Setting Individualized Positive End-Expiratory Pressure Level with a Positive End-Expiratory Pressure Decrement Trial After a Recruitment Maneuver Improves Oxygenation and Lung Mechanics During One-Lung Ventilation

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BACKGROUND: We investigated whether individualized positive end-expiratory pressure (PEEP) improves oxygenation, ventilation, and lung mechanics during one-lung ventilation compared with standardized PEEP.

METHODS: Thirty patients undergoing thoracic surgery were randomly allocated to the study or control group. Both groups received an alveolar recruitment maneuver at the beginning and end of one-lung ventilation. After the alveolar recruitment maneuver, the control group had their lungs ventilated with a 5 cm H₂O PEEP, while the study group had their lungs ventilated with an individualized PEEP level determined by a PEEP decrement trial. Arterial blood samples, lung mechanics, and volumetric capnography were recorded at multiple timepoints throughout the procedure.

RESULTS: The individualized PEEP values in study group were higher than the standardized PEEP values (10 ± 2 vs 5 cm H₂O; P < 0.001). In both groups, arterial oxygenation decreased when bilateral-lung ventilation was switched to one-lung ventilation and increased after the alveolar recruitment maneuver. During one-lung ventilation, oxygenation was maintained in the study group but decreased in the control group. After one-lung ventilation, arterial oxygenation was significantly higher in the study group (306 vs 231 mm Hg, P = 0.007). Static compliance decreased in both groups when bilateral-lung ventilation was switched to one-lung ventilation. Static compliance increased significantly only in the study group (P < 0.001) after the alveolar recruitment maneuver and optimal PEEP adjustment. The alveolar recruitment maneuver did not decrease cardiac index in any patient.

CONCLUSIONS: During one-lung ventilation, the improvements in oxygenation and lung mechanics after an alveolar recruitment maneuver were better preserved by ventilation using individualized PEEP with a PEEP decrement trial than with a standardized 5 cm H₂O of PEEP. (Anesth Analg 2014;118:657–65)

In many surgical procedures, one-lung ventilation is required to provide optimum surgical exposure. During one-lung ventilation, a shunt-like effect may arise from continued perfusion of the nonventilated lung and inadequate expansion of the ventilated-dependent lung in the presence of a high inspired O₂ fraction (FiO₂ = 1.0) or related to anesthesia and position.¹ Lung-protective ventilation strategies can reduce acute lung injury²⁻⁴ but may promote alveolar collapse as a consequence of low tidal volume.⁵⁻⁷ Atelectasis prevention during lung-protective ventilation requires positive end-expiratory pressure (PEEP)⁸⁻¹¹; however, optimal PEEP levels and actual effects of PEEP are not clear.¹²⁻¹⁹

Two reviews suggest that application of 5 cm H₂O PEEP after an alveolar recruitment maneuver is the best method for treating ventilation-perfusion mismatch during one-lung ventilation.¹⁰⁻¹¹ Several clinical studies of thoracic surgery with one-lung ventilation have reported improved oxygenation and ventilation when an alveolar recruitment maneuver is performed with a standardized PEEP of 5 to 10 cm H₂O.¹²⁻¹⁶ However, individualized PEEP determined by using a PEEP decrement titration trial after an alveolar recruitment maneuver also improves oxygenation, ventilation, and lung mechanics in anesthetized patients with healthy lungs or lung injury.¹⁷⁻²⁹

There are no reported studies of the effects of an alveolar recruitment maneuver with individualized PEEP settings titrated with a PEEP decrement trial during one-lung ventilation in thoracic surgery. We hypothesized that such a procedure would improve gas exchange and lung mechanics compared with the establishment of a standardized 5 cm H₂O PEEP after an alveolar recruitment maneuver during one-lung ventilation. We performed a prospective, randomized controlled trial to test this hypothesis.
METHODS
The study was performed at the Department of Anesthesiology and Critical Care at the Hospital Clínico Universitario de Valencia, Spain, from May to December 2012. Written informed consent was obtained from all patients, and the study was approved by the Local Ethics Committee for Clinical Research. The study included patients with ASA physical status I to III undergoing elective lung resection. Exclusion criteria were age <18 years, ASA physical status IV, pneumonectomy, New York Heart Association III to IV, and preoperative hemoglobin <10 mg/dL.

