation measured via EIT has not yet been evaluated. We assume that the effect size will be lower, but still clinically relevant, and consider a small to medium effect size of f=0.16 to be both relevant and realistic. Assuming an alpha error of 5% and a statistical power of 80%, detecting an effect size of 0.16 requires a sample size of 72 participants (calculated using G*Power, ANOVA with repeated measures, 3 measurements). Accounting for a 5% dropout rate due to mask ventilation difficulties,[17] we initially aimed to include 76 patients in our study.

Statistics

The measured data were entered into an Excel spreadsheet and coded in a pseudonymized form for analysis. Statistical analyses were performed using IBM SPSS Statistics for Mac, Version 27.0 (IBM Corp., Armonk, NY, USA) and the R programming language.[18] The primary analyses were performed in the per-protocol (EIT-evaluable) population, defined as patients with successful facemask ventilation and adequate EIT/ICON signal quality. Excluded patients were included in the description of baseline characteristics and participant flow but were excluded from analyses of EIT-based and

hemodynamic endpoints because outcome data were not available. Baseline characteristics are presented as mean (SD) for continuous variables and as number (%) for categorical variables. Group balance was assessed using standardized differences. For repeated measures, a one-way repeated measures analysis of variance (ANOVA) was conducted. A mixed-design ANOVA was conducted to assess the effects of PEEP level or time (three levels; within-subjects factor) and group (iPEEP vs. dPEEP sequence; between-subjects factor) to rule out potential group effects and interactions. The assumption of sphericity in the repeated measures ANOVA was assessed with Mauchly's test. Where violations occurred, the Greenhouse–Geisser and Huynh–Feldt corrections were applied to adjust the degrees of freedom, and the corrected F-values and significance levels are reported. Pairwise post hoc comparisons between individual PEEP levels were performed with Bonferroni correction for multiple testing, and adjusted p-values are reported. All statistical tests were two-sided, and a p-value <.05 was considered statistically significant.

RESULTS

Between July 2024 and December 2024, 79 patients scheduled for surgery under general anesthesia were assessed for participation in the trial. 76 adult patients fulfilled the inclusion criteria and were included in this study. Patient flow through the trial is shown in Figure 1. Three patients had to be excluded after study inclusion due to insufficient facemask ventilation and one patient due to poor signal quality in the ICON cardiometry, leaving 72 patients for the final analysis.

Demographics

Of the 76 included patients, 39 patients were female. The mean (SD) age was 60 (14) years, and the mean (SD) BMI was 26.4 (4.6) kg/m^2. Baseline characteristics are shown in Table 1. Several variables exhibited standardized differences greater than 0.1, reflecting expected random imbalances given the modest sample size.

Pulmonary parameters

No adverse effects related to EIT were observed during the analysis, and all patients tolerated the belt application well. Figure 2 shows a representative example of an EIT measurement of a patient from the iPEEP group, as recorded by the PulmoVista500 following an analysis of the different sections during induction.

Dorsoventral ventilation gradient

Results of the ANOVA indicated a significant effect of the PEEP level on the dorsoventral ventilation gradient in the iPEEP ($F(1.67, 58.43)= 11.1$, $p<.001$, $\eta^2_p=0.403$)

