Use of dynamic compliance for open lung positive end-expiratory pressure titration in an experimental study

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Objective: We tested whether the continuous monitoring of dynamic compliance could become a useful bedside tool for detecting the beginning of collapse of a fully recruited lung.

Design: Prospective laboratory animal investigation.

Setting: Clinical physiology research laboratory, University of Uppsala, Sweden.

Subjects: Eight pigs submitted to repeated lung lavages.

Interventions: Lung recruitment maneuver, the effect of which was confirmed by predefined oxygenation, lung mechanics, and computed tomography scan criteria, was followed by a positive end-expiratory pressure (PEEP) reduction trial in a volume control mode with a tidal volume of 6 mL/kg. Every 10 mins, PEEP was reduced in steps of 2 cm H₂O starting from 24 cm H₂O. During PEEP reduction, lung collapse was defined by the maximum dynamic compliance value after which a first measurable decrease occurred. Open lung PEEP according to dynamic compliance was then defined as the level of PEEP before the point of collapse. This value was compared with oxygenation (PaO₂) and CT scans.

Measurements and Main Results: PaO₂ and dynamic compliance were monitored continuously, whereas computed tomography scans were obtained at the end of each pressure step. Collapse defined by dynamic compliance occurred at a PEEP of 14 cm H₂O. This level coincided with the oxygenation-based collapse point when also shunt started to increase and occurred one step before the percentage of nonaerated tissue on the computed tomography exceeded 5%. Open lung PEEP was thus at 16 cm H₂O, the level at which oxygenation and computed tomography scan confirmed a fully open, not yet collapsed lung condition.

Conclusions: In this experimental model, the continuous monitoring of dynamic compliance identified the beginning of collapse after lung recruitment. These findings were confirmed by oxygenation and computed tomography scans. This method might become a valuable bedside tool for identifying the level of PEEP that prevents end-expiratory collapse. (Crit Care Med 2007; 35:214–221)

Key Words: lung compliance; recruitment; lung collapse; positive end-expiratory pressure; open lung; tomography; spiral computed tomography scans were obtained at the end of each pressure step. Collapse defined by dynamic compliance occurred at a PEEP of 14 cm H₂O. This level coincided with the oxygenation-based collapse point when also shunt started to increase and occurred one step before the percentage of nonaerated tissue on the computed tomography exceeded 5%. Open lung PEEP was thus at 16 cm H₂O, the level at which oxygenation and computed tomography scan confirmed a fully open, not yet collapsed lung condition.

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First, recruitment is a highly empirical intervention with ill-defined end points that are particularly difficult to assess at the bedside. Second, alveolar collapse and tidal recruitment are hidden phenomena that cannot be detected with conventional monitoring means. To date, oxygenation is the principal clinical variable used for assessing recruitment, but it lacks specificity and is insensitive for detecting lung overdistension and tidal recruitment (11).

Lung mechanics have been studied extensively by means of pressure-volume (PV) curves. It is now increasingly accepted that only the deflation limb of the PV curve provides information about OL-PEEP (12, 13). However, PV curves are not easily obtained at the bedside, and their interpretation is complex as they are profoundly affected by the previous...
lung volume history and do not reflect steady-state lung conditions (14).

A decremental PEEP trial (DPT) after full lung recruitment allows the clinician to titrate PEEP along the deflation limb of the PV curve while observing changes in both oxygenation and lung mechanics (12, 15). During a decremental PEEP trial, the point of maximal tidal compliance and the point of maximum curvature have been shown to correspond to OL-PEEP (12, 13).

The aim of this study was to investigate whether changes in dynamic compliance, measured on a breath-by-breath basis during a decremental PEEP trial, could detect the occurrence of lung collapse as defined by oxygenation and CT scan and hence identify OL-PEEP.

MATERIALS AND METHODS

The study was performed at the Departments of Clinical Physiology and Radiology of the University Hospital of Uppsala, Sweden. Eight healthy pigs (weight 29.8 ± 2.1, Swedish mixed country breed) were studied after approval by the local animal ethics committee.

