Ventilatory Protective Strategies during Thoracic Surgery

Effects of Alveolar Recruitment Maneuver and Low-tidal Volume Ventilation on Lung Density Distribution

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ABSTRACT

Background: The increased tidal volume (VT) applied to the ventilated lung during one-lung ventilation (OLV) enhances cyclic alveolar recruitment and mechanical stress. It is unknown whether alveolar recruitment maneuvers (ARMs) and reduced VT may influence tidal recruitment and lung density. Therefore, the effects of ARM and OLV with different VT on pulmonary gas/tissue distribution are examined.

Methods: Eight anesthetized piglets were mechanically ventilated (VT = 10 ml/kg). A defined ARM was applied to the whole lung (40 cm H2O for 10 s). Spiral computed tomographic lung scans were acquired before and after ARM. Thereafter, the lungs were separated with an endobronchial blocker. The pigs were randomized to receive OLV in the dependent lung with a VT of either 5 or 10 ml/kg. Computed tomography was repeated during and after OLV. The voxels were categorized by density intervals (i.e., atelectasis, poorly aerated, normally aerated, or overaerated). Tidal recruitment was defined as the addition of gas to collapsed lung regions before ARM. After ARM, lung volume and aeration increased (426 ± 35 vs. 526 ± 69 ml). Respiratory compliance enhanced, and tidal recruitment decreased (95% vs. 79% of the whole end-expiratory lung volume). OLV with 10 ml/kg further increased aeration (atelectasis, 15 ± 2 ml; poorly aerated, 94 ± 24 ml; normally aerated, 580 ± 98 ml) and tidal recruitment (81% of the dependent lung). OLV with 5 ml/kg did not affect tidal recruitment or lung density distribution. (Data are given as mean ± SD.)

Conclusions: The ARM improves aeration and respiratory mechanics. In contrast to OLV with high VT, OLV with reduced VT does not reinforce tidal recruitment, indicating decreased mechanical stress.

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What We Already Know about This Topic

• One-lung ventilation (OLV) may be associated with increased mechanical stress and hypoxemia.

What This Article Tells Us That Is New

• A single recruitment maneuver before OLV and ventilation with 5 ml/kg during OLV has beneficial effects on aeration of the ventilated lung.
Lung resection surgery commonly requires exclusion of the nondependent lung from ventilation (one-lung ventilation [OLV]) to improve surgical conditions. However, OLV is associated with an increased intrapulmonary shunt that results from residual perfusion in the nondependent collapsed lung and from insufficient oxygenation of blood in atelectatic and poorly ventilated regions of the dependent ventilated lung. As a result, hypoxemia is observed in approximately 10% of patients despite the use of high inspiratory fractions of oxygen (FIO₂) during OLV.

Different ventilation approaches may overcome OLV-induced hypoxemia. In addition to the application of continuous positive airway pressure and pure oxygen insufflations into the nonventilated lung, relatively high tidal volumes (VT) with zero end-expiratory pressure have been used to recruit poorly aerated alveoli in the ventilated lung and to avoid blood shift to the nondependent lung during OLV. This strategy may reinforce airway pressure, alveolar stretching, and shearing secondary to cyclic recruitment/derecruitment of alveoli. Consequently, OLV results in significant diffuse alveolar damage. However, OLV with reduced VT (VT = 5 ml/kg) has decreased the expression of alveolar proinflammatory mediators in a clinical setting and has reduced the risk of postpneumonectomy respiratory failure. Nevertheless, the simple reduction of VT seems to be insufficient to completely abolish OLV-induced lung injury.

A more rational approach to avoid alveolar collapse and to improve oxygenation during OLV may include application of repetitive alveolar recruitment maneuvers (ARMs) and reduced VT and positive end-expiratory airway pressure (PEEP) to minimize atelectasis and cyclic tidal recruitment. An effect of ARM lasting 30–40 min may be anticipated if subsequent ventilation is provided with moderate inspired oxygen concentrations of approximately 40% or even with a higher FIO₂ if sufficient PEEP is applied to the ventilated lung.

Therefore, this randomized computed tomographic (CT) study was undertaken to establish the effects of ARM and tidal recruitment/derecruitment. The following null hypothesis was tested: ARM and OLV with different VT did not affect cyclic recruitment and the distribution of overaerated, normally aerated, poorly aerated, and atelectatic lung regions in the ventilated lung.

