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Original Article

# PEEP Titration Guided by Electrical Impedance Tomography in Critically Ill Mechanically Ventilated Patients with Acute Hypoxemic Respiratory Failure

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## Abstract

**Introduction:** Positive end-expiratory pressure (PEEP) titration is crucial for improving oxygenation and preventing ventilator-induced lung injury in acute hypoxemic respiratory failure. Electrical impedance tomography (EIT) offers real-time, bedside monitoring of lung ventilation distribution, potentially guiding individualized PEEP settings.

**Aim:** The aim of this study was to assess the effect of EIT-based PEEP titration on respiratory mechanics and gas exchange in critically ill mechanically ventilated patients with acute hypoxemic respiratory failure.

**Materials and methods:** A prospective, interventional study was conducted from April 2022 to January 2024, including adult patients with acute hypoxemic respiratory failure on invasive mechanical ventilation. Continuous EIT monitoring was performed with electrode belts positioned at the fourth to fifth intercostal space. Patients were divided into two groups, low and high recruiters, based on the absolute reduction of the collapse percentage in the dorsal lung segments measured by EIT when increasing PEEP from 6 mbar to 20 mbar. EIT data, respiratory mechanics parameters and arterial blood gases were obtained during PEEP titration maneuvers. Optimum PEEP based on EIT was defined as the crossing point of the collapse and overdistention curves, generated during decremental PEEP trial.

**Results:** A total of 45 patients with a mean age of 54.33 years were included in the study. In low recruiters, the EIT-based PEEP was lower (9.18±2.11) than baseline PEEP (10.73±3.07) ($p$=0.0008). In high recruiters, the EIT-based PEEP was higher (13.91±2.45) than baseline PEEP (10.22±2.24) ($p$=0.0006). A statistically significant positive correlation was found between BMI and EIT-based PEEP. The crossing point method of PEEP titration led to improvement of oxygenation in high recruiters and improvement of respiratory mechanics parameters in low recruiters.

**Conclusion:** As a non-invasive and radiation-free monitoring tool EIT allows personalization of PEEP titration with minimum alveolar collapse and overdistention.

## Keywords

alveolar collapse, electrical impedance tomography, lung recruitment, overdistention, positive pressure

## INTRODUCTION

Acute hypoxemic respiratory failure (AHRF) is among the most common causes of death in intensive care units worldwide.[1] Invasive mechanical ventilation is the cornerstone in the treatment of this group of patients and selecting parameters that do not correspond to the needs of the diseased lung can lead to further damage of the lung parenchyma. Protective ventilation can not only prevent mechanical lung injury, but also reduce the risk of systemic release of cytokines, which is associated with the development of multiorgan failure.[2] Application of positive end-expiratory pressure (PEEP) increases airway pressure and modifies pleural and transpulmonary pressure, resulting in blood volume alteration into the pulmonary circulation. PEEP in itself is neither beneficious nor detrimental to end-organ hemodynamics, but its hemodynamic effects vary.[3] Because of the heterogenous characteristics of the injured lung, the response to pressure differs significantly among patients and finding the best compromise between alveolar recruitment and overdistention is still challenging.[4] However, no validated bedside method is available for identifying the optimal level of PEEP in mechanically ventilated patients.

Electrical impedance tomography (EIT) is a non-invasive, radiation-free monitoring tool that can be used continuously at the bedside to visualize the regional distribution of lung volumes and assess the effects of therapeutic maneuvers on lung volume changes.[5] EIT gives information about alveolar recruitment and overdistention in different regions of interest at the selected PEEP levels.[6] The dynamic information provided can be used by clinicians to assess lung recruitability at the bedside and find the PEEP level at which there is optimal alveolar recruitment with minimum overdistention.

## AIM

The aim of this study was to assess the effect of EIT-based PEEP titration on respiratory mechanics and gas exchange in critically ill mechanically ventilated patients with acute hypoxemic respiratory failure.

## MATERIALS AND METHODS

We conducted a prospective, interventional study from April 2022 to January 2024 including a total of 45 patients admitted to the adult intensive care unit. The inclusion criteria were the following: 1) age >18 years; 2) acute hypoxemic respiratory failure with $PaO_2/FiO_2$ <300; and 3) invasive mechanical ventilation. The exclusion criteria were as follows: 1) age >75 years, 2) exacerbation of chronic obstructive pulmonary disease; 3) pregnancy; 4) pacemaker or implantable cardioverter-defibrillator; 5) wounds, burns, bandages or drainages limiting electrode belt placement; 6) cardiogenic cause for respiratory failure; and 7) lack of informed consent. We performed continuous EIT monitoring using the EIT device Dräger PulmoVista 500, Dräger Medical GmbH. The electrode belts were placed at the fourth to fifth intercostal space.