Experimental Model. After induction of anesthesia, animals were tracheotomized and ventilated through a 7-mm inner diameter endotracheal tube (Mallinkrodt, Athlone, Ireland). A constant flow ventilation mode (Servo-i, Maquet Critical Care, Solna, Sweden), a tidal volume of 6 mL/kg of body weight, a respiratory rate of 30 breaths/min, a PEEP level of 6 cm H2O, and an inspiratory/expiratory ratio of 1:2 were started. FIO2 was maintained at 1.0 during the entire study period.

Lung lavages with warm saline (16) were repeated every 5 mins until a sustained reduction in the PaO2/FIO2 < 100 mm Hg during a period of 60 mins was obtained.

Blood Gases and Hemodynamic Monitoring. Femoral artery pressure was monitored. Pulmonary arterial pressures, cardiac output, and mixed venous saturation were continuously measured via a fiberoptic pulmonary oximetry catheter (CCombo 7.5-Fr, Edwards Life Sciences LLC, Irvine, CA).

Arterial blood gases were monitored continuously (Trendcare, Diagnostics Medical Ltd, High Newcombe, UK). Independent arterial and mixed venous blood samples were obtained at the end of each PEEP step (ABL 300, OSM 3 and cooximeter, Radiometer, Copenhagen, Denmark).

Lung Mechanics. Breath-by-breath dynamic compliance was calculated and its online trend displayed on the ventilator’s screen using the Open Lung Tool (Servo-i Maquet Critical Care, Solna, Sweden). At the end of each protocol step, two 5-sec end-inspiratory and end-expiratory hold maneuvers were performed for calculating static compliance and to exclude intrinsic PEEP, respectively. Airway resistance was calculated using independent flow and pressure sensors (CO2SMO Plus, Novametrix Medical Systems, Wallingford, CT).

Computed Tomography Analysis. The changes in lung aeration were studied by computed tomography (CT) (Somatom Sensation 16, Siemens, Forchheim, Germany). Transverse CT slices were obtained 2 cm cranial of the right diaphragmatic dome (as determined by a prior scout view) during end-expiratory and end-inspiratory hold maneuvers at the end of each protocol step. CT exposure time was 0.75 secs at 120 mA and 100 Kv. Images were reconstructed with 6-mm slice thickness using a standard body reconstruction filter (Siemens notation, B40s).

For CT image analysis, the software Maluma (Mannheim Lung Analyzing Tool, version 2.02, Mannheim, Germany) was used. Differently aerated lung regions were classified using standard definitions based on Houndsfield units (HU) (17): nonaerated (NonA, +100 to −100 HU), poorly aerated (−100 to −500 HU), normally aerated (−500 to −900 HU), and hyperinflated (−900 and −1000 HU). The amount of NonA (equals atelectasis) was expressed as a percentage of the total lung area (18). The extent of tidal recruitment was computed by subtracting the area of NonA at end-expiration from the one at end-inspiration (19).

A fully recruited lung was defined by all of the following criteria:
a) Gain in compliance of >30% compared with baseline
b) PaO2/FIO2 > 400 mm Hg
c) NonA ≤ 5%

Likewise, lung collapse was defined as follows:

a) Maximum value of dynamic compliance during stepwise PEEP reduction
b) PaO2/FIO2 reduction of ≥10% of any individual maximum value reached after recruitment
c) NonA ≥ 5% of the total lung section

OL-PEEP was defined as the pressure level just before point of collapse as defined by dynamic compliance (Cdyn).