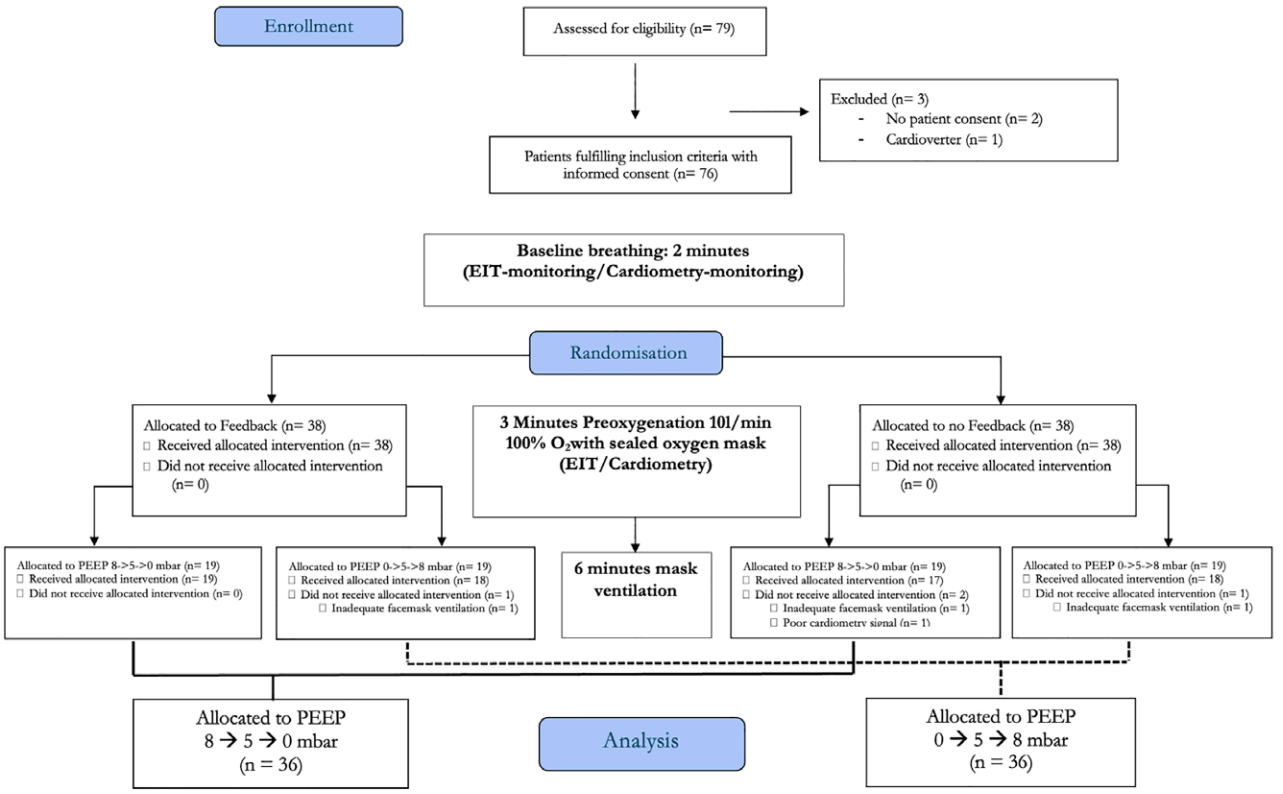


Figure 1. CONsolidated Standards of Reporting Trials Flow Diagram.

Table 1. Patients characteristics and overall demographics in the decremental PEEP group (dPEEP) and the incremental PEEP group (iPEEP).

Characteristic	Overall N = 76[1]	iPEEP N = 38[1]	dPEEP N = 38[1]	Standardized Difference
Age (years)	59.8 (13.9)	59.1 (12.4)	60.5 (15.2)	-0.10
Height (m)	1.71 (0.11)	1.72 (0.10)	1.69 (0.11)	0.27
Weight (kg)	76.8 (17.0)	77.9 (14.2)	75.6 (19.2)	0.14
BMI (kg/m^2)	26.4 (4.6)	26.25 (3.89)	26.45 (5.15)	-0.04
Male	34 (45%)	21 (55%)	13 (34%)	0.43
ASA-Score				
1	14 (18%)	10 (26%)	4 (11%)	0.42
2	53 (70%)	25 (66%)	28 (74%)	0.18
3	9 (12%)	3 (8%)	6 (16%)	-0.25
Diabetes Mellitus	7 (9.2%)	5 (13%)	2 (5.3%)	0.28
IDDM	3 (3.9%)	1 (2.6%)	2 (5.3%)	-0.14
Obesity	17 (22%)	8 (21%)	9 (24%)	-0.06
Arterial Hypertension	24 (31.6%)	11 (29%)	13 (34%)	-0.11
Cardiovascular Disease	11 (14.5%)	4 (11%)	7 (18%)	-0.23
Cardiac Dysrhythmia	4 (5.3%)	1 (2.6%)	3 (7.9%)	-0.24
Renal Insufficiency	1 (1.3%)	1 (2.6%)	0 (0%)	0.23
Pulmonary Comorbidity	6 (7.9%)	1 (2.6%)	5 (13%)	-0.40
COPD	2 (2.6%)	0 (0%)	2 (5.3%)	-0.33
History of Smoking	18 (23.7%)	12 (32%)	6 (16%)	0.38
Alcoholism	14 (18.4%)	8 (21%)	6 (16%)	0.14
Malignancy/Hematooncologic Comorbidity	1 (1.3%)	0 (0%)	1 (2.6%)	-0.23

ASA: American Society of Anesthesiologists, BMI: Body mass index, COPD: Chronic obstructive pulmonary disease IDDM: Insulin dependent Diabetes Mellitus, PEEP: positive end-expiratory pressure. Numbers (N) are patients included per group, the unit (in brackets) is the number without brackets in the columns, and the numbers in brackets are the percentage of patients of this group compared to all patients, either overall, iPEEP, or dPEEP (increasing or decreasing positive end-expiratory pressure). Standardized differences are shown for between-group comparisons.