In all patients, EIT recording was started at the mode of ventilation selected by the attending physician. EIT recording was performed for 10 minutes at the baseline ventilation settings. Respiratory mechanics parameters (PEEP, plateau pressure, and driving pressure ΔP) were recorded and blood-gas analysis was obtained for measurement of baseline $PaO_2/FiO_2$ ratio and baseline $PaCO_2$.

After initial data recording, PEEP in all patients was reduced from clinically selected level to 6 mbar, then in the pressure-controlled ventilation (PCV) mode of ventilation PEEP was stepwise increased to 20 mbar (6 to 10 to 15 to 20 mbar). Every step lasted 2 minutes. Driving pressure remained constant (ΔP=15 mbar), the maximum inspiratory pressure ($P_{insp}$) reached was 35 mbar. Intolerance to a PEEP level was recorded if mean arterial pressure (MAP) could not be kept above 65 mmHg, despite vasopressor use, or $SpO_2$ was below 83%. If a previous step was tolerated, PEEP was reduced to the previous level, and the trial continued. Based on the absolute reduction in the collapse percentage in the dorsal lung segments measured by EIT when increasing PEEP from 6 mbar to 20 mbar (or to the highest tolerated level), patients were divided into two groups – with low and high recruitability (ΔCollapse <20% – low recruitability; ΔCollapse ≥20% – high recruitability).

In the next step, ventilation was switched to volume-controlled mode of ventilation with tidal volume (Vt) of maximum 6 ml/kg PBW (predicted body weight) and a maximum $P_{plat}$ of 35 mbar. Decremental PEEP trial was performed and PEEP was decreased from 20 to 6 mbar in steps of 2 mbar with a duration of 2 minutes each. Optimum PEEP based on EIT was defined as the crossing point of the collapse and overdistention curves, generated during the decremental PEEP trial. In cases when the crossing point was between two PEEP levels, the higher PEEP was chosen. For comparison we also documented the PEEP level at which the highest respiratory system compliance was recorded (Crs).

After the optimum EIT-based PEEP was found, patients were ventilated with the selected PEEP for one hour. After that the dynamics in the parameters of breathing mechanics were documented and another BGA was obtained for comparison.

All EIT recordings and data were subsequently analyzed using specialized software (Dräger: PV500 Data Analysis SW130).

Quantitative variables are presented as means, standard deviation (±SD) and a range. To test whether the data is normally distributed, the Shapiro-Wilk test was used. When testing means of paired measurements, dependent samples t-test was used. For means of two unrelated groups the independent samples t-test was used. To test for linear correlation between two sets of data, Pearson's r correlation coefficient was calculated. For statistical analysis SPSS ver. 29.0.2 and Excel 2013 were used.

## RESULTS

In two patients, a PEEP level of 20 mbar was not reached because of hemodynamic instability. Their highest tolerated PEEP was 18 mbar and the protocol allowed the decremental PEEP trial to start from this PEEP level. The protocol was well tolerated by all other patients. The patient characteristics are shown in **Table 1**.

The mean value of ΔCollapse in the total population was 18.71% [6; 33] and is displayed in **Fig. 1**. Two equally sized groups were formed – 22 patients with low recruitability (ΔCollapse <20%) and 23 patients with high recruitability (ΔCollapse ≥20%). After analyzing the data, a statistically significant difference was found in age, BMI and SOFA score between patients in the two groups. High recruiters were younger, had higher BMI and a higher SOFA score, as shown in **Table 2**.