Materials and Methods

The study was conducted as a prospective randomized animal experiment. The Institutional Committee on Care and Use of Animals at Uppsala University, Uppsala, Sweden, approved the experimental protocol.

Animals and Randomization

Two-month-old piglets (n = 8; mean ± SD weight, 28 ± 2.4 kg) of the Hampshire, Yorkshire, and Swedish country breeds, which fasted overnight with free access to water, were examined.

After preparation and baseline two-lung ventilation (TLV), pre-OLV-ARM and measurement algorithms including CT scans (1 and 2), the animals were randomly assigned to two groups (random number list generated by EXCEL [Microsoft Corp, Redmond, WA]): the first group (n = 4) underwent OLV with a VT of 10 ml/kg, and the second group (n = 4) underwent OLV with a VT of 5 ml/kg. Figure 1 presents the experimental protocol.
General Procedures
All pigs received an intramuscular injection of xylazine (2.2 mg/kg; Bayer, Leverkusen, Germany), tiletamine–zolazepam (6 mg/kg; Virbac, Carros, France), and atropine (0.04 mg/kg; NM Pharma, Stockholm, Sweden). The pigs were placed in a supine position, and 18-gauge catheters (Becton Dickinson, Heidelberg, Germany) were placed in both ear veins. Anesthesia was maintained by continuous administration of fentanyl (5 μg · kg\(^{-1} \cdot h^{-1}\); Janssen-Cilag AB, Sollentuna, Sweden), pancuronium (0.24 mg · kg\(^{-1} \cdot h^{-1}\); Organon, Oss, The Netherlands), ketamine (25 mg · kg\(^{-1} \cdot h^{-1}\); Intervet, Boxmeer, The Netherlands), and propofol (3 mg · kg\(^{-1} \cdot h^{-1}\); Astra, Södertälje, Sweden). The animals received 3 ml · kg\(^{-1} \cdot h^{-1}\) of isotonic sodium chloride solution (Fresenius Kabi AB, Halden, Norway).

After loss of the hind limb flexion reflexes and corneal reflex responses, which reflected adequate depth of anesthesia, the trachea was intubated (ID 7.0 mm; Mallinckrodt, Athlone, Ireland). The endotracheal tube was replaced with another tube (ID 8.5 mm; Mallinckrodt) by median tracheotomy. A bronchial blocker (9.0 French Arndt-Endobronchial Blocker Set; COOK®, Bjaeverskov, Denmark) was placed in the left main bronchus. The correct endobronchial blocker position was confirmed by fiberoptic bronchoscopy (EF-B 14L; Xion Medical Ltd., Berlin, Germany).

Invasive hemodynamic monitoring included a carotid arterial catheter (20 gauge; Becton-Dickinson Critical Care Systems, Yishun, Singapore), a central venous catheter (4.0 French; Becton-Dickinson Critical Care Systems), a flow-directed pulmonary artery catheter (7.0 French Swan-Ganz thermodilution catheter; Baxter, Irvine, CA), and a suprapubic urinary catheter (Sympakath®; Ruesch, St Gallen, Switzerland). Body temperature was monitored continuously.

Thereafter, the animals were placed into the right lateral decubitus position. This position was kept throughout the study (fig. 1).

The left thoracic cavity was opened by lateral thoracotomy, cranial of the diaphragm. The pigs were allowed to stabilize for 30 min after instrumentation and preparation procedures.

After final measurement, the animals were killed by an intravenous bolus injection of potassium chloride (150 mEq).

Ventilation Management and ARM
Mechanical ventilation started after tracheal intubation (baseline TLV: \(V_T = 10\) ml/kg, \(FIO_2 = 0.40\), PEEP = 5 cm \(H_2O\), and inspiration/expiration ratio = 1:2) using a ventilator (Servo I; Maquet Critical Care, Solna, Sweden). Respiratory rates were adjusted to maintain the \(\text{PACO}_2\) at approximately 40 mmHg. After right lateral positioning and stabilization, measurement of cardiopulmonary variables (time 1) and first CT scan were performed (fig. 1).

The lungs were recruited using the integrated inspiratory-hold function of the ventilator (Servo I) in a standardized manner. A constant airway pressure of 40 cm \(H_2O\) was applied to the whole lung for 10 s (ARM)\(^16\) during TLV.