General Procedures
Patients were monitored for nasopharyngeal temperature, electrocardiogram, pulse oximetry, and invasive arterial blood pressure by using the GE Aisys Carestation™ monitor. The depth of anesthesia was monitored with the Bispectral Index (BIS vista, Aspect Medical Systems, The Netherlands) and cardiac index with the Vigileo (Edwards Lifesciences, Irvine, CA). Despite cardiac output measurement by using pulse contour analysis not being validated during one-lung ventilation, this method has been used in previous studies with consistent results.30,31

Before anesthesia induction, a thoracic epidural catheter (Tuho; Braun Laboratories, Melsungen AG, Germany) was placed at T3 to T6, and 3 mL bupivacaine 0.25% with epinephrine was administered. After 5 minutes breathing 100% oxygen, anesthesia was induced with fentanyl 5 μg·kg⁻¹, propofol 2.5 mg·kg⁻¹, and rocuronium 0.6 mg·kg⁻¹. Sevoflurane was administered to maintain a BIS between 40 and 50. Patients received a continuous infusion of remifentanil 0.1 to 0.4 μg·kg⁻¹·min⁻¹. Crystalloid solutions were continuously infused at a rate of 3 mL·kg⁻¹·h⁻¹. The trachea was intubated with an appropriately sized left-side double-lumen tube (Broncho-part; Rush, Kernen, Germany). Tube position was confirmed by bronchoscopy in the supine and lateral positions.

The patient’s lungs were ventilated with the GE Aisys Carestation™ by using volume-controlled ventilation with square-wave flow. Tidal volume was set to 8 mL·kg⁻¹ of predicted body weight during 2-lung (bilateral) ventilation and 5 to 7 mL·kg⁻¹ during one-lung ventilation to maintain a plateau pressure ≤25 cm·H₂O. When plateau pressure was above 25 cm·H₂O, tidal volume was reduced in 1 mL·kg⁻¹ steps until plateau pressure ≤25. To avoid hypoxemia during one-lung ventilation and interference from Fio₂ in the measurement of PaO₂, we used 100% Fio₂ during the study period. The inspiratory-to-expiratory ratio was 1:2 with an end-inspiratory pause of 10%, and frequency was adjusted to maintain arterial CO₂ partial pressure (Paco₂) between 35 and 60 mm·Hg. All patients had an initial PEEP level of 5 cm·H₂O during bilateral-lung ventilation, which was maintained in the control group throughout the study.

Monitoring
Intraoperative blood gas was monitored with the i-STAT® Analyzer (Abbott laboratories, East Windsor, NJ), which measured acid-base status (pH), oxygen arterial pressure (PaO₂), and PacO₂.

Static compliance during volume-controlled ventilation and dynamic compliance during pressure-controlled ventilation, airway resistance, peak inspiratory pressure, and plateau pressure were determined by using the NICO capnograph (Respironics, Wallingford, CT). Static compliance was calculated as tidal volume/(plateau pressure–total PEEP). Alveolar dead space was measured by using volumetric capnography. We calculated the ratios of physiological and alveolar dead-space to tidal volume (physiologic dead-space volume/tidal volume and alveolar dead-space volume/alveolar tidal volume, respectively), by applying the Bohr-Enghoff formula32 as previously described.22–26

The presence of auto-PEEP was evaluated in real-time by observing the flow-volume curves on the Nico monitor.33 In the presence of an interrupted expiratory flow, inspiratory flow began before expiratory flow ceased, that is, reached zero, suggesting that passive expiration is incomplete, and the airway pressure reflects the recoil pressure of the respiratory system (auto-PEEP) at the elevated end-expiratory volume.