[1]Mean and standard deviation or frequency (%)

and the dPEEP ($F(1.69, 59.28)= 11.1$, $p<.001$, $\eta^2_p=0.24$) group, as well as the patients overall ($F(1.68, 117.35)= 31.1$, $p <.001$, $\eta^2_p=0.308$). Higher PEEP levels were associated with an increased dorsoventral gradient. Post-hoc Bonferroni corrected pairwise comparisons of the dorsoventral gradient showed that pairwise differences between each PEEP level were significant in both PEEP groups except for PEEP 8 mbar versus PEEP 5 mbar in the dPEEP group ($p=.059$) (see Figure 3 and supplementary Table S1, https://links.lww.com/AA/F831).

The compliance gain/loss ratio

The compliance gain/loss ratio increased with higher PEEP levels in both groups. Overall, there

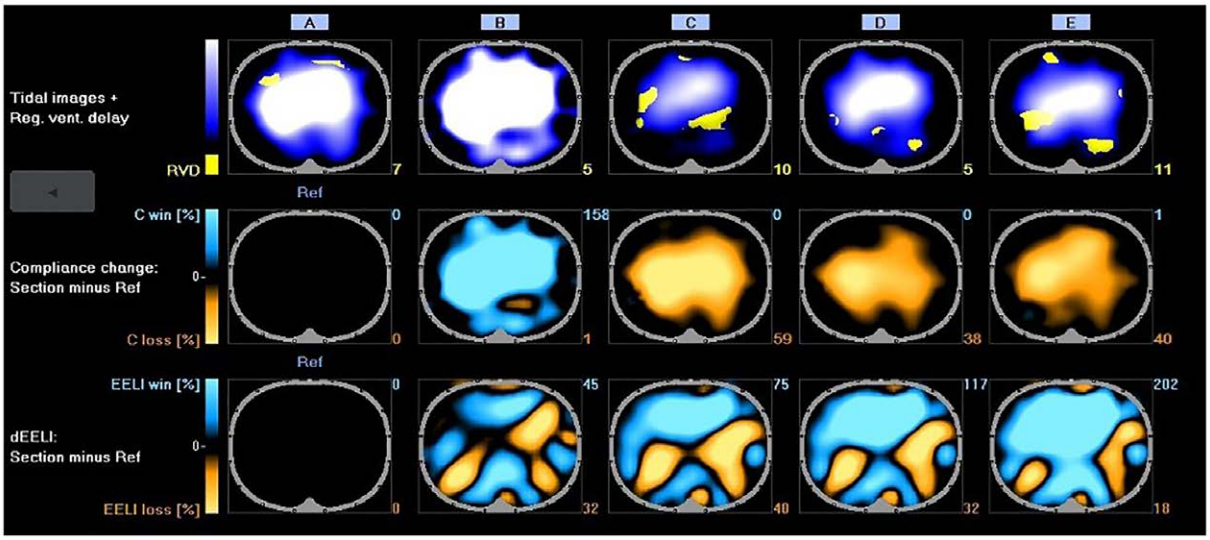


Figure 2. Example of EIT monitoring in a representative patient during baseline (A), preoxygenation (B), and mask ventilation with PEEP 0 mbar (C), 5 mbar (D), and 8 mbar (E). The first row shows the regional ventilation delay (RVD), the second row shows regional compliance changes, displayed as compliance gain (Cwin) or compliance loss (Closs), indicating areas that become more or less compliant compared with baseline. The third row presents changes in end-expiratory lung impedance (EELI), reflecting relative increases or decreases in end-expiratory aeration compared with baseline. Color coding indicates regional changes in compliance or EELI, with loss shown in orange to yellow and gain shown in white to blue. PEEP: positive end-expiratory pressure.