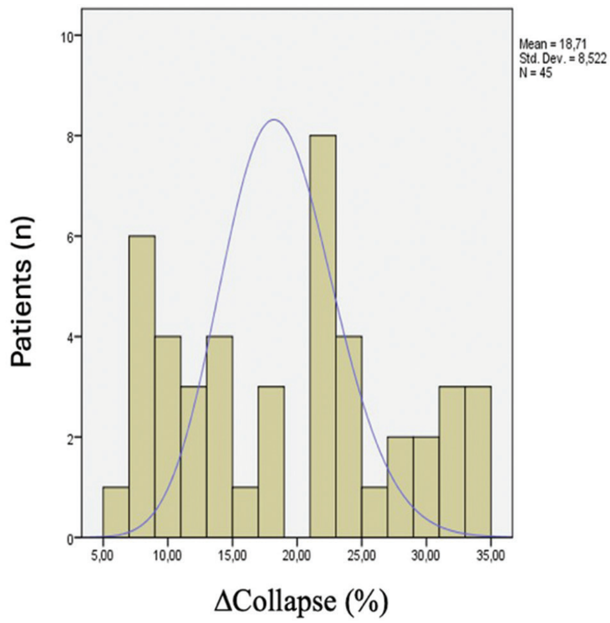


**Figure 1.** ΔCollapse distribution in the population.

**Table 1.** Patient characteristics

| Characteristic | Total population (N=45) |
|---|---|
| Age, years | 54.33 [19; 75] |
| Sex, M/F | 24/21 |
| BMI, kg/m$^2$ | 27.38 [22.9; 33.2] |
| SOFA score at enrollment | 5.27 [2; 9] |
| ARDS, Yes/No | 25/20 |
| Ramsey sedation scale at enrollment | 4.53 [2; 6] |
| ΔCollapse, % | 18.71 [6; 33] |
| Recruitability, Low/High | 22/23 |
| Baseline PEEP, mbar | 10.47 [5; 16] |
| Baseline $PaO_2/FiO_2$ | 131.68 [59.6; 245] |
| Baseline Crs, ml/mbar | 38.21 [15; 94] |
| Baseline Pplat, mbar | 23.68 [12; 35] |
| Baseline driving pressure, mbar | 13.22 [6; 22] |
| Baseline $PaCO_2$ | 41.11 [29; 56] |

BMI: body mass index; SOFA: sequential organ failure assessment; ARDS: acute respiratory distress syndrome; Crs: respiratory system compliance; Pplat: plateau pressure; Results are displayed as means and the range is given in brackets.

Baseline PEEP in the total population had a mean value of 10.47 (mean=10.47±2.66). The mean value of PEEP at the crossing point on EIT was 11.60 (mean=11.60±3.29) which was statistically significantly higher than the baseline PEEP ($p$=0.006). Dependent samples t-test was used and no statistically significant difference was found between baseline PEEP and PEEP level with highest Crs, as well as between PEEP at the crossing point and PEEP with highest Crs in the total population ($p$>0.05) **(Fig. 2)**.

Mean PEEP levels in the two recruitability groups are displayed in **Fig. 3** and **Table 3**. In the group of low recruiters, PEEP at the crossing point was statistically significantly higher than the PEEP with the highest Crs ($p$<0.001). A statistically significant difference in this group was also reported regarding baseline PEEP compared with PEEP at the crossing point ($p$<0.001) and with PEEP with the highest Crs ($p$<0.001), respectively. In the group of high recruiters, statistically significant difference was found regarding baseline PEEP compared with PEEP at the crossing point ($p$<0.001) and with PEEP with highest Crs ($p$<0.001), respectively. PEEP at crossing point and PEEP with highest

**Table 2.** Mean age, BMI and SOFA score in the two recruitability groups (Independent samples T-test)

| | Low recruitability | | High recruitability | | *P* |
|---|---|---|---|---|---|
| | Mean X±SD | Min/Max | Mean X±SD | Min/Max | |
| Age | 61.59±10.51 | 35/75 | 47.39±16.32 | 19/74 | <0.001 |
| BMI | 26.36±2.17 | 23/31 | 28.35±3.07 | 23/33 | 0.005 |
| SOFA Score | 4.82±1.99 | 2/8 | 5.70±1.72 | 2/9 | 0.02 |

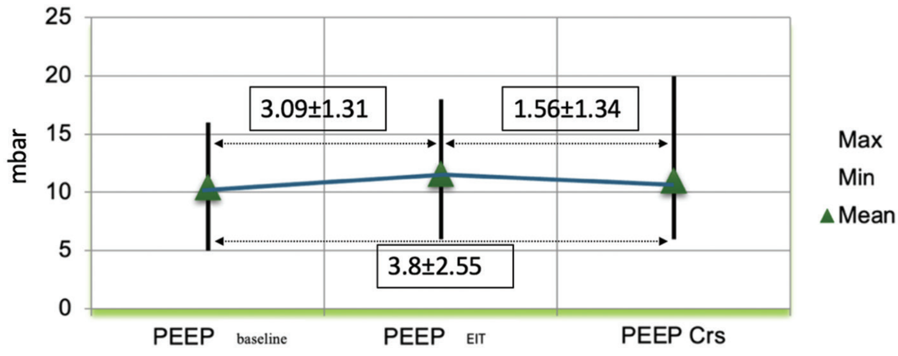


**Figure 2.** Comparison between baseline PEEP levels, PEEP at the crossing point and PEEP with highest Crs in the total population. Differences between each PEEP value with standard deviation are given in boxes.