Experimental Protocol
Measurements during one-lung ventilation were performed with the patients in lateral position, with pleura opened, after collapse of the nondependent lung.

In the study group, one-lung ventilation was initiated after checking the correct position of the double-lumen tube and correct sealing of both cuffs. The recruitment maneuver was applied to the dependent lung following a standard protocol. The ventilator was switched to pressure-control ventilation with a driving pressure of 20 cm·H₂O and 15 bpm. PEEP was increased in 5 cm·H₂O steps and was held at each step for 10 breaths. A recruitment opening pressure of 40 cm·H₂O (20 cm·H₂O of driving pressure and 20 cm·H₂O PEEP) was applied for 20 breaths. After the alveolar recruitment maneuver was performed, a PEEP decrement trial was initiated. PEEP was decreased in 2 cm·H₂O steps until the maximal dynamic compliance was obtained, which was considered the individualized (optimal) PEEP level.34 The duration of each step was 2 minutes. Thereafter, a new alveolar recruitment maneuver was performed as described above. The ventilator was switched to volume-controlled ventilation, and the individualized PEEP level was established and maintained throughout the study period.

In the control group, the same procedures were followed except for the PEEP titration (Fig. 1). After an alveolar recruitment maneuver, a level of 5 cm·H₂O PEEP was fixed. The second alveolar recruitment maneuver was performed 10 minutes after the first, and a PEEP level of 5 cm·H₂O was again established and maintained during the study period.

After the one-lung ventilation period and before bilateral-lung ventilation, a sustained manual expansion of the reservoir bag (40 cm·H₂O for 10 seconds) of the nondependent lung was performed in all patients, without altering the PEEP level. All studied variables were recorded at 5 different timepoints:

1. during bilateral-lung ventilation 10 minutes after intubation,
2. during one-lung ventilation 5 minutes after collapse of the nondependent lung (pleura opened) and before the alveolar recruitment maneuver,
3. during one-lung ventilation 5 minutes before collapse of the nondependent lung (pleura opened),
4. during one-lung ventilation 5 minutes before the alveolar recruitment maneuver,
3. during one-lung ventilation 20 minutes after applying PEEP (5 cm·H₂O in the control group and optimal PEEP in the study group),
4. at the end of one-lung ventilation before reexpansion of the nondependent lung,
5. at the end of bilateral-lung ventilation just before extubation.

Statistical Analysis

Based on previous studies, it was estimated that a total of 30 patients were needed to detect at least a 10% difference in oxygenation at the end of one-lung ventilation, with a 5% significance level and 80% power. The Kolgomorov-Smirnov test was performed for variable normality and Levene’s test was used for homogeneity of variances. When the homogeneity hypothesis was rejected (test P value <0.05), the Mann-Whitney U test and Friedmann were applied. This test was used for airway resistance, where the magnitude of heterogeneity of variances between groups is not enough to influence conclusions. If the null hypothesis was not rejected, a Student t test and analysis of variance (ANOVA) were performed. For multiple comparisons, the Bonferroni correction was used to maintain the risk of a type 1 error at the chosen significance level (α = 0.05). When Bonferroni was used, P-values and confidence intervals (CI) are presented as “corrected.” The denominator for the correction was the total number of comparisons for each variable (5, corresponding to the 5 times). The parameters are presented as mean (±SD). Statistical analysis was performed by using the SPSS 15.0 software package (SPSS, Chicago, IL).

RESULTS

Thirty patients undergoing thoracic surgery were studied (Fig 2). Table 1 presents the demographic data. There were no baseline differences between the 2 groups. In the study group, individualized PEEP during the PEEP titration trial was 10 (±2) cm·H₂O, which was significantly different from the 5 cm·H₂O used in the control group (95% CI of the difference was +4 to +6 cm·H₂O, P < 0.001). Fig. 3 shows dynamic compliance versus PEEP in the study group during the PEEP decrement trial.