Study Protocol. After baseline data acquisition at a PEEP of 6 cm H2O, ventilation pressures were stepwise increased before applying the recruitment pressures. The RM was performed in pressure control mode with a PEEP of 30 cm H2O and a peak inspiratory pressure of 60 cm H2O for 2 mins. The inspiratory/expiratory ratio was increased to 1:1. Thereafter, the ventilator was switched back to the previous settings but with a PEEP of 24 cm H2O. PEEP was then reduced in steps of 2 cm H2O starting from 24 down to 6 cm H2O and finally in one step to zero end-expiratory pressure. The total duration of the DPT was 110 mins. Tidal volume was maintained constant at 6 mL/kg. Each PEEP was applied for 10 mins to allow for hemodynamic and respiratory stabilization (Fig. 1).

A custom-made data acquisition system programmed in LabView (version 6.0, National Instruments, Austin, TX) recorded all variables except for off-line blood gases. Mean data from 30 breaths before blood sampling and breath hold maneuvers were used as representatives for each protocol step.

Statistical Analysis. Results are expressed as mean ± SD unless otherwise specified. Continuous variables were analyzed by analysis of variance using Bonferroni’s multiple comparison test for post hoc analysis. Correlations between the percentage of NonA and oxygenation variables were made by linear regression analysis. Agreement between dynamic and static compliance was tested by the Bland-Altman method (20). Sensitivity and specificity of Cdyn and oxygenation to detect a 5% lung collapse on the CT scan (the reference method) were evaluated by constructing a receiver operating characteristics curve (20–22). Significance was assumed at p < .05.

RESULTS

The RM fulfilled the predefined criteria in all animals. No animal developed
barotrauma detectable by CT scan. Main variables at selected protocol steps are shown in Table 1.

Changes in Cdyn during the DPT showed a similar pattern in all animals (Fig. 2), and visual identification of each maximum value was easy. The point of maximum Cdyn was reached at a PEEP of 14 cm H2O, and its first visual decrease occurred at 12 cm H2O. Consequently, OL-PEEP was set to 16 cm H2O. Cdyn measured at the airway opening using the CO2SMO Plus and static compliance both were slightly higher than Cdyn measured within the ventilator (mean difference 1.3 ± 0.6 and 3.3 ± 0.8 mL/cm H2O, respectively). However, irrespective of the method, all curves ran in parallel, showed a similar overall behavior, and reached their respective maxima at identical PEEP levels. Correlations between Cdyn of the ventilator and Cdyn at the airway opening on the one hand (R = .98) and static compliance on the other (R = .92) were high (p < .01). Figure 3 shows Cdyn and static compliance of the ventilator.

Maximum values of airway resistance of 23.2 ± 4.8 cm H2O·L−1·sec−1 were seen during baseline ventilation. After recruitment, resistance significantly decreased and continued to decrease in parallel with PEEP until its lowest value (10.1 ± 0.7 cm H2O·L−1·sec−1) at PEEP 12 cm H2O, only to increase again at even lower PEEPs.

Oxygenation remained stable throughout the first four PEEP decrements. Maximum oxygenation occurred at PEEP 22 cm H2O (PaO2 = 557 ± 26 mm Hg). A decrease of ≥10% in oxygenation occurred at a PEEP of 14 cm H2O, although the first statistically significant reduction was at PEEP 12 cm H2O, corresponding to a 17% decrease from maximal PaO2 (p < .001). Further reductions in PEEP led to a continuous and rapid decrease in PaO2 in parallel with the reduction in Cdyn (Fig. 4). The curve representing the shunt fraction was a mere mirror image of PaO2.

After RM, PaCO2 significantly decreased and remained stable during the DPT until the lowest PEEP levels were reached. Initially, carbon dioxide elimination decreased after recruitment but reached its maximum at OL-PEEP (Table 2).

After recruitment, the percentage of NonA tissue decreased to values <3%. During the first PEEP decrements, NonA showed minimal variability. The CT collapse criterion (>5% NonA) was met at PEEP 12 cm H2O (7.3 ± 5.4% NonA). The first significant increase in NonA, however, occurred at PEEP 8 cm H2O (18% NonA, p < .001). Changes in NonA correlated with changes in shunt (R = .85, p < .001) (Fig. 4) and showed a negative correlation with changes in PaO2 (R = −.86, p < .001). Figure 5 shows CT images at selected protocol steps and the corresponding HU frequency distribution in a representative animal.