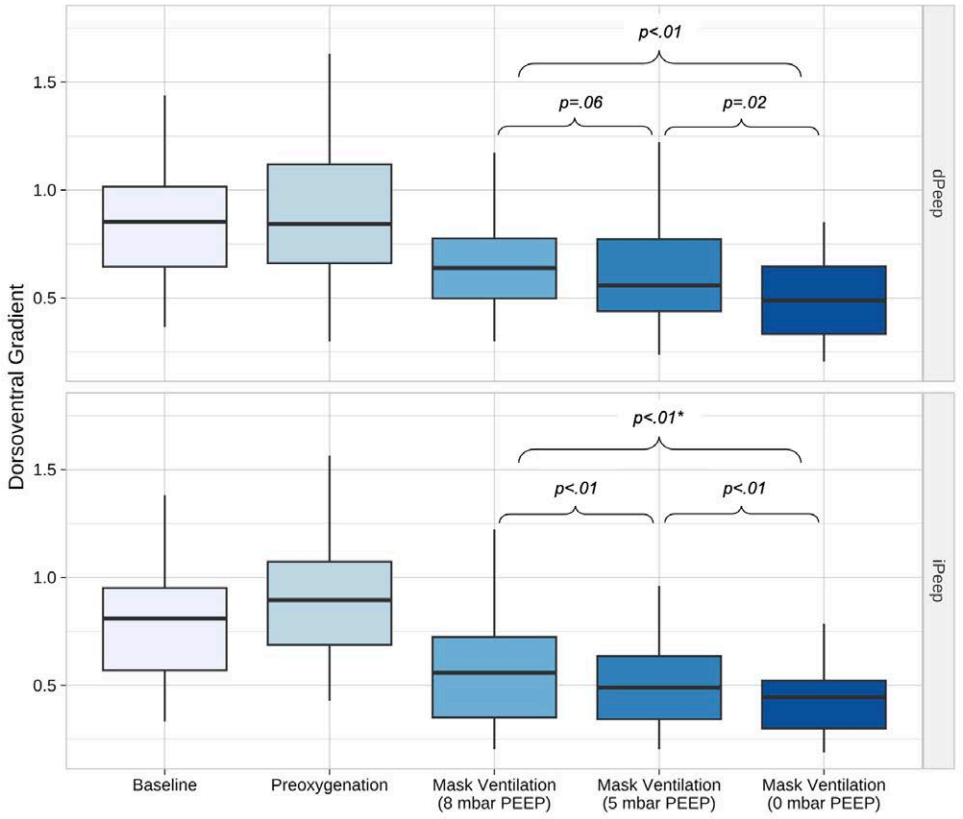


Figure 3. Dorsoventral gradient in EIT monitoring in the incremental PEEP group (iPEEP) and decremental PEEP group (dPEEP) (baseline, preoxygenation and mask ventilation with PEEP 0, 5 and 8 mbar). *p-value for post-hoc Bonferroni corrected pairwise comparisons of repeated measures ANOVA analysis. PEEP: positive end-expiratory pressure.

was a significant effect of PEEP level on the compliance gain/loss ratio ($F(1.67, 116.85) = 5.14$, $p=.011$, $\eta^2_p=0.068$) (see Table 2).

End-expiratory lung impedance gain/loss ratio

The EELI gain/loss ratio as a marker for the increase in end-expiratory lung volume increased with higher PEEP levels in both groups as well as overall ($F(1.14, 39.95) = 16.36$, $p<.001$, $\eta^2_p=0.32$) (see Table 2).

Regional ventilation delay

Moreover, higher PEEP levels did not reduce the regional ventilation delay, a marker for heterogeneous ventilation distribution ($F(1.77, 123.64) = 0.73$, $p=.467$, $\eta^2_p=0.01$) (see Table 2).

Peak inspiratory pressure and oxygen saturation

Peak inspiratory airway pressure was higher with increased PEEP in both groups as well as overall ($F(1.82, 127.23) = 84.21$, $p<.001$, $\eta^2_p= 0.546$) (Table 2). Oxygen saturation did not differ between PEEP levels.

Comparison of pulmonary parameters in the incremental vs. decremental PEEP group

No significant interaction between PEEP level and group was found among pulmonary parameters, indicating that the response pattern did not differ between the incremental and decremental groups. The between-subjects effect of group was also not significant (see supplementary Table S2, https://links.lww.com/AA/F831).

Hemodynamic parameters

Cardiac index, mean arterial pressure, heart rate, stroke volume, and stroke volume variation decreased over time in both groups during anesthesia induction (see Table 3).

A mixed-design ANOVA for the three timepoints during mask ventilation revealed a significant main effect of time on all hemodynamic parameters while there was no interaction between time and group (incremental vs. decremental). Likewise, no between-subjects effect of group was found for any variable, indicating that average values across time points were similar between the groups regardless of PEEP level applied (see supplementary Table S3, https://links.lww.com/AA/F831).

DISCUSSION

Previous studies using CT scans have demonstrated that PEEP application during general anesthesia minimizes atelectasis formation and increases functional residual capacity and intrapulmonary oxygen stores.[19] Higher PEEP levels at induction have been shown to prolong non-hypoxic apnea time in both infants and adults.[6,7,20]

Table 2. Pulmonary parameters during mask ventilation in the decremental PEEP group (dPEEP) and the incremental PEEP group (iPEEP) and overall.