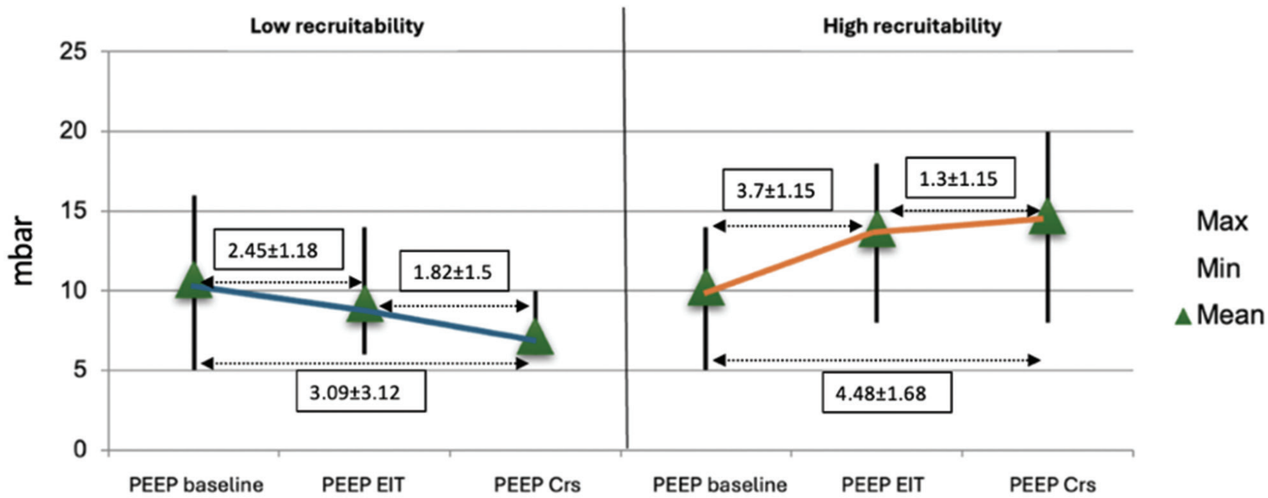


**Figure 3.** Comparison between baseline PEEP levels, PEEP at the crossing point and PEEP with highest Crs in the groups with low and high recruitability. Differences between each PEEP value with standard deviation are given in boxes.

**Table 3.** Mean values of baseline PEEP, PEEP at the crossing point and PEEP with highest Crs in the groups with low and high recruitability

| | Low recruitability | | High recruitability | | *P* |
|---|---|---|---|---|---|
| | Mean X±SD | Min/Max | Mean X±SD | Min/Max | |
| Baseline PEEP | 10.73±3.07 | 5/16 | 10.22±2.24 | 5/14 | NS |
| PEEP at the crossing point on EIT | 9.18±2.11 | 6/14 | 13.91±2.45 | 8/18 | <0.001 |
| PEEP with highest Crs | 7.18±1.59 | 6/10 | 14.70±2.46 | 8/20 | <0.001 |

compliance were not significantly different in high recruiters ($p>0.05$). When testing means of paired measurements, dependent samples t-test was used. For means of the two unrelated groups, the independent samples t-test was used.

When analyzing the total population, a statistically significant positive correlation was found between BMI and PEEP at the crossing point (Pearson's $r=0.53$; $p<0.001$), as well as between BMI and PEEP with highest Crs (Pearson's $r=0.53$; $p<0.001$).

After the decremental PEEP trial, the baseline PEEP was changed to crossing point PEEP. **Table 4** displays the comparison between gas exchange and respiratory mechanics parameters before and after PEEP correction in the total population. For testing means of paired measurements, dependent samples t-test was used. The comparisons of gas exchange and respiratory mechanics parameters in low and high recruitability groups are displayed in **Tables 5** and **6**, respectively.