Tidal recruitment remained <0.25% until OL-PEEP (16 cm H2O) but progressively increased with further PEEP reductions (Fig. 6).

Both definitions of collapse, the point of maximal compliance and a >10% fall in oxygenation from its post-RM maximum, showed a sensitivity of 84.4% and a specificity of 87.5 and 95.8% (p < .001), respectively, for detecting a fraction of NonA tissue on the CT images of >5% (Fig. 7).

Table 1. Main variables at selected protocol steps

<table>
<thead>
<tr>
<th>Variable</th>
<th>Baseline</th>
<th>Post-RM</th>
<th>OL-PEEP</th>
<th>Collapse</th>
<th>Post-Collapse</th>
<th>Final PEEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEEP, cm H2O</td>
<td>6</td>
<td>24</td>
<td>16</td>
<td>14</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Cdyn, mL/cm H2O</td>
<td>10.2 ± 1.9</td>
<td>11.8 ± 1.9</td>
<td>22.1 ± 4.2</td>
<td>23.2 ± 3.9</td>
<td>22.6 ± 4.4</td>
<td>14.6 ± 3.2</td>
</tr>
<tr>
<td>PaO2/FIO2, mm Hg</td>
<td>89 ± 65</td>
<td>557 ± 47</td>
<td>520 ± 47</td>
<td>477 ± 83</td>
<td>408 ± 115</td>
<td>184 ± 91</td>
</tr>
<tr>
<td>CT Non-A, %</td>
<td>38.3 ± 11.5</td>
<td>2.3 ± 1.3</td>
<td>2.7 ± 2.3</td>
<td>4.4 ± 3.8</td>
<td>7.3 ± 5.4</td>
<td>27.1 ± 10.3</td>
</tr>
<tr>
<td>Shunt, %</td>
<td>43.6 ± 12.9</td>
<td>4.4 ± 1.4</td>
<td>6.8 ± 2.2</td>
<td>8.9 ± 3.9</td>
<td>12.8 ± 5.4</td>
<td>29.1 ± 5.9</td>
</tr>
</tbody>
</table>

Baseline, after induction of lung injury; post-RM, post recruitment at first decremental PEEP step; OL-PEEP, open lung positive end-expiratory pressure 2 cm H2O above maximal dynamic compliance; collapse, PEEP level resulting in maximal dynamic compliance; post-collapse, first decremental PEEP step after maximal compliance; final PEEP, PEEP level equal to baseline but during decremental PEEP trial; Cdyn, dynamic compliance; CT NonA, percentage of nonaerated tissue (−100 to 100 Hounsfield units) on the computed tomography scan.
Hemodynamics. At baseline and after significant lung collapse reappeared during the DPT, hemodynamics were characterized by a hyperdynamic state with high cardiac index, low systemic vascular resistance, and high pulmonary arterial pressure. Cardiac index and oxygen delivery decreased after RM showing normal values at OL-PEEP, reaching maximum values at the lowest PEEP level. Mean pulmonary arterial pressure decreased significantly after RM and during the first decremental PEEP steps until a PEEP of 10 cm H2O, when it started to increase again. Ventilation and hemodynamic variables at selected PEEP steps are provided in Table 2.

**DISCUSSION**

In this study we propose the continuous bedside monitoring of dynamic compliance for identifying the level of PEEP that prevents end-expiratory collapse of a recruited lung. In this porcine surfactant depletion model, we found that during a decremental PEEP trial after full lung recruitment, any decrease in compliance—after reaching its maximum value—was associated with ongoing and progressive lung collapse. The point of maximum dynamic compliance indicated the PEEP level below which lung collapse started to occur, which was confirmed by the appearance of atelectasis on the CT scan and a parallel decrease in oxygenation. In addition, the point of maximum dynamic compliance was easily identified visually in all animals.

