Lung computed tomography density distribution in a porcine model of one-lung ventilation

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Background. One-lung ventilation (OLV) exposes the dependent lung to increased mechanical stress which may affect the postoperative course. This study evaluates regional pulmonary gas/tissue distribution in a porcine model of OLV.

Methods. Nine anaesthetized and mechanically ventilated ($V_T=10 \text{ ml kg}^{-1}$, $F_{IO_2}=0.40$, PEEP=5 cm H$_2$O) pigs were studied. After lung separation by an endobronchial blocker, lateral thoracotomy and OLV were performed in six pigs. Three animals served as controls. Static end-expiratory and end-inspiratory spiral computed tomography (CT) scans were done before, during, and after OLV and at corresponding times in controls. CT images were analysed by defined regions of interest and summarized voxels were classified by defined lung X-ray density intervals (atelectasis, poorly aerated, normally aerated, and overaerated).

Results. Dependent lungs contained poorly aerated regions and atelectasis with a significant tidal recruitment during conventional two-lung ventilation (TLV) before OLV (expiration vs inspiration: atelectasis 29% vs 14%; poorly aerated 66% vs 44%; normally aerated 4% vs 41% of the dependent lung volume, $P<0.05$). During OLV ($V_T=10 \text{ ml kg}^{-1}$), cyclic recruitment was increased. The density spectrum of the ventilated lung changed from consolidation to aeration (expiration vs inspiration: atelectasis 10% vs 2%; poorly aerated 71% vs 18%; normally aerated 19% vs 79%, $P<0.05$). After OLV, increased aeration remained with less atelectasis and poorly aerated regions. Lung density distribution in the non-dependent lung of OLV pigs was unaltered after the period of complete lung collapse.

Conclusions. Cyclic tidal recruitment during OLV in pigs was associated with a persistent increase of aeration in the dependent lung.


Keywords: Animals Procedures Act; lung, tidal volume; measurement techniques; surgery, thoracic; ventilation, one-lung; ventilation volumes

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There are no systematic studies visualizing pulmonary gas/tissue distribution and cyclic recruitment/de-recruitment before, during, and after OLV. The present animal study was thus initiated to localize lung regions afflicted with tidal recruitment and overaeration. The null hypothesis ($H_0$) that OLV and surgical manipulation have had no effects on the distribution of overaerated, normally, poorly aerated, and atelectatic lung regions in pigs undergoing experimental thoracic surgery was tested.

**Methods**

The study was conducted as a controlled, prospective animal experiment. The protocol was approved by the Animal Ethics Committee of Uppsala University (Sweden).

**Animals**

Nine 2-month-old piglets of the Hampshire, Yorkshire, and Swedish country breeds from a local breeder were examined. Pigs were assigned into two groups: an OLV group [$n=6$, mean weight 29.7 (sd 1.8) kg] and a control group [$n=3$, mean weight 28.7 (0.6) kg]. The controls underwent a study protocol similar to the OLV pigs (Fig. 1, anaesthesia, preparation, positioning, and measurements), but were kept on two-lung ventilation (TLV) throughout the study.

**General procedures**

All pigs were anaesthetized by an i.m. injection of xylazine (2.2 mg kg$^{-1}$, Rompun®; Bayer, Leverkusen, Germany), tiletamine/zolazepam (6 mg kg$^{-1}$, Zoletil®; Virbac, Carros, France), and atropine (0.04 mg kg$^{-1}$ NM Pharma, Stockholm, Sweden). The pigs were mechanically ventilated after intubation with an ID 7.0 mm cuffed endotracheal tube (Mallinckrodt, Athlone, Ireland).

Anaesthesia was maintained by continuous administration of fentanyl (5 μg kg$^{-1}$ h$^{-1}$, Leptanal®; Janssen-Cilag AB, Sweden), pancuronium (0.3 mg kg$^{-1}$ h$^{-1}$, Pavulon®; Organon, Oss, The Netherlands), ketamine (25 mg kg$^{-1}$ h$^{-1}$, Ketaminol vet.®; Intervet, Boxmeer, The Netherlands), and propofol (3 mg kg$^{-1}$ h$^{-1}$, Diprivan®; Astra, Södertälje, Sweden). Before manipulation, the adequate depth of surgical anaesthesia was confirmed by the absence of both the hind limb flexion reflex and the corneal reflex responses according to the laboratory standard of the Animal Ethics Committee of Uppsala University.

After tracheostomy, the orotracheal tube was replaced by an ID 8.5 mm tracheal tube (Mallinckrodt). A bronchial blocker (9.0 French Arndt-Endobronchial Blocker Set, COOK®, Bjaeverskov, Denmark) was placed in the left main bronchus (EF-B 14L, Xion medical, Berlin, Germany) in all pigs.

A carotid arterial catheter (20 G; Becton-Dickinson Critical Care Systems, Singapore), a flow-directed pulmonary artery catheter (7.0 French, Swan-Ganz thermodilution catheter, Baxter, Irvine, CA, USA), a single-lumen central venous catheter (4.0 French, Becton-Dickinson Critical Care Systems), and a suprapubic urinary catheter (Sympakath®; Ruesch, St Gallen, Switzerland) were inserted in all animals.