One-lung Ventilation
OLV was started by inflation of the left-sided bronchial blocker for 60 min. The \(V_T\) was set to either 5 or 10 ml/kg on the basis of the randomization protocol. The respiratory rates were adjusted to maintain a normal \(\text{PACO}_2\), PEEP, inspiration/expiration ratio, and \(FIO_2\) were not changed during OLV (PEEP = 5 cm \(H_2O\); inspiration/expiration ratio = 1:2; \(FIO_2 = 0.40\)). The left nondependent lung collapsed without any application of continuous positive airway pressure. The lung collapse was verified by inspection and by CT scout scans.

After OLV, the nondependent lung was re-inflated by ARM as described. Thereafter, TLV was re-established (\(V_T = 10\) ml/kg; \(FIO_2 = 0.40\); and PEEP = 5 cm \(H_2O\)).

Measurements
Hemodynamic variables (e.g., cardiac index, heart rate, mean arterial pressure, and central venous pressure) and ventilation and gas exchange data (arterial and mixed venous blood gases) were assessed at defined points (time 1–time 4). The dynamic respiratory compliance was continuously recorded using the ventilator-integrated function. The quasi-static respiratory compliance was calculated on the basis of differences in airway pressure after 5 s of end-inspiratory and end-expiratory hold maneuvers.

CT Acquisition and Analysis
The CT images were acquired via a scanner (Somatom Sensation 16CT; Siemens Medical Systems; Erlangen, Germany) in a standardized manner: expiration-hold and subsequent inspiration-hold maneuvers were performed using the ventilator-integrated functions without disconnecting the closed breathing circuit. Transverse CT scans were acquired with the following settings: 120 kV; 100 mA; rotation time, 0.5 s; collimation, 16 × 1.5 mm; pitch, 1.05; and slice thickness, 5 mm. This algorithm resulted in a scan time of 7 s.

The images were reconstructed and analyzed as follows: Raw image data files from the CT scanner were converted into the Analyze format (1995, Biomedical Imaging Resource, Mayo Foundation, Jacksonville, FL) by the Dicom2Analyze script (V 1.33; Matthew Robson, Ph.D., John Radcliffe Hospital, Headington, Oxford, United Kingdom). The original image metadata and voxel intensities (dimensions and scaling Hounsfield units) were preserved. Regions of interest that followed the boundaries of the lungs along the ribs and the mediastinal organs were drawn manually in each CT image. Voxels that covered the trachea, main bronchi, and large blood vessels were excluded. The regions of interest were defined in the CT images using software (MRICO, V 1.40 build 1; Chris Rorden, Ph.D., Georgia State University/Georgia Institute of Technology Center for Advanced Brain Imaging, Atlanta, GA). The processing and analysis of CT data were conducted by an investigator (H.S.) blinded to the experimental protocol and randomization.
Image Analysis
CT images were filtered with the regions of interest using scripts (MATLAB® V 7.0; MathWorks Inc., Natick, MA) that used statistical parametric mapping functions (2002 Wellcome Department of Cognitive Neurology, University College London, London, United Kingdom). The gray values of all voxels of each slice were classified by counting the voxels falling into the intensity windows of the four compartments (Hounsfield units in parentheses): atelectatic (from 100 to −100), poorly aerated (from −100 to −500), normally aerated (from −500 to −900), and overaerated (from −900 to −1000). As a result, the size of the four compartments could be estimated, either relative to the whole lung volume or in relation to the actual slice.

The distribution of the lung density was normalized to a common length of 100 points without changing the value magnitude to compare lungs of different dimensions. Therefore, all spatial distributions provide the size of the four compartments at certain percentages of the total lung length in craniocaudal orientation.

Cyclic tidal recruitment/derecruitment was defined as the difference in the amount of collapsed lung tissue (atelectatic and poorly aerated, Hounsfield units from 100 to −500) during the ventilatory cycle, with atelectasis/poorly aerated lung regions decreasing during inspiration and increasing during expiration.

Statistical Analysis
With reference to a previous study,17 power calculations on ventilatory cycle, with atelectasis/poorly aerated regions decreased to 41 ± 12 ml. Normally aerated lung compartments were increased to 57 ± 18 ml of the dependent lung volume, which reflected the recruitment of collapsed lung tissue. The volume of poorly aerated compartments was unchanged (table 1).