The use of best compliance for optimum PEEP titration was first proposed by Suter et al. (23). However, in this landmark publication, the authors did not explore the effects of lung recruit-

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**Table 2. Respiratory and hemodynamic variables at selected protocol steps**

<table>
<thead>
<tr>
<th>PEEP, cm H2O</th>
<th>Baseline</th>
<th>Post-RM</th>
<th>OL-PEEP</th>
<th>Collapse</th>
<th>Post-Collapse</th>
<th>Final PEEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEEP, cm H2O</td>
<td>6</td>
<td>24</td>
<td>16</td>
<td>14</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Respiratory variables</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Ppeak, cm H2O</td>
<td>27 ± 3</td>
<td>42 ± 3a</td>
<td>25 ± 1b</td>
<td>25 ± 1b</td>
<td>23 ± 2b</td>
<td>21 ± 2c</td>
</tr>
<tr>
<td>Pplat, cm H2O</td>
<td>25 ± 3</td>
<td>41 ± 3b</td>
<td>25 ± 1b</td>
<td>22 ± 1b</td>
<td>20 ± 2b</td>
<td>20 ± 2b</td>
</tr>
<tr>
<td>Mean, cm H2O</td>
<td>11 ± 1</td>
<td>28 ± 1c</td>
<td>18 ± 1b</td>
<td>17 ± 1b</td>
<td>14 ± 1b</td>
<td>10 ± 1b</td>
</tr>
<tr>
<td>Raw, cm H2O L-1·sec-1</td>
<td>23.2 ± 4.8</td>
<td>14.9 ± 2.1b</td>
<td>10.4 ± 0.6b</td>
<td>10.1 ± 0.5b</td>
<td>10.1 ± 0.7b</td>
<td>13.0 ± 1.5c</td>
</tr>
<tr>
<td>Vr, mL</td>
<td>196 ± 15</td>
<td>195 ± 14</td>
<td>194 ± 14</td>
<td>194 ± 15</td>
<td>195 ± 15</td>
<td>195 ± 16</td>
</tr>
<tr>
<td>PacO2, mm Hg</td>
<td>59.6 ± 6.9</td>
<td>48.4 ± 5.4b</td>
<td>45.2 ± 4.9</td>
<td>46.5 ± 5.3</td>
<td>46.6 ± 5.7</td>
<td>51.3 ± 6.1</td>
</tr>
<tr>
<td>pH</td>
<td>7.23 ± 0.06</td>
<td>7.28 ± 0.04</td>
<td>7.29 ± 0.05</td>
<td>7.31 ± 0.06</td>
<td>7.32 ± 0.06</td>
<td>7.28 ± 0.06</td>
</tr>
<tr>
<td>VCO2, mL/min</td>
<td>91.2 ± 20</td>
<td>77.5 ± 19b</td>
<td>96.3 ± 18.6a</td>
<td>98.8 ± 19.1b</td>
<td>97 ± 20b</td>
<td>95.3 ± 19.8c</td>
</tr>
<tr>
<td>Hemodynamic variables</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>MAP, mm Hg</td>
<td>90 ± 12</td>
<td>71 ± 7a</td>
<td>81 ± 11</td>
<td>83 ± 12</td>
<td>82 ± 12</td>
<td>87 ± 17</td>
</tr>
<tr>
<td>PAPM, mm Hg</td>
<td>41.7 ± 5.3</td>
<td>40.2 ± 2.4</td>
<td>36.4 ± 1.6</td>
<td>35.5 ± 2.4</td>
<td>34.4 ± 3.6</td>
<td>40.4 ± 3.3</td>
</tr>
<tr>
<td>CI, L/min-m2</td>
<td>6.6 ± 2.2</td>
<td>3.2 ± 0.9a</td>
<td>3.5 ± 0.9</td>
<td>3.7 ± 0.9</td>
<td>4.0 ± 0.9</td>
<td>5.4 ± 1.1</td>
</tr>
<tr>
<td>Do2, L/min·m2</td>
<td>639 ± 216</td>
<td>373 ± 168a</td>
<td>446 ± 143b</td>
<td>460 ± 133b</td>
<td>492 ± 140b</td>
<td>610 ± 140b</td>
</tr>
<tr>
<td>SVRI, dynes·sec/cm5·m2</td>
<td>1173 ± 836</td>
<td>1495 ± 441</td>
<td>1680 ± 887</td>
<td>1648 ± 852</td>
<td>1482 ± 659</td>
<td>1127 ± 255</td>
</tr>
<tr>
<td>PVRI, dynes·sec/cm5·m2</td>
<td>211 ± 167</td>
<td>194 ± 69</td>
<td>187 ± 53</td>
<td>192 ± 54</td>
<td>171 ± 75</td>
<td>189 ± 50</td>
</tr>
</tbody>
</table>