In both groups, arterial oxygenation decreased by approximately 50% when bilateral-lung ventilation was switched to one-lung ventilation and increased after an alveolar recruitment maneuver (Table 2). Thereafter, oxygenation during one-lung ventilation was maintained in the study group and decreased in the control group by 18% at the end of one-lung ventilation (Table 2). At the end of one-lung ventilation, arterial oxygenation was significantly higher (P = 0.007) with the individualized PEEP when compared with 5 cm·H₂O (Table 3). The sample size was relatively small to evaluate differences in the Pao₂/Fio₂ between surgical sites (right versus left). In the control group, with bilateral-lung ventilation, the 95% CI of the difference was −108 to +165 mm·Hg, P = 0.62, and with one-lung ventilation 20 minutes after PEEP, the 95% CI of the difference was −211 to +25 mm·Hg, P = 0.10. In the study group, with bilateral-lung ventilation, the 95% CI of the difference was −176 to +111, P = 0.60, and with one-lung ventilation 20 minutes after PEEP, the 95% CI of the difference was −199 to +43, P = 0.16. When all patients with bilateral lung ventilation were compared, the 95% CI of the difference was −29 to +115, P = 0.60, and with one-lung ventilation 20 minutes after PEEP, the 95% CI of the difference was −150 to +23, P = 0.14.

In both groups, static compliance decreased when bilateral-lung ventilation was switched to one-lung ventilation (Table 2). After an alveolar recruitment maneuver, static compliance increased significantly in the study group (corrected 95% CI of the difference was +3 to +30 mL·cm·H₂O−1, corrected P < 0.007) and remained increased throughout
Individualized PEEP Improves Lung Function During one-lung ventilation (Table 2). The results obtained for compliance in the control group after alveolar recruitment were inconclusive (Table 2).

Peak inspiratory pressures showed no differences between groups despite the higher PEEP levels in the study group (Table 4). Airway resistance increased in both groups when bilateral-lung ventilation changed to one-lung ventilation (in the study group, corrected 95% CI of the difference was +3 to +14 cm·H₂O, corrected P < 0.001 and in the control group, corrected 95% CI of the difference was +2 to +12 cm·H₂O, corrected P < 0.001), and remained increased throughout one-lung ventilation (Table 4). No differences were found between groups (Table 4). None of the study patients had auto-PEEP during the study period.

After an alveolar recruitment maneuver and PEEP adjustment, tidal volume was reduced in most patients in the study group to keep plateau pressure below 25 cm·H₂O. In these patients, the ventilatory rate was increased to keep Paco₂ within the target range. Hence, tidal volume trended slightly lower, and ventilatory rate tended higher.
findings suggest that an optimal PEEP level kept the lung in the control group during one-lung ventilation. \( \text{Paco}_2 \) was higher in the study group since the initial measurement during bilateral-lung ventilation and the between-group differences did not vary along the study period (Table 3).

Dead-space/tidal volume showed no differences between groups when switching from bilateral-lung ventilation to one-lung ventilation (dead-space volume/tidal volume, \( P = 0.06 \)) and alveolar dead-space volume/ tidal volume, \( P = 0.14 \). In the study group, alveolar dead-space volume/alveolar tidal volume decreased slightly after an alveolar recruitment maneuver during one-lung ventilation (one-lung ventilation 20 minutes after starting PEEP, corrected 95% CI of the difference was +0.007 to +0.04, corrected \( P = 0.008 \) to +0.02, corrected \( P = 0.002 \)). The results obtained in the control group for alveolar dead-space volume/alveolar tidal volume were inconclusive (Table 2).

The cardiac index did not differ between groups, and the alveolar recruitment maneuver did not produce a cardiac index decrease in any patient (Table 3).