	iPEEP N=36[1]	p-value[2]	dPEEP N=36[1]	p-value[2]	Overall N=72[1]	p-value[2]
EELI gain/loss						
0mbar	2.5 (4.0)	<0.001	3.7 (5.5)	<0.001	3.1 (4.8)	<.001
5mbar	7.7 (9.6)		4.5 (5.9)		6.1 (8.1)	
8mbar	12.4 (14.5)		8.6 (9.2)		10.5 (12.2)	
C gain/loss						
0mbar	2.7 (10.8)	.178	2.8 (7.3)	.062	2.7 (9.2)	.011
5mbar	3.4 (10.0)		4.2 (10.6)		3.8 (10.3)	
8mbar	3.9 (12.6)		4.7 (10.0)		4.3 (11.3)	
RVD (%)						
0mbar	6.3 (6.7)	.819	5.4 (4.1)	.237	5.8 (5.5)	.467
5mbar	5.7 (7.1)		6.1 (7.2)		5.9 (7.1)	
8mbar	5.5 (3.9)		4.5 (3.4)		5.0 (3.7)	
P-peak (mbar)						
0mbar	13.6 (2.7)	<.001	13.0 (3.0)	<.001	13.3 (2.8)	<.001
5mbar	15.0 (2.5)		14.9 (3.0)		15.0 (2.8)	
8mbar	16.8 (1.6)		17.2 (3.1)		17.0 (2.5)	
SpO_2 (%)						
0mbar	99.78 (0.96)	.401	99.97 (0.17)	1.00	99.9 (0.7)	.428
5mbar	99.79 (1.0)		99.97 (0.17)		99.9 (0.7)	
8mbar	99.89 (0.4)		99.97 (0.17)		99.9 (0.3)	
Dorsoventral gradient						
0mbar	0.44 (0.17)	<.001	0.53 (0.24)	<.001	0.48 (0.21)	<.001
5mbar	0.52 (0.24)		0.59 (0.24)		0.56 (0.28)	
8mbar	0.60 (0.27)		0.67 (0.23)		0.63 (0.25)	

[1] Mean and standard deviation

[2]One-way repeated measures analysis of variance (Greenhouse–Geisser/Huynh–Feldt corrections if applicable).

1 mbar ≈ 1.02 cmH_2O

C: compliance, EELI: end-expiratory lung impedance, PEEP: positive end-expiratory pressure, p-peak: peak inspiratory pressure, RVD: regional ventilation delay, SpO_2: oxygen saturation.

Rusca et al. used CT imaging before anesthesia induction and after intubation, showing that patients ventilated without PEEP had a marked increase in atelectasis, while those with 6 cmH_2O PEEP showed no significant change in ventilation distribution.[16] Similarly, Coussa et al. found that applying 10 cmH_2O PEEP during mask ventilation in obese patients prevented atelectasis compared to no PEEP.[8] Kim et al. used lung ultrasound in infants after anesthesia induction. Mask ventilation with PEEP reduced atelectasis scores, though not significantly in children over six months.[6]

Electrical impedance tomography does not directly visualize radiographic atelectasis but provides functional information on regional ventilation distribution and changes in end-expiratory lung impedance as surrogate markers of lung aeration. Previous studies have demonstrated that changes in EIT-derived end-expiratory lung impedance and ventilation distribution correlate with for example CT-based measures of lung aeration, supporting their use as functional surrogates for atelectasis development.[21–24] In our study, higher PEEP levels resulted in an increased dorsoventral gradient, an increased compliance gain/loss ratio, and an improved EELI gain/loss ratio, reflecting a better distribution of lung ventilation and, therefore, an indication for less atelectasis.

The observed improvements suggest that early reduction of atelectasis is physiologically achievable already during induction. These effects may help preserve oxygen reserves and peri-induction pulmonary stability during airway management. Perioperative atelectasis has been consistently associated with clinically relevant adverse outcomes, including postoperative hypoxemia, pneumonia, respiratory failure, and prolonged hospital stay.[2,3,25] Although no universally accepted clinical thresholds exist for EIT-derived parameters, these indices reflect core physiological mechanisms underlying peri-induction atelectasis, including loss of end-expiratory aeration, dependent derecruitment, and increased ventilation heterogeneity. The improvements observed with higher PEEP levels therefore represent physiologically favorable changes providing a strong physiological rationale for integrating modest PEEP into routine peri-induction mask ventilation. However, the present study was not designed to determine whether these differences translate into reductions in postoperative pulmonary complications.

During surgical procedures, protective mechanical ventilation with higher PEEP levels has already been shown to improve postoperative pulmonary function and clinical outcomes.[25,26] Nevertheless, the optimal PEEP level for this improvement remains controversial.[27,28] High PEEP levels and inspiratory pressures exceeding 15-20 mbar in facemask ventilation are associated with the risk of gastric insufflation,

Table 3. Hemodynamic parameters during mask ventilation in the decremental PEEP group (dPEEP), the incremental PEEP group (iPEEP) and overall.