Baseline, after induction of lung injury; post-RM, post-recruitment at first decremental PEEP step; OL-PEEP, open lung positive end-expiratory pressure 2 cm H2O above maximal dynamic compliance; collapse, PEEP level resulting in maximal dynamic compliance; post-collapse, first decremental PEEP step after maximal compliance; final PEEP, PEEP level equal to baseline but during decremental PEEP trial; Ppeak, peak airway inspiratory pressure; Pplat, plateau airway pressure; Pmean, mean airway pressure; Raw, airway resistance; Vr, tidal volume; VCO2, elimination of CO2 per minute; MAP, mean systemic arterial pressure; PAPM, mean pulmonary artery pressure; CI, cardiac index; Do2, indexed oxygen delivery; SVRI, systemic vascular resistance index; PVRI, pulmonary vascular resistance index.

*p < .001, post-RM PEEP of 24 cm H2O vs. baseline; *p < .05, post-RM PEEP of 24 cm H2O vs. OL-PEEP; **p < .05, final PEEP vs. baseline PEEP.
ment, limiting their analysis to the inflation limb of the PV relationship.

In a mathematical simulation of the ARDS lung, Hickling (12) found that during a DPT after full lung recruitment, the best tidal compliance was related to OL-PEEP.

We followed this theoretical consideration to derive a clinical method to detect the beginning of lung collapse and hence to estimate OL-PEEP. If a DPT starts at high levels of PEEP after full lung recruitment, tidal ventilation moves downward on the outer envelope of the deflation limb of the PV curve provided tidal volumes are kept constant and low (14, 15). In this situation, three main factors affect the changes in compliance: a) Initially, the reduction of alveolar volume and inflation increases tidal compliance; b) as PEEP decreases below OL-PEEP, end-expiratory collapse begins reducing tidal compliance; and c) immediately after the onset of end-expiratory collapse, the emergence of tidal recruitment will increase tidal compliance, opposing a collapse-related decrease. The complex interrelation between these factors accounts for the fact that in theory, maximal dynamic compliance will tend to underestimate true open lung PEEP (12, 24) especially in the heterogeneous ARDS lung. Nevertheless, an important clinical conclusion can be drawn from this behavior: During a DPT after full lung recruitment, the reduction in tidal compliance after reaching a maximum is related to the onset of end-expiratory lung collapse. Furthermore, if tidal volume is kept low

Figure 5. Upper panel, end-expiratory computed tomography (CT) scans of a representative animal: (A) during baseline ventilation after induction of lung injury; (B) during postrecruitment at the first decremental positive end-expiratory pressure (PEEP) step of 24 cm H2O; (C) open lung PEEP; (D) onset of lung collapse corresponding to maximum dynamic compliance; (E) PEEP level right after collapse; and (F) PEEP level equal to baseline but during decremental PEEP trial. Lower panel, corresponding frequency distribution of Hounsfield units (HU) for each of the above CT images. Open boxes, inspiration; filled boxes, expiration.
during the DPT, as we did in this study, the effects of tidal recruitment can be minimized, thereby increasing the correspondence between best dynamic compliance and OL-PEEP. In the present study we have observed that maximal dynamic compliance immediately preceded the onset of relevant (>5%) lung collapse seen on the CT scan. At the anatomical level at which the CT scan was taken, tidal recruitment was virtually absent above OL-PEEP; however, some degree of tidal recruitment in other lung regions could not be excluded.