## DISCUSSION

The results of this clinical study show that oxygenation and lung mechanics improvement secondary to the alveolar recruitment maneuver were better maintained during one-lung ventilation with an individualized PEEP level determined with a PEEP decrement trial than with a standardized PEEP level.

We found that an alveolar recruitment maneuver improved oxygenation during one-lung ventilation in both groups. The improvement in oxygenation should be related to a decrease in intrapulmonary shunt as shown by several studies.\(^{26} \) However, our results showed that only the study group maintained this oxygenation improvement throughout the procedure until the end of one-lung ventilation; the study group also maintained improved static compliance after an alveolar recruitment maneuver, suggesting a constant end-expiratory lung volume. In contrast, in the control group, the improvements in oxygenation and static compliance were not maintained after an alveolar recruitment maneuver, possibly due to a partial loss in the end-expiratory lung volume. These findings suggest that an optimal PEEP level kept the lung

### Table 1. Demographic Data

<table>
<thead>
<tr>
<th></th>
<th>Study group</th>
<th>Control group</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. patients</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Age</td>
<td>61 (9)</td>
<td>67 (9)</td>
</tr>
<tr>
<td>PBW (kg)</td>
<td>63 (8)</td>
<td>63 (6)</td>
</tr>
<tr>
<td>ASA II/III</td>
<td>3/12</td>
<td>4/11</td>
</tr>
<tr>
<td>Preoperative FVC (%predicted)</td>
<td>93 (19)</td>
<td>94 (17)</td>
</tr>
<tr>
<td>Preoperative FEV(_1) (%predicted)</td>
<td>91 (23)</td>
<td>87 (24)</td>
</tr>
<tr>
<td>Preoperative FE(_V) (L)/FVC (Kpredicted)</td>
<td>76 (9)</td>
<td>79 (17)</td>
</tr>
<tr>
<td>Hemoglobin (g/dL)</td>
<td>14.2 (1.4)</td>
<td>14.6 (1.9)</td>
</tr>
<tr>
<td>Duration of mechanical ventilation (min)</td>
<td>172 (46)</td>
<td>173 (49)</td>
</tr>
<tr>
<td>Duration one-lung ventilation (min)</td>
<td>119 (44)</td>
<td>135 (50)</td>
</tr>
<tr>
<td>Surgical site R/L</td>
<td>7/8</td>
<td>8/7</td>
</tr>
</tbody>
</table>

Mean (SD) for continuous variables and \( n \) for categorical variable.

PBW = predicted body weight; FVC = forced vital capacity; FE\(_V\) = forced expiratory volume; MV = mechanical ventilation; One-Lung Ventilation = one-lung ventilation; \( R \) = right; \( L \) = left.

### Table 2. Intragroup Differences of Oxygenation and Ventilatory Variables

<table>
<thead>
<tr>
<th>Study group</th>
<th>Control group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pa(_o) (mm Hg)</td>
<td>−199; [−293 to –114](*); ( P &lt; 0.001 )</td>
</tr>
<tr>
<td>Alveolar dead space (mL)</td>
<td>0.02; [−0.05 to 0.11]</td>
</tr>
<tr>
<td>Alveolar dead space/tidal volume</td>
<td>0.01; [−0.04 to 0.03]</td>
</tr>
<tr>
<td>Bioelectric dead space (mL)</td>
<td>0.02; [−0.05 to 0.05]</td>
</tr>
<tr>
<td>Bioelectric dead space/tidal volume</td>
<td>0.001; [−0.05 to 0.05]</td>
</tr>
<tr>
<td>Physiologic dead space (mL)</td>
<td>0.02; [−0.05 to 0.11]</td>
</tr>
<tr>
<td>Physiologic dead space/tidal volume</td>
<td>0.01; [−0.04 to 0.03]</td>
</tr>
<tr>
<td>Volume ( V ) (L)</td>
<td>1.00</td>
</tr>
<tr>
<td>Volume (L)</td>
<td>0.009; [−0.02 to 0.05]</td>
</tr>
<tr>
<td>Volume (L)</td>
<td>0.002; [−0.05 to 0.11]</td>
</tr>
<tr>
<td>Volume (L)</td>
<td>0.008; [−0.06 to 0.10]</td>
</tr>
<tr>
<td>Volume (L)</td>
<td>0.001; [−0.04 to 0.03]</td>
</tr>
<tr>
<td>Volume (L)</td>
<td>0.000; [−0.05 to 0.05]</td>
</tr>
</tbody>
</table>