Inspiration after ARM further increased normally aerated regions up to 355 ± 49 ml of the dependent lung volume (table 1). Nonaerated and poorly aerated regions became smaller (26 ± 9 ml and 144 ± 33 ml, respectively) in favor of normally aerated lung tissue. The change in aeration of previously atelectatic and poorly aerated lung regions by the ARM was significant (P < 0.001). There was no evidence of overaeration (lower than 1% of the dependent lung volume after ARM).

Cyclic recruitment/derecruitment included 95% of the end-expiratory dependent lung volume before ARM but only 79% after ARM (P < 0.001).

As a result of ARM, the PAO2 (P = 0.02) and respiratory compliance (P = 0.018) were enhanced (tables 2 and 3).

Dependent Lung Density Distribution during and after OLV
OLV with VT = 10 ml/kg reinforced the dependent lung volume and shifted the inspiratory density spectrum toward compartments with a lower density (fig. 3; table 1). This was accompanied by reduced poorly aerated (305 ± 66 vs. 94 ± 24 ml; P < 0.001) and atelectatic (27 ± 2 vs. 15 ± 2 ml; P = 0.005) regions and by increased normally aerated lung compartments (76 ± 9 vs. 580 ± 98 ml; P < 0.001) during the ventilatory cycle. The overaerated lung volume covered an insignificant fraction.

TLV after ARM
The mean end-expiratory lung volume was increased by 36% after ARM (P < 0.001, fig. 2). The amount of atelectasis was reduced to 41 ± 12 ml. Normally aerated lung compartments were increased to 57 ± 18 ml of the dependent lung volume, which reflected the recruitment of collapsed lung tissue. The volume of poorly aerated compartments was unchanged (table 1).

Inspiration after ARM further increased normally aerated regions up to 355 ± 49 ml of the dependent lung volume (table 1). Nonaerated and poorly aerated regions became smaller (26 ± 9 ml and 144 ± 33 ml, respectively) in favor of normally aerated lung tissue. The change in aeration of previously atelectatic and poorly aerated lung regions by the ARM was significant (P < 0.001). There was no evidence of overaeration (lower than 1% of the dependent lung volume after ARM).

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Results
TLV before ARM
The end-expiratory dependent lung volume consisted of a small fraction of normally aerated tissue (15 ± 9 ml) during baseline TLV (CT 1). The dependent lung had mainly poorly aerated (213 ± 13 ml) and atelectatic (90 ± 16 ml) lung regions before ARM. Atelectasis was observed in the most dependent, caudal, and paradiaphragmatic regions (fig. 2). The apical lung zones contained exclusively normally and poorly aerated lung tissue; no overaerated regions were seen.

Inspiration increased the dependent lung volume (table 1). It was associated with reduced atelectatic (56 ± 10 ml) and poorly aerated (183 ± 10 ml) compartments, in favor of normally aerated regions (187 ± 29 ml), which indicated tidal recruitment (table 1; fig. 2).

The density of the nondependent lung was distributed in the same way: atelectatic lung tissue (inspiration/expiration, 18 ± 8 ml/21 ± 9 ml), poorly aerated (inspiration/expiration, 62 ± 11 ml/100 ± 14 ml), and normally aerated regions (inspiration/expiration, 438 ± 74 ml/275 ± 55 ml), without any signs of overaeration (table 1).

Hemodynamic, ventilation, and gas exchange data reflected normal values for pigs that underwent mechanical TLV (table 2 and table 3).

Dependent Lung Density Distribution during and after OLV
OLV with VT = 10 ml/kg reinforced the dependent lung volume and shifted the inspiratory density spectrum toward compartments with a lower density (fig. 3; table 1). This was accompanied by reduced poorly aerated (305 ± 66 vs. 94 ± 24 ml; P < 0.001) and atelectatic (27 ± 2 vs. 15 ± 2 ml; P = 0.005) regions and by increased normally aerated lung compartments (76 ± 9 vs. 580 ± 98 ml; P < 0.001) during the ventilatory cycle. The overaerated lung volume covered an insignificant fraction.
In contrast, OLV with VT\textsubscript{H11005} 5 ml/kg did not change the lung density distribution compared with TLV after ARM, neither at end-expiration nor at end-inspiration (fig. 3; table 1). As a result, the cyclic change in lung volume was smaller during OLV with VT\textsubscript{H11005} 5 ml/kg compared with VT\textsubscript{H11005} 10 ml/kg. The difference of atelectasis and poorly aerated tissue between expiration and inspiration (cyclic recruitment/derecruitment) was 65% of the dependent lung volume in the high VT group and 42% in the low VT group (\(P < 0.008\), table 1).