**Table 4.** Comparative analysis between gas exchange and respiratory mechanics parameters at baseline and one hour after PEEP correction in the total population

| Total population | Values at baseline | | Values 1 hour after PEEP correction | | *P* |
|---|---|---|---|---|---|
| | Mean X±SD | Min/Max | Mean X±SD | Min/Max | |
| $PaO_2/FiO_2$ ratio | 131.68±43.92 | 59.60/245 | 152.36±53.11 | 64/288 | 0.001 |
| Crs (ml/mbar) | 38.21±14.82 | 15/94 | 43.40±15.29 | 19/88 | 0.009 |
| Pplat (mbar) | 23.68±5.05 | 12/36 | 22.80±4.99 | 15/36 | NS |
| Driving pressure ΔP (mbar) | 13.22±3.26 | 5/22 | 11.11±2.77 | 4/20 | 0.006 |
| $PaCO_2$ (mmHg) | 41.11±7.08 | 29/56 | 39.87±7.11 | 30/67 | NS |

**Table 5.** Comparative analysis between gas exchange and respiratory mechanics parameters at baseline and one hour after PEEP correction in the low recruitability group (dependent samples t-test)

| Low recruitability | Values at baseline | | Values 1 hour after PEEP correction | | *P* |
|---|---|---|---|---|---|
| | Mean X±SD/ | Min/Max | Mean X±SD | Min/Max | |
| $PaO_2/FiO_2$ ratio | 134.71±51.13 | 59.60/245 | 156.36±63.45 | 64/288 | NS |
| Crs (ml/mbar) | 39.68±19.36 | 15/94 | 46.25±19.53 | 19/88 | 0.01 |
| Pplat (mbar) | 23.45±5.16 | 12/30 | 19.95±4.07 | 15/28 | <0.001 |
| Driving pressure ΔP (mbar) | 12.73±2.76 | 5/16 | 10.77±2.62 | 6/16 | 0.006 |
| $PaCO_2$ (mmHg) | 42.00±8.50 | 29/56 | 39.00±6.95 | 30/51 | 0.008 |

**Table 6.** Comparative analysis between gas exchange and respiratory mechanics parameters at baseline and one hour after PEEP correction in the high recruitability group (dependent samples t-test)

| High recruitability | Values at baseline | | Values 1 hours after PEEP correction | | *P* |
|---|---|---|---|---|---|
| | Mean X±SD | Min/Max | Mean X±SD | Min/Max | |
| $PaO_2/FiO_2$ ratio | 128.78±36.67 | 74/210 | 148.52±42.03 | 68/288 | 0.01 |
| Crs (ml/mbar) | 36.80±8.79 | 21.80/53 | 40.67±9.35 | 22/55 | NS |
| Pplat (mbar) | 23.90±5.05 | 16/36 | 25.52±4.25 | 19/36 | NS |
| Driving pressure ΔP (mbar) | 13.68±3.68 | 6/22 | 11.43±2.92 | 4/20 | 0.03 |
| $PaCO_2$ (mmHg) | 40.26±5.46 | 32/54 | 40.70±7.33 | 31/67 | NS |

## DISCUSSION

Since no bedside method has been validated yet, finding optimal PEEP level in mechanically ventilated patients with acute hypoxemic respiratory failure is still challenging for intensivists. The results of this study show that the clinically selected PEEP based on PEEP-$FiO_2$ tables does not differ significantly between high and low recruiters and can lead to either alveolar collapse or overdistention, respectively. On the other hand, EIT at the bedside can be used during a decremental PEEP trial to identify the crossing point of the collapse and overdistention curves, where collapse and overdistention are both minimal. PEEP at the crossing point was statistically significantly different between high and low recruiters, which was also shown by Jonkman and colleagues in a recent study in COVID-19 patients.[7] EIT can be used to differentiate between high and low recruiters based on regional lung ventilation, which cannot be assessed using basic respiratory mechanics parameters or oxygenation response to high PEEP. Our study demonstrates that the best respiratory system compliance method does not match PEEP at the crossing point and both PEEP levels are significantly different in low recruiters.

Our results show that changing PEEP based on the crossing point method can lead to improvement of oxygenation in high recruiters and improvement of respiratory mechanics in low recruiters. A significant correlation was also found between PEEP level at the crossing point and

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BMI, as well as between PEEP associated with highest Crs and BMI. This can be explained by the fact that obese patients have higher pressure from the chest wall, which leads to lower transpulmonary pressure and lower end-expiratory lung volumes.[8]

A limitation of EIT is that the method uses only one horizontal plane for its measurements. In our study, we placed the electrode belts within fourth to fifth intercostal space in all our patients.