Data described as mean of the difference; corrected 95% of the confidence interval and corrected \( P \) value of the difference.

PEEP = positive end-expiratory pressure.

\( \* P < 0.05 \)
open, while an inadequate PEEP level could not prevent alveolar recollapse after an alveolar recruitment maneuver in thoracic surgeries.

Our results are in agreement with other studies, showing that PEEP improves oxygenation during one-lung ventilation. However, the effects of different PEEP levels on

### Table 4. Ventilatory Variables

<table>
<thead>
<tr>
<th></th>
<th>Bilateral-lung ventilation</th>
<th>One-lung ventilation, prerecruitment maneuver</th>
<th>One-lung ventilation 20 min after PEEP</th>
<th>End one-lung ventilation</th>
<th>End bilateral-lung ventilation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static compliance (mL·cm⁻¹·H₂O⁻¹)</td>
<td>53 (21)</td>
<td>33 (7)</td>
<td>35 (7)</td>
<td>33 (6)</td>
<td>49 (24)</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
<td>0.39</td>
</tr>
<tr>
<td>Physiologic dead-space volume/tidal volume</td>
<td>0.63 (0.4)</td>
<td>0.65 (0.8)</td>
<td>0.62 (0.8)</td>
<td>0.65 (0.8)</td>
<td>0.65 (0.9)</td>
</tr>
<tr>
<td></td>
<td>0.06</td>
<td>0.10</td>
<td>0.10</td>
<td>0.27</td>
<td>0.55</td>
</tr>
<tr>
<td>Alveolar dead-space volume/alveolar tidal volume</td>
<td>0.31 (0.2)</td>
<td>0.32 (0.5)</td>
<td>0.31 (0.4)</td>
<td>0.33 (0.4)</td>
<td>0.33 (0.4)</td>
</tr>
<tr>
<td></td>
<td>0.14</td>
<td>0.31 (0.1)</td>
<td>0.31 (0.1)</td>
<td>0.32 (0.1)</td>
<td>0.32 (0.1)</td>
</tr>
<tr>
<td>Peak inspiratory pressure (cm·H₂O)</td>
<td>21 (4)</td>
<td>26 (4)</td>
<td>26 (6)</td>
<td>26 (6)</td>
<td>26 (6)</td>
</tr>
<tr>
<td></td>
<td>0.16</td>
<td>0.31</td>
<td>0.41</td>
<td>0.53</td>
<td>0.53</td>
</tr>
<tr>
<td>Tidal volume (mL)</td>
<td>8 (0)</td>
<td>6.7 (0.4)</td>
<td>6.8 (0.4)</td>
<td>6.8 (0.4)</td>
<td>7.8 (0.4)</td>
</tr>
<tr>
<td></td>
<td>0.09</td>
<td>0.09</td>
<td>0.05</td>
<td>0.34</td>
<td>0.34</td>
</tr>
<tr>
<td>Ventilatory rate (breaths/min)</td>
<td>13 (1)</td>
<td>15 (1)</td>
<td>16 (1)</td>
<td>16 (1)</td>
<td>15 (1)</td>
</tr>
<tr>
<td></td>
<td>0.69</td>
<td>0.53</td>
<td>0.47</td>
<td>0.62</td>
<td>0.62</td>
</tr>
<tr>
<td>Airway resistance (cm·H₂O L⁻¹·s⁻¹)</td>
<td>11(3)</td>
<td>20(3)</td>
<td>23(6)</td>
<td>23(6)</td>
<td>13(4)</td>
</tr>
<tr>
<td></td>
<td>0.19</td>
<td>0.37</td>
<td>0.06</td>
<td>0.07</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Data are presented as mean (SD). P < 0.05 in all groups.