After resuming TLV, the distribution of poorly aerated lung regions differed between the groups, which were ventilated with a VT\textsubscript{H11005} of either 5 or 10 ml/kg. The poorly aerated lung volume was increased after OLV with the higher VT\textsubscript{H11005} (fig. 4).

Spatial Density Distribution in the Dependent Lung

Figure 5 displays the spatial distribution of normally, poorly aerated, and atelectatic regions in the dependent lung. The use of different VT\textsubscript{H11005} values during OLV did not affect the distribution of normally aerated lung regions in any stage of the experiment (i.e., after ARM, during OLV, and during TLV; fig. 5, A–C, respectively). The distribution of poorly aerated areas did not change after ARM (fig. 5D), but the use of high or low VT\textsubscript{H11005} resulted in a different amount of poorly aerated tissue during OLV (fig. 5E) and during TLV after OLV (fig. 5F). OLV with a VT\textsubscript{H11005} of 10 ml/kg decreased poorly aerated paradiaphragmatic lung areas compared with OLV with a VT\textsubscript{H11005} of 5 ml/kg (fig. 5E: slices 60–100), whereas the distribution was reversed 60 min thereafter during TLV. Poorly aerated compartments were increased in pigs subject to a VT\textsubscript{H11005} of 10 ml/kg (fig. 5F: slices 10–80). The spatial distribution of atelectatic regions was unchanged in all pigs throughout the experiment (fig. 5, G–I).

Hemodynamic and Gas Exchange Data during and after OLV

OLV with a VT\textsubscript{H11005} of 10 ml/kg increased peak, plateau, and mean airway pressures compared with TLV before OLV. The intrapulmonary shunt increased in all animals without differences between OLV groups. OLV with a VT\textsubscript{H11005} of 5 ml/kg resulted in lower \(P_{\text{aO}_2}\) (\(P = 0.03\)) and respiratory compliance (\(P = 0.001\)) than OLV with a VT\textsubscript{H11005} of 10 ml/kg (tables 2 and 3).

After restoration of TLV, airway pressures, lung compliance, and arterial oxygenation returned to the values before OLV in all animals.

Discussion

The main finding of this study is that the combination of a lung recruitment maneuver before OLV and ventilation with a VT\textsubscript{H11005} of...
Table 1. Changes in Radiological Density Distribution in Differently Aerated Regions of the Dependent Lung from Expiration to Inspiration

<table>
<thead>
<tr>
<th>Variables</th>
<th>TLV before Expiration</th>
<th>TLV before Inspiration</th>
<th>Difference Expiration-Inspiration</th>
<th>TLV after Expiration</th>
<th>TLV after Inspiration</th>
<th>Difference Expiration-Inspiration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependent Lung</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume, ml</td>
<td>318 ± 34</td>
<td>426 ± 35</td>
<td>108 ± 34</td>
<td>379 ± 41</td>
<td>526 ± 69</td>
<td>147 ± 55*</td>
</tr>
<tr>
<td>Atelectasis, %</td>
<td>28 ± 3</td>
<td>13 ± 1</td>
<td>−15 ± 6</td>
<td>10 ± 3*</td>
<td>5 ± 2</td>
<td>−5 ± 4*</td>
</tr>
<tr>
<td>Poorly Aerated, %</td>
<td>67 ± 4</td>
<td>43 ± 1</td>
<td>−24 ± 11</td>
<td>69 ± 4*</td>
<td>27 ± 4*</td>
<td>−42 ± 13*</td>
</tr>
<tr>
<td>Normally Aerated, %</td>
<td>5 ± 2</td>
<td>44 ± 2</td>
<td>39 ± 16</td>
<td>21 ± 6*</td>
<td>68 ± 4*</td>
<td>47 ± 14</td>
</tr>
</tbody>
</table>
| Data are given as mean ± SD. The ARM caused an alveolar opening that included the expiratory lung tissue distribution. The effects of different VT values (5 or 10 ml/kg) on lung density distribution during OLV was detected only during inspiration, but the difference between expiration and inspiration is significant.