	iPEEP N=36[1]	p-value[2]	dPEEP N=36[1]	p-value[2]	Overall N=72[1]	p-value[2]
CI (l/min/m²)						
Baseline	3.0 (0.7)	<0.01	3.1 (0.9)	<.001	3.0 (0.8)	<.001
Preoxygenation	3.2 (0.7)		3.2 (0.9)		3.2 (0.8)	
0mbar	2.5 (0.5)		2.2 (1.0)		2.3 (0.8)	
5mbar	2.2 (0.5)		2.3 (1.0)		2.3 (0.8)	
8mbar	2.1 (0.5)		2.7 (1.0)		2.4 (0.8)	
SV (ml)						
Baseline	75.7 (15.1)	<.001	72.3 (14.9)	<.001	74.0 (15.0)	<.001
Preoxygenation	78.0 (15.7)		74.6 (14.9)		76.3 (15.3)	
0mbar	70.4 (14.6)		62.1 (13.7)		66.3 (14.6)	
5mbar	65.3 (12.1)		62.5 (12.9)		63.9 (12.5)	
8mbar	63.6 (10.7)		65.3 (13.4)		64.4 (12.1)	
SVV (%)						
Baseline	15.3 (13.1)	<.001	15.3 (6.3)	.047	15.3 (6.1)	<.001
Preoxygenation	13.1 (6.2)		14.9 (8.9)		14.0 (7.7)	
0mbar	12.7 (5.3)		11.7 (7.4)		12.2 (6.4)	
5mbar	10.8 (5.4)		12.3 (7.3)		11.6 (6.5)	
8mbar	11.2 (4.9)		13.8 (9.7)		12.5 (7.8)	
MAP (mmHg)						
Baseline	103.2 (13.6)	<.001	97.0 (10.0)	<.001	100.1 (12.4)	<.001
Preoxygenation	101.6 (14.2)		97.2 (10.2)		99.4 (12.5)	
0mbar	90.1 (17.2)		73.9 (13.2)		82.0 (17.3)	
5mbar	77.0 (16.3)		71.3 (15.5)		74.2 (16.1)	
8mbar	75.4 (15.8)		85.7 (16.5)		80.5 (16.9)	
Heart rate (/min)						
Baseline	74.2 (18.2)	<.001	73.8 (12.6)	<.001	74.0 (15.5)	<.001
Preoxygenation	76.5 (18.5)		75.1 (13.8)		75.8 (16.2)	
0mbar	64.9 (15.3)		55.5 (11.6)		60.2 (14.3)	
5mbar	61.8 (14.8)		57.2 (10.2)		59.5 (12.8)	
8mbar	58.7 (13.8)		65.2 (19.3)		61.9 (17.0)	

[1] Mean and std.-deviation
[2]One-way repeated measures analysis of variance (Greenhouse–Geisser/Huynh–Feldt corrections if applicable)
1 mbar ≈ 1.02 cmH_2O
CI: Cardiac index, MAP: Mean arterial pressure, PEEP: positive end-expiratory pressure, SV: stroke volume, SVV: Stroke volume variation

which may lead to gastric regurgitation and pulmonary aspiration.[29,30] An individualized PEEP level that maintains lung-protective driving pressure while minimizing the risk of gastric insufflation may be most beneficial. In our study, peak inspiratory pressure was significantly higher with increased PEEP levels in both groups. However, the mean peak pressure levels and consequently the mean plateau pressure remained below 20 mbar and increased by only 3.2 mbar and 4.2 mbar, respectively, compared to a 0 mbar PEEP level. If airway pressures are high, the use of pressure-controlled ventilation rather than volume-controlled ventilation may reduce peak airway pressure and, consequently, the risk of gastric insufflation during facemask ventilation.[31] In our study, we used a two-handed mask ventilation technique. While difficult mask ventilation is reported in 1.4–5% of adult patients,[17,32] a two-handed approach increases the likelihood of successful mask ventilation and also allows for the application of PEEP to counteract the adverse effects[33,34] of atelectasis formation. Regarding the two commonly used techniques for two-handed mask ventilation, recent data show that the modified V-E technique is more effective than the C-E technique, which has been standard practice for a long time.[35,36]

While increased PEEP levels may have beneficial effects on pulmonary function during lung recruitment, they can also restrict venous return and reduce cardiac output.[12] In our study, the cardiac index, heart rate, stroke volume/stroke volume variation, and mean arterial pressure all decreased during anesthesia induction in both groups with no apparent correlation to the PEEP level applied. It was not possible here to dissect out the influence of PEEP versus that of propofol induction. Nevertheless, it is important to note, however, that most patients in our study were ASA II patients without underlying heart diseases, potentially limiting the applicability to patients with more severe comorbidities, specifically with cardiovascular comorbidities.[37] Additionally, electrical cardiometry is not as accurate as thermodilution and transthoracic echocardiography for measuring cardiac output.[14]

LIMITATIONS AND STRENGTHS

There are some limitations in addition to those mentioned above. The study was not designed to assess

clinical outcomes, no conclusions regarding the long-term clinical effects of varying PEEP levels for mask ventilation after induction of general anesthesia can be made. Our selection of predominantly healthy ASA I–II patients undergoing ophthalmic surgery also limits generalizations.

Patients excluded for inadequate facemask ventilation did not contribute any valid physiological measurements, precluding intention-to-treat analysis and introducing potential selection bias.