PEEP = positive end-expiratory pressure.

*Control versus study.

1**Bilateral versus one-lung ventilation prerecruitment maneuver.

1**One-lung ventilation prerecruitment maneuver vs 20 minutes after PEEP during one-lung ventilation, and end of one-lung ventilation, P value for control versus study difference.
oxygenation during one-lung ventilation have been contro-
versial, because heterogeneity in lung pathology produces
different responses to PEEP. Michelet et al.13 found that 5
and 10 cm-H2O of PEEP improved oxygenation to the same
degree, but 15 cm-H2O worsened oxygenation because over
distension can increase shunt by diverting pulmonary blood
flow to nonaerated areas. Several studies showed that 4 to
5 cm-H2O of PEEP during one-lung ventilation improved
oxygenation, but increasing PEEP level to 8 to 10 cm-H2O
did not improve oxygenation and was sometimes counter-
productive.16,17 Leong et al.18 compared PEEP levels 0, 5, 8,
and 10 cm-H2O during one-lung ventilation and found no
differences in oxygenation.

Based on these results, several authors have promoted
the use of 5 cm-H2O during one-lung ventilation for all
patients.11,21,35 However, some studies suggest that it is
unreasonable to apply a standardized PEEP level for all
patients during one-lung ventilation and that PEEP levels
should be individualized. Valenza et al.19 showed that PEEP
was more effective in nonobstructive patients (high forced
expiratory volume in 1 second) with lower risk of auto-
PEEP than in patients with low high forced expiratory vol-
ume in 1 second. Slinger and Scott16 also showed that PEEP
effectiveness regarding oxygenation and lung mechanics
depends on the interaction between PEEP and auto-PEEP,
which in turn depends on patient mechanical character-
istics. In another study, Slinger et al.12 showed that PEEP
effectively prevented atelectasis, but that the applied PEEP
level should be individualized based on the static compli-
ance curve.

The physiological and clinical effects of a particular
level of PEEP are different when PEEP is used isolated or
in combination with an alveolar recruitment maneuver.37
Therefore, it is difficult to compare the above studies with
the ones by using the concept of lung recruitment.

Alveolar recruitment maneuver strategies are not rou-
tinely done by anesthesiologists during one-lung venti-
lation and are usually conducted only when hypoxemia
appears.11,35,38 However, previous studies have shown that
an alveolar recruitment maneuver during one-lung venti-
lation improves oxygenation, ventilation efficiency, and
lung mechanics due to reopening of atelectatic areas.22–26
Each of these studies fixed PEEP levels between 5 and 10
cm-H2O without determining individual optimized PEEP
settings. Therefore, the difference between using a standard
PEEP level versus an individualized level after an alveolar
recruitment maneuver in one-lung ventilation has not been
eucidated.

Optimal PEEP is defined as the postalveolar recruitment
maneuver PEEP level that prevents alveolar collapse while
minimizing overdistension. Optimal PEEP encourages
maximal arterial oxygen tension and compliance and mini-
mal dead-space29 in restrictive,27 healthy,32 and obstructive12
lungs. Our study showed that the improved oxygenation
after an alveolar recruitment maneuver was only main-
tained at the end of one-lung ventilation in the group with
an individualized PEEP level. These results suggest that an
optimal PEEP level keeps the lung open, while 5 cm-H2O
of PEEP level may not prevent alveolar recollapse or dere-
cruitment. Despite the differences of PEEP with and with-
out an alveolar recruitment maneuver, our results are not
comparable with previous studies due to methodological
differences. First, we recruited both groups; to our knowl-
edge, this is the first study comparing the effects of indi-
vidualized PEEP and standardized PEEP after applying
an alveolar recruitment maneuver in both groups. Second,
we performed the alveolar recruitment maneuver during
one-lung ventilation. Cinnella et al.24 and Tusman et al.25
recruited during one-lung ventilation, but they established
a standardized PEEP level in all patients and did not evalu-
ate oxygenation at the end of one-lung ventilation.