5 ml/kg during OLV is associated with a more homogeneous distribution of lung tissue in the dependent ventilated lung. The ARM results in an increased fraction of normally aerated areas; therefore, the ratio of poorly aerated and atelectatic regions remains low during and after OLV, independent from VT. Although there is a further increase in normally aerated regions during OLV with a VT of 10 ml/kg, this effect is limited to the end-inspiratory lung density distribution, without any difference between a VT of 10 and 5 ml/kg at end-expiration.

Different experimental and clinical studies have established that mechanical ventilation with a large VT results in diffuse lung injury. Consequently, a protective approach of mechanical ventilation is advocated in patients with acute lung injury.

Table 2. Hemodynamic and Gas Exchange Data at Different Points: During Two-lung Ventilation before and after Alveolar Recruitment, during One-lung Ventilation with Different VT Values, and 60 min Later

<table>
<thead>
<tr>
<th>Variables</th>
<th>Before ARM</th>
<th>After ARM</th>
<th>VT = 5 ml/kg</th>
<th>VT = 10 ml/kg</th>
<th>OLV-VT = 5 ml/kg</th>
<th>OLV-VT = 10 ml/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR/min</td>
<td>99 ± 9</td>
<td>91 ± 6</td>
<td>92 ± 5</td>
<td>95 ± 7</td>
<td>93 ± 6</td>
<td>95 ± 8</td>
</tr>
<tr>
<td>MAP, mmHg</td>
<td>79 ± 11</td>
<td>77 ± 8</td>
<td>76 ± 9</td>
<td>79 ± 5</td>
<td>78 ± 9</td>
<td>77 ± 5</td>
</tr>
<tr>
<td>CVP, mmHg</td>
<td>6 ± 1</td>
<td>6 ± 1</td>
<td>8 ± 1</td>
<td>9 ± 1</td>
<td>7 ± 1</td>
<td>6 ± 1</td>
</tr>
<tr>
<td>CI, l/m·min⁻¹·m⁻²</td>
<td>3.7 ± 0.9</td>
<td>3.8 ± 0.6</td>
<td>3.6 ± 0.7</td>
<td>4.1 ± 0.6</td>
<td>3.9 ± 0.5</td>
<td>3.9 ± 0.5</td>
</tr>
<tr>
<td>PAP, mmHg</td>
<td>138 ± 38</td>
<td>191 ± 18*</td>
<td>139 ± 15†</td>
<td>164 ± 22‡</td>
<td>194 ± 22</td>
<td>193 ± 18</td>
</tr>
<tr>
<td>PACO₂, mmHg</td>
<td>42 ± 3</td>
<td>43 ± 2</td>
<td>47 ± 2†</td>
<td>41 ± 2</td>
<td>44 ± 2</td>
<td>43 ± 2</td>
</tr>
<tr>
<td>Qs/Qt, %</td>
<td>4.6 ± 2.2</td>
<td>3.6 ± 1.7</td>
<td>6.4 ± 2.6†</td>
<td>5.8 ± 3.0‡</td>
<td>3.2 ± 1.9</td>
<td>3.6 ± 1.8</td>
</tr>
</tbody>
</table>

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5 ml/kg during OLV is associated with a more homogeneous distribution of lung tissue in the dependent ventilated lung. The ARM results in an increased fraction of normally aerated areas; therefore, the ratio of poorly aerated and atelectatic regions remains low during and after OLV, independent from VT. Although there is a further increase in normally aerated regions during OLV with a VT of 10 ml/kg, this effect is limited to the end-inspiratory lung density distribution, without any difference between a VT of 10 and 5 ml/kg at end-expiration.

Different experimental and clinical studies have established that mechanical ventilation with a large VT results in diffuse lung injury. Consequently, a protective approach of mechanical ventilation is advocated in patients with acute lung injury. However, studies have shown that...
address the effects of a VT of 10 ml/kg or greater during OLV report controversial results. The application of a relatively high VT may prevent atelectasis during OLV and achieves better oxygenation and reduced lung injury.5

On the other hand, a VT of 10 ml/kg or greater during OLV is associated with increased alveolar damage and enhanced expression of proinflammatory cytokines in the bronchoalveolar lavage fluid.9,20–22