Although mask ventilation was performed by trained providers under consultant supervision, inter-provider variability in mask seal and ventilation technique cannot be fully excluded. Because clinicians were not blinded to group allocation and formal blinding of data analysts was not implemented, performance and detection bias remain possible. Though we ensured acceptable ventilation by tolerating up to 20% leak based on the attending consultant's judgment, leak magnitude was not captured as a quantitative outcome variable, which limits the precision of interpreting PEEP delivery.

No formal multivariable adjusted sensitivity analysis was performed, which may allow for residual confounding. Finally, baseline values were not incorporated as covariates in an ANCOVA model. Notably, the EELI gain/loss and compliance gain/loss ratios are inherently normalized to each patient's baseline measurement and therefore represent relative changes from baseline aeration and mechanics.

Strengths of the study include its prospective, randomized and highly standardized design, which assessed different PEEP levels in increasing versus decreasing order. Additionally, our assessments were made in a very homogeneous study population with very homogeneous ventilator and hemodynamic settings. Hemodynamic monitoring and EIT monitoring were performed simultaneously with each PEEP adjustment, demonstrating the direct physiological effects of the intervention on ventilation and hemodynamics.

CONCLUSIONS

In summary, we demonstrate that EIT can be a useful, noninvasive tool for real-time monitoring of ventilation distribution and atelectasis during mask ventilation after the induction of general anesthesia. A mask ventilation approach with increased PEEP levels during anesthesia induction can improve the distribution of lung ventilation as detected by EIT monitoring, without a negative impact on hemodynamic parameters.

DISCLOSURES

Conflicts of Interest: None. **Funding:** None. **This manuscript was handled by:** Jaideep Pandit.

REFERENCES

1. Edmark L, Kostova-Aherdan K, Enlund M, Hedenstierna G. Optimal oxygen concentration during induction of general anesthesia. *Anesthesiology*. 2003;98:28–33.
2. Nimmagadda U, Salem MR, Crystal GJ. Preoxygenation: physiologic basis, benefits, and potential risks. *Anesth Analg*. 2017;124:507–517.
3. Hedenstierna G, Edmark L. Mechanisms of atelectasis in the perioperative period. *Best Pract Res Clin Anaesthesiol*. 2010;24:157–169.
4. Edmark L, Auner U, Enlund M, Ostberg E, Hedenstierna G. Oxygen concentration and characteristics of progressive atelectasis formation during anaesthesia. *Acta Anaesthesiol Scand*. 2011;55:75–81.
5. Herriger A, Frascarolo P, Spahn DR, Magnusson L. The effect of positive airway pressure during pre-oxygenation and induction of anaesthesia upon duration of non-hypoxic apnoea. *Anaesthesia*. 2004;59:243–247.
6. Kim E-H, Park J-B, Kang P, et al. Effect of positive end expiratory pressure on non-hypoxic apnea time and atelectasis during induction of anesthesia in infant: a randomized controlled trial. *Paediatr Anaesth*. 2024;34:1146–1153.
7. Hao C, Ma X, Piao X, et al. Effects of positive end-expiratory pressure and oxygen concentration on non-hypoxemic apnea time during face mask ventilation of anesthesia induction: a randomized controlled trial. *Front Physiol*. 2022;13:1090612.
8. Coussa M, Proietti S, Schnyder P, et al. Prevention of atelectasis formation during the induction of general anesthesia in morbidly obese patients. *Anesth Analg*. 2004;98:1491–1495, table of contents.
9. Gao L, Zhu Y, Pan C, et al. A randomised trial evaluating mask ventilation using electrical impedance tomography during anesthetic induction: one-handed technique versus two-handed technique. *Physiol Meas*. 2022;43:064004.
10. Scaramuzzo G, Pavlovsky B, Adler A, et al. Electrical impedance tomography monitoring in adult ICU patients: state-of-the-art, recommendations for standardized acquisition, processing, and clinical use, and future directions. *Crit Care*. 2024;28:377.
11. Xu J, Wang L, Tong L, et al. Novel three-dimensional electrical impedance tomography for noninvasive detection of lung perfusion. *J Thorac Dis*. 2025;17:4837–4848.
12. Luecke T, Pelosi P. Clinical review: positive end-expiratory pressure and cardiac output. *Crit Care*. 2005;9:607–621.
13. Bernstein DP, Lemmens HJM. Stroke volume equation for impedance cardiography. *Med Biol Eng Comput*. 2005;43:443–450.
14. Sanders M, Servaas S, Slagt C. Accuracy and precision of non-invasive cardiac output monitoring by electrical cardiometry: a systematic review and meta-analysis. *J Clin Monit Comput*. 2020;34:433–460.
15. Trinkmann F, Berger M, Michels JD, et al. Influence of electrode positioning on accuracy and reproducibility of electrical velocimetry cardiac output measurements. *Physiol Meas*. 2016;37:1422–1435.
16. Rusca M, Proietti S, Schnyder P, et al. Prevention of atelectasis formation during induction of general anesthesia. *Anesth Analg*. 2003;97:1835–1839.
17. Kheterpal S, Han R, Tremper KK, et al. Incidence and predictors of difficult and impossible mask ventilation. *Anesthesiology*. 2006;105:885–891.
18. R Core Team. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing; 2021. https://www.R-project.org/