Our hypothesis was reinforced by the lung mechanics
results. In the study group, static compliance improved
after the alveolar recruitment maneuver, and the improve-
ment was maintained during the whole procedure with
one-lung ventilation. In contrast, in the control group,
Individualized PEEP Improves Lung Function During one-lung ventilation

the post-alveolar recruitment maneuver static compliance improvement was lost, presumably due to alveolar recollapse. These results are compatible with those obtained by Unzueta et al. and Park et al., who found no differences in static compliance between groups with and without an alveolar recruitment maneuver when a fixed PEEP was applied.

Previous studies showed that an alveolar recruitment maneuver decreases the dead-space effect produced by atelectasis and improves ventilation efficiency as demonstrated by reduced alveolar dead-space volume/alveolar tidal volume in cardiothoracic surgery. We hypothesized that an optimal PEEP level might more effectively maintain the benefits of an alveolar recruitment maneuver in terms of ventilation efficiency, compared with by using a standardized PEEP level; however, our results did not confirm this. We believe that the lack of difference in dead space observed between groups depended on the amount of lung collapse. Because both groups were recruited, it is reasonable to think that the control group kept some recruitment effect by 5 cm H2O of PEEP and that such an effect minimized the difference in dead space. Alveolar dead-space volume/alveolar tidal volume increased <5% in our study while Unzueta et al. showed an increase >35% because an alveolar recruitment maneuver was not performed in their control patients. Increased levels of atelectasis in patients make the changes produced by an alveolar recruitment maneuver more evident.

Despite a lack of statistical differences in pH, Paco2 was significantly higher in the study group than in the control group. Based on the results of previous studies, this may have contributed to a decreased shunt and improved oxygenation in the study group through an improvement in hypoxic pulmonary vasoconstriction. This limitation should be considered in future studies.

In concordance with previous studies, we found no differences in cardiac index between groups with different levels of PEEP. No clinically relevant changes to cardiac index occurred during the alveolar recruitment maneuver.

Our study has some limitations. The main limitation of the study is that our discussion is based on the effects of the alveolar recruitment maneuver and PEEP on atelectasis without providing evidence from lung images or shunt measurements. Previous studies showed the effect of an alveolar recruitment maneuver on shunt and/or atelectasis by using a computed tomography scan and magnetic resonance images. We determined the effect of lung recruitment by using classical indirect measurements such as Paco2, static compliance and alveolar dead space. The second limitation is that the use of 100% FiO2 may have contributed to an increase in the amount of reabsorption atelectasis, thereby reducing Paco2 in the control group. In this way, the use of lower levels of FiO2 may have varied the differences in oxygenation observed between groups. However, the use of 100% FiO2 is the first rescue therapy when hypoxemia appears. In this case, the use of an individualized level of PEEP would prevent reabsorption atelectasis more than a standardized level of PEEP.

In conclusion, the present results showed that during one-lung ventilation, the effects of an alveolar recruitment maneuver on lung function is better preserved with an individualized level of PEEP based on a PEEP decrement trial compared with that of simple arbitrary PEEP levels of 5 cm H2O.

DISCLOSURES
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Name: Francisco Javier Belda, MD, PhD.
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REFERENCES
9. Fujiwara M, Abe K, Mashimo T. The effect of positive end-expiratory pressure and continuous positive airway pressure on the