<table>
<thead>
<tr>
<th>Variables</th>
<th>TLV at VT = 10 ml/kg</th>
<th>OLV</th>
<th>TLV after OLV (VT = 10 ml/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before ARM</td>
<td>After ARM</td>
<td>VT = 5 ml/kg</td>
</tr>
<tr>
<td>MV, l/min</td>
<td>6.2 ± 0.6</td>
<td>6.3 ± 0.6</td>
<td>6.5 ± 0.6</td>
</tr>
<tr>
<td>RR/min</td>
<td>22 ± 3</td>
<td>21 ± 2</td>
<td>44 ± 4*</td>
</tr>
<tr>
<td>VT, ml/kg</td>
<td>10.1 ± 0.1</td>
<td>10.3 ± 0.4</td>
<td>5.2 ± 0.2*</td>
</tr>
<tr>
<td>PAW, cm H2O</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak</td>
<td>27 ± 4</td>
<td>25 ± 4</td>
<td>25 ± 4</td>
</tr>
<tr>
<td>Plateau</td>
<td>21 ± 3</td>
<td>20 ± 3</td>
<td>19 ± 3</td>
</tr>
<tr>
<td>Mean</td>
<td>9 ± 2</td>
<td>10 ± 1</td>
<td>10 ± 1</td>
</tr>
<tr>
<td>Effective</td>
<td>16 ± 3</td>
<td>15 ± 3</td>
<td>14 ± 3</td>
</tr>
<tr>
<td>Effective</td>
<td>16 ± 3</td>
<td>15 ± 3</td>
<td>14 ± 3</td>
</tr>
<tr>
<td>PEEP, cm H2O</td>
<td>5 ± 0</td>
<td>5 ± 0</td>
<td>5 ± 0</td>
</tr>
<tr>
<td>Cst, ml/cm H2O</td>
<td>19.2 ± 2.4</td>
<td>23.3 ± 2.7†</td>
<td>12.1 ± 1.7*</td>
</tr>
<tr>
<td>Cdyn, ml/cm H2O</td>
<td>17.3 ± 3.1</td>
<td>20.0 ± 3.5†</td>
<td>10.0 ± 1.5*</td>
</tr>
</tbody>
</table>

Data are given as mean ± SD.

* OLV vs. TLV after ARM (P < 0.05). † OLV with VT = 5 vs. 10 ml/ kg (P < 0.05). ‡ TLV after vs. before ARM (P = 0.04).

ARM = alveolar recruitment maneuver; Cst = static compliance; Cdyn = dynamic compliance; MV = minute ventilation; OLV = one-lung ventilation; PAW = airway pressure; PEEP = positive end-expiratory pressure; RR = respiratory rate; TLV = two-lung ventilation; VT = tidal volume.

Fig. 3. Juxtadiaphragmatic lung computed tomographic scans of pigs during one-lung ventilation (OLV) with a tidal volume (VT) of 5 or 10 ml/kg. In each image, the region of interest includes the following (Hounsfield units in parentheses): overaerated (from 1000 to 900), normally aerated (from −900 to −500), poorly aerated (from −500 to −100), and atelectatic (from −100 to 100) lung areas. The regions are coded by gray scale. There were differences in lung density during ventilation with high or low VT values at inspiration. On the other hand, a VT of 10 ml/kg or greater during OLV is associated with increased alveolar damage and enhanced expression of proinflammatory cytokines in the bronchoalveolar lavage fluid.9,20–22
The data of the current study may explain this discrepancy. Mechanical ventilation with a VT of 10 ml/kg is associated with expanded normally aerated lung regions at end-inspiration but not at end-expiration. In fact, there is an increase in the cyclic transitional area, which suggests alveolar collapse and reopening during each expiration and inspiration. These cyclic changes during mechanical ventilation induce diffuse inflammation in normally aerated regions. In addition, alveolar damage can also occur at the boundaries of atelectatic, poorly aerated, and normally aerated tissue. Thus, the increase of normally aerated regions during inspiration seems to be harmful rather than beneficial, during both TLV and OLV.

The current results indicate that ARM of the whole lung before OLV provides sustained effects that extend to OLV. The first CT scan confirms the presence of atelectatic and poorly aerated lung regions after induction of anesthesia. The recruitment maneuver enhances aeration and reduces cyclic recruitment during inspiration and during the entire cycle of ventilation, irrespective of whether OLV is continued with a VT of 5 or 10 ml/kg. In addition, improved aeration and reduced cyclic recruitment/derecruitment of alveoli are responsible for changes in respiratory compliance and oxygenation.