19. Barbosa FT, Castro AA, de Sousa-Rodrigues CF. Positive end-expiratory pressure (PEEP) during anaesthesia for prevention of mortality and postoperative pulmonary complications. *Cochrane Database Syst Rev*. 2014;2014:CD007922.
20. Kim EH, Lee JH, Jang YE, et al. Effect of positive end-expiratory pressure during anaesthesia induction on non-hypoxic apnoea time in infants: a randomised controlled trial. *Eur J Anaesthesiol*. 2021;38:1012–1018.
21. Ukere A, März A, Wodack KH, et al. Perioperative assessment of regional ventilation during changing body positions and ventilation conditions by electrical impedance tomography. *Br J Anaesth*. 2016;117:228–235.
22. Costa EL, Borges JB, Melo A, et al. Bedside estimation of recruitable alveolar collapse and hyperdistension by electrical impedance tomography. *Intensive Care Med*. 2009;35:1132–1137.
23. Victorino JA, Borges JB, Okamoto VN, et al. Imbalances in regional lung ventilation: a validation study on electrical impedance tomography. *Am J Respir Crit Care Med*. 2004;169:791–800.
24. Hinz J, Hahn G, Neumann P, et al. End-expiratory lung impedance change enables bedside monitoring of end-expiratory lung volume change. *Intensive Care Med*. 2003;29:37–43.
25. Futier E, Constantin JM, Paugam-Burtz C, et al; IMPROVE Study Group. A trial of intraoperative low-tidal-volume ventilation in abdominal surgery. *N Engl J Med*. 2013;369:428–437.
26. Severgnini P, Selmo G, Lanza C, et al. Protective mechanical ventilation during general anesthesia for open abdominal surgery improves postoperative pulmonary function. *Anesthesiology*. 2013;118:1307–1321.
27. Neto AS, Hemmes SNT, Barbas CSV, et al; PROVE Network Investigators. Association between driving pressure and development of postoperative pulmonary complications in patients undergoing mechanical ventilation for general anaesthesia: a meta-analysis of individual patient data. *Lancet Respir Med*. 2016;4:272–280.
28. Jiang L, Deng Y, Xu F, Qiao S, Wang C. Individualized PEEP guided by EIT in patients undergoing general anesthesia: a systematic review and meta-analysis. *J Clin Anesth*. 2024;94:111397.
29. Bouvet L, Albert ML, Augris C, et al. Real-time detection of gastric insufflation related to facemask pressure-controlled ventilation using ultrasonography of the antrum and epigastric auscultation in nonparalyzed patients: a prospective, randomized, double-blind study. *Anesthesiology*. 2014;120:326–334.
30. Cajander P, Edmark L, Ahlstrand R, Magnuson A, de Leon A. Effect of positive end-expiratory pressure on gastric insufflation during induction of anaesthesia when using pressure-controlled ventilation via a face mask: a randomised controlled trial. *Eur J Anaesthesiol*. 2019;36:625–632.
31. Seet MM, Soliman KM, Sbeih ZF. Comparison of three modes of positive pressure mask ventilation during induction of anaesthesia: a prospective, randomized, crossover study. *Eur J Anaesthesiol*. 2009;26:913–916.
32. Langeron O, Masso E, Huraux C, et al. Prediction of difficult mask ventilation. *Anesthesiology*. 2000;92:1229–1236.
33. Hart D, Reardon R, Ward C, Miner J. Face mask ventilation: a comparison of three techniques. *J Emerg Med*. 2013;44:1028–1033.
34. Wheatley S, Thomas AN, Taylor RJ, Brown T. A comparison of three methods of bag valve mask ventilation. *Resuscitation*. 1997;33:207–210.
35. Gerstein NS, Carey MC, Braude DA, et al. Efficacy of facemask ventilation techniques in novice providers. *J Clin Anesth*. 2013;25:193–197.
36. Fei M, Blair JL, Rice MJ, et al. Comparison of effectiveness of two commonly used two-handed mask ventilation techniques on unconscious apnoeic obese adults. *Br J Anaesth*. 2017;118:618–624.
37. Fairfield JE, Dritsas A, Beale RJ. Haemodynamic effects of propofol: induction with 2.5 mg kg-1. *Br J Anaesth*. 1991;67:618–620.