Airway resistance decreased after recruitment and during the first DPT steps. Although we do not have a conclusive explanation for this behavior, we speculate that after RM at maximum PEEP levels, the distension of the nondependent regions may result in a compression of dependent lung regions. As PEEP is reduced, the more homogeneous distribution of ventilation results in a reduction in resistance until lung tissue begins to collapse.

In several clinical and experimental studies, $\text{PaO}_2$/FiO$_2$ levels $>400$ mm Hg have been shown to mark an open lung condition (25–27). Decreases in oxygenation during a DPT are related to progressive derecruitment (28), although the empirical criterion of a decrease $>10\%$ of the maximum post-RM $\text{PaO}_2$ for defining lung collapse has not been validated systematically (29).

The CT scan is a sensitive and validated method for detecting lung collapse (17, 27, 33). We empirically chose the threshold value of 5% of nonaerated tissue to define relevant lung collapse, but the biological significance of this threshold is unknown.

Although cardiac index remained normal during the DPT, it markedly decreased after RM emphasizing the caution with which such maneuvers must be performed (34). Others did not find any such effect during and after RM in ARDS patients (35). Oxygen delivery and cardiac index were highest, reaching supranormal values at lowest PEEP levels. We think that this was the net result of a reduction in intrathoracic pressure, an increased PaCO$_2$, and a compensation for a decreased efficiency of ventilation. After RM, mean pulmonary arterial pressure decreased despite higher PEEP levels suggesting both a direct vasodilator effect of oxygen and the efficient reexpansion of collapsed tissue.

Limitations. The surfactant depletion model used in this study as opposed to other experimental models and human acute respiratory distress syndrome (36) is characterized by a homogeneous distribution of the lung lesions in which full lung recruitment is easily obtained. In established acute respiratory distress syndrome, full lung recruitment as defined in our study may not be achievable even with highest recruitment pressures. It has yet to be established whether the changes in $C_{\text{dyn}}$ will effectively detect OL-PEEP in patients with acute respiratory distress syndrome. The effects of chest wall compliance and abdominal pressure were not taken into account in the measurements and were considered unchanged during the protocol.

The use of pure oxygen may have promoted lung collapse due to resorption atelectasis. However, this fact did not blur the detection of lung collapse, the primary goal of this study.
The observation period for each PEEP step was limited to 10 mins. It cannot be inferred from these data whether the positive physiologic effects seen at OL-PEEP could be maintained for a longer period of time. However, it has been shown that if airway pressure is not lost, lung stability can be maintained for many hours (27, 37). The time spent at high levels of PEEP could have introduced a time-dependent recruitment effect in this model. Finally, the number of animals was small, limiting the power of the statistical analysis.

CONCLUSIONS

During a decremental PEEP trial after full lung recruitment, dynamic compliance identified the beginning of lung collapse in a pig model. Collapse was confirmed by both CT scans and PaO2. Provided these findings can be reproduced in patients with acute respiratory distress syndrome, the continuous monitoring of dynamic compliance might become a valuable bedside tool for easily identifying the level of PEEP that prevents end-expiratory lung collapse.

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REFERENCES

12. Hickling KG: Best compliance during a decremental, but not incremental, positive end expiratory pressure trial is related to open lung positive end expiratory pressure. Am J Respir Crit Care Med 2001; 163:69–78
33. Lu Q, Malbouisson L, Mourgeo E, et al: Assessment of PEEP induced reopening of collapsed lung regions in acute lung injury: are one or three CT sections representative of