The CT images of healthy pig lungs demonstrate at most only minor overaeration, even during OLV with a VT of 10 ml/kg, which confirms the results of a previous study. These data disagree with findings in patients with acute respiratory distress syndrome, in whom mechanical ventilation with a large VT results in overinflation of the lung. Although speculative, open lung conditions may allow a more even distribution of ventilation, with less distension of non-dependent regions. However, distribution of almost the entire perfusion to the dependent lung during OLV may have influenced X-ray attenuation and may shift voxels toward a higher density, thereby masking overaeration. In addition, the lack of overaerated regions in CT scans does not imply that the ventilation is protective. Consequently, OLV can induce an acute pulmonary inflammatory response, even if lung-protective strategies are applied.

The reduction of VT preserves the lung density distribution resulting from ARM during OLV. Based on the redistribution of lung density from collapse to aeration by ARM, OLV with a VT of 5 ml/kg does not change the global density distribution and does not increase tidal recruitment. Most important, OLV with a VT of 5 ml/kg is not associated with increased atelectasis formation if it is combined with a PEEP of 5 cm H2O; this may confirm recent CT data during TLV.

In contrast, OLV with a VT of 10 ml/kg expands the poorly aerated lung tissue, especially in paradiaphragmatic regions. This may increase the amount of poorly aerated tissue in exactly these lung areas after OLV, and it may be attributed to the repetitive reopening of collapsed alveoli. In addition, high VT ventilation and sequential inflation to total lung capacity have

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**Fig. 4.** The images were acquired during two-lung ventilation (TLV) (tidal volume [VT] = 10 ml/kg) after one-lung ventilation (OLV) with a VT of 5 or 10 ml/kg. In each image, the dashed line marks (Hounsfield units in parentheses): overaerated (from −1000 to −900), normally aerated (from −900 to −500), poorly aerated (from −500 to −100), and atelectatic (from −100 to 100) lung regions. VT = tidal volume.
been demonstrated to inhibit surfactant production, which, in turn, affects alveolar recoil forces.

Therefore, protective ventilation approaches should consider the increased mechanical stress during OLV. The incidence of acute lung failure is significantly reduced by the use of lower VT values during OLV. However, the reduction of VT does not completely abolish alveolar inflammation, suggesting the existence of persistent shear forces in the lung induced by cyclic opening and collapse of lung tissue. These forces may occur even at low inspiratory pressures and low inspiratory volumes. The avoidance of cyclic recruitment and alveolar overdistention seems to be a key factor of lung-protective mechanical ventilation and may be achieved by a combination of ARM, sufficient PEEP, and reduced VT.

The most significant limitations of this study are the short postoperative observation period and the lack of a control group for the effects of ARM before OLV. Therefore, it is unclear whether the OLV effects with different VT on lung tissue are similar to conditions in which OLV is applied without preceding ARM. However, ARM is a key component in lung-protective ventilation and was, therefore, included to analyze the more important effects of different VT during OLV. It is commonly held that the change from poor to normal aeration by ARM would be beneficial; however, the optimal ratio of this change has not been defined. Therefore, this study reports only relative differences with low and high VT values before and after OLV.

Furthermore, the experimental setup does not include data demonstrating that cyclic recruitment during OLV with a higher VT has increased lung injury (e.g., by measurement of proinflammatory mediators). However, possible deleterious effects of either ARM or mechanical ventilation have been well established during OLV and in various experimental and clinical studies. In fact, histologic examination findings of the lungs of pigs that underwent a similar experimental setup have demonstrated that an OLV with a VT of 10 ml/kg induces significant diffuse alveolar damage.

In conclusion, a single ARM before OLV has persistent effects on aeration of the dependent lung tissue. In addition, it improves respiratory compliance and enhances arterial oxygenation. OLV with a VT of 10 ml/kg results in a higher ratio of normally aerated lung regions and increases PaO₂. These changes are less pronounced during OLV with a VT of 5 ml/kg after ARM. However, the improved oxygenation by a higher VT results in inhomogeneous distribution of aeration and increased mechanical stress that predisposes the lungs to postoperative lung injury. Therefore, a protective...
ventilation strategy with preceding ARM, \textsuperscript{11,12} reduced V\textsubscript{T}, \textsuperscript{9,10} and sufficient PEEP\textsuperscript{36} ensures oxygenation during OLV and may decrease mechanical stress in the lung by reduced cyclic alveolar collapse. The positive effects of this ventilatory setup on lung injury and outcome after OLV need to be confirmed in further clinical studies.

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