One major limitation of our study is that we do not compare EIT recruitability assessment with other methods of recruitability assessment. We used EIT to measure the absolute reduction in alveolar collapse when increasing PEEP stepwise from 6 to 20 mbar. We named the parameter ΔCollapse and used it to divide the population into two groups – with low and high recruitability.

Other major limitation of our study is that outcome was not studied. In our center, the recommendation is that low PEEP/high $FiO_2$ tables are used for PEEP selection. The study suggests that PEEP at the crossing point improves oxygenation and respiratory mechanics in different groups, but it is still uncertain if it provides the optimal PEEP. Although radiation-free, noninvasive and relatively easy to use, future larger randomized trials are needed to verify if EIT can be used routinely by the clinicians to find the optimal PEEP, which will improve outcome.

# CONCLUSION

Every mechanically ventilated patient responds differently to positive pressure. EIT shows promising results as a method used for guiding PEEP titration individually based on best compromise between alveolar recruitment and overdistention. Future larger studies are needed to verify if PEEP at the crossing point is really optimal and improves outcome.

## Author contributions

Study conception and design: Dimitar Kazakov, Georgi Pavlov, Chavdar Stefanov; Data collection: Dimitar Kazakov, Siyana Nikolova-Kamburova, Valentin Stoilov, Emil Mitkovski; Analysis and interpretation of results: Dimitar Kazakov, Emral Kyosebekirov, Milena Sandeva; Draft manuscript preparation: Dimitar Kazakov, Georgi Pavlov. All authors reviewed the results and approved the final version of the manuscript.


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## Competing Interests

The authors have declared that no competing interests exist.

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# Титрация PEEP с помощью электроимпедансной томографии у тяжёлобольных пациентов с острой гипоксической дыхательной недостаточностью, находящихся на искусственной вентиляции лёгких

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## Резюме

**Введение:** Титрование положительного давления в конце выдоха (PEEP) имеет решающее значение для улучшения оксигенации и предотвращения повреждения лёгких, вызванного вентилятором при острой гипоксической дыхательной недостаточности. Электроимпедансная томография (ЭИТ) обеспечивает мониторинг распределения вентиляции лёгких в режиме реального времени у постели больного, потенциально направляя индивидуальные настройки PEEP.

**Цель:** Целью данного исследования была оценка влияния титрования PEEP на основе ЭИТ на респираторную механику и газообмен у тяжёлобольных пациентов с острой гипоксической дыхательной недостаточностью, находящихся на искусственной вентиляции лёгких.

**Материалы и методы:** Проспективное интервенционное исследование проводилось с апреля 2022 года по январь 2024 года, включая взрослых пациентов с острой гипоксической дыхательной недостаточностью на инвазивной искусственной вентиляции лёгких. Непрерывный мониторинг ЭИТ проводился с помощью электродных ремней, расположенных в четвёртом-пятом межребёрье. Пациенты были разделены на две группы, с низким и высоким рекрутерами, на основе абсолютного снижения процента коллапса в дорсальных сегментах лёгких, измеренного с помощью ЭИТ при увеличении PEEP с 6 mbar до 20 mbar. Данные ЭИТ, параметры респираторной механики и газы артериальной крови были получены во время манёвров титрования PEEP. Оптимальный PEEP на основе ЭИТ был определён как точка пересечения кривых коллапса и перерастяжения, полученных во время испытания декрементного PEEP.

**Результаты:** В исследование было включено в общей сложности 45 пациентов со средним возрастом 54.33 года. У низких рекрутеров PEEP на основе ЭИТ был ниже (9.18 ± 2.11), чем базовый PEEP (10.73 ± 3.07) ($p$ = 0.0008). У рекрутеров с высоким показателем PEEP на основе ЭИТ был выше (13.91±2.45), чем базовый PEEP (10.22±2,24) ($p$=0.0006). Статистически значимая положительная корреляция была обнаружена между ИМТ и PEEP на основе ЭИТ. Метод точки пересечения титрования PEEP привёл к улучшению оксигенации у рекрутеров с высоким показателем и улучшению параметров респираторной механики у рекрутеров с низким показателем.

**Заключение:** Как неинвазивный и не требующий облучения инструмент мониторинга ЭИТ позволяет персонализировать титрование PEEP с минимальным альвеолярным коллапсом и перерастяжением.

## Ключевые слова

альвеолярный коллапс, электроимпедансная томография, рекрутмент лёгких, перерастяжение, положительное давление