The pigs received 8–10 ml kg$^{-1}$ h$^{-1}$ of isotonic saline solution (Fresenius Kabi AB; Halden, Norway) during the study to maintain urine output at >2 ml kg$^{-1}$ h$^{-1}$. Body temperature was kept constant by thermoconvection. The animals were allowed to stabilize after instrumentation for 30 min.

**Study protocol**

At T1, haemodynamic and ventilation data [cardiac output, heart rate (HR), mean arterial pressure (MAP), mean pulmonary artery pressure (MPAP), central venous pressure (CVP), pulmonary artery occlusion pressure (PAOP), and arterial and mixed venous blood gases] were assessed and spiral computerized tomography scans (CT I, end-expiratory, and end-inspiratory) were performed. The procedure was repeated after 90 min OLV or TLV in controls (OLV/TLV, T2) and during TLV, 90 min after OLV/TLV (TLV after OLV/TLV, T3; Fig. 1).

**OLV and thoracic surgery**

All animals were mechanically ventilated with intermittent positive pressure ventilation with $F_{iO_2}$ of 0.40 and PEEP of

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**Fig 1** Experimental workflow.
5 cm H₂O (Servo I; Maquet Critical Care, Solna, Sweden). The tidal volume was set to 10 ml kg⁻¹ throughout the study. Respiratory frequencies were adjusted to achieve an arterial PCO₂ of 40 mm Hg.

After positioning in the CT scanner, correct placement of the bronchial blocker in the left main bronchus of OLV pigs was confirmed by bronchoscopic. Sufficient bronchial blockade was tested by blocker inflation for 4–6 respiratory cycles.

A left-sided lateral thoracotomy was performed and the thorax was opened cranial to the diaphragm after CT I. Ventilation of the non-dependent left lung was discontinued by inflation of the bronchial blocker for 90 min (OLV). Successful left lung collapse was verified by direct inspection and by CT scout scans. A surgical procedure was simulated by intermittent handling of the collapsed left lung. Chest wound margins were loosely adapted after OLV.

Ventilation settings remained unchanged during OLV. The tidal volume of 10 ml kg⁻¹ was completely delivered to the dependent lung with a successive increase in dependent lung VT over 3–5 respiratory cycles. The bronchial blocker was removed immediately after CT II (OLV/TLV).

The non-dependent lung was re-inflated by a standardized procedure: two vital capacity manoeuvres were applied to the whole lung up to an airway pressure of 30 cm H₂O for 5 s. After complete re-inflation of the left lung, TLV was re-established.

After completion of the experiment, the pigs were killed by an i.v. bolus injection of potassium chloride (150 mval) confirmed by ECG.

**CT scanning and analysis**

CT images were acquired by a Somatom Sensation 16 CT Scanner (Siemens Medical Systems; Erlangen, Germany). All scans were done in a standardized manner: expiratory hold and subsequent inspiratory hold manoeuvres using the available ventilator functions without disconnecting the closed breathing circuit. By pressing the inspiratory hold button of the ventilator, expiratory valves closed automatically after application of the defined tidal volume (VT = 10 ml kg⁻¹). The Servo I ventilator held the applied volume until the button was released after CT.

Transverse scans were performed with the following settings: 120 kV, 100 mA, rotation time 0.5 s, collimation 16×1.5 mm, pitch 1.05, slice thickness of 5 mm, and a scan time of ~7 s. Images were reconstructed with an increment of 5 mm, yielding 43–52 slices from each scan depending on lung dimensions, defined by an initial frontal chest tomogram.

CT images were transferred to a personal computer (MAXDATA Notebook ECO 4000 A) connected to a separate screen (EIZO FlexScan S1911, resolution: 1280×1024) for further analysis.

Files were recorded as GE proprietary interfile format and subsequently converted to Analyze™ format (1995, Biomedical Imaging Resource, Mayo Foundation) by header file parsing. The binary image data were not changed in this process. Image scaling units (Hounsfield units, HU) were preserved. Regions of interest (ROIs) were defined in each CT image using the MRICO software (V 1.40, 2005, C. Rorden).

In all slices from expiratory and inspiratory CT scans, the entire left and right lungs were chosen as an ROI by drawing the external boundaries of the lungs at the inside of the ribs and the internal boundaries along the mediastinal organs. ROIs were defined slice-wise manually in the lung window (−500 to 1500 HU) and corrected in the mediastinal window (50–350 HU) in cases of low contrast. The trachea, main bronchi, and large blood vessels were excluded from ROI; voxels outside the ROI were ignored.

**ROI analysis and statistics**

The ROIs were applied onto the CT images using MATLAB (V 7.0, MathWorks Inc.) scripts that utilized SPM functions (SPM2, 2002 Wellcome Department of Cognitive Neurology, UCL, London), and thus reading the gray values for each voxel. By counting the voxels in given intensity intervals, the size of four compartments (non-aerated (HU from +100 to −100), poorly aerated (−100 to −500), normally aerated (−500 to −900), and overaerated (−900 to −1000)) was calculated for each slice along the longitudinal axis, either relative to the whole lung volume or relative to the actual slice. The results were additionally plotted as continuous HU density distributions for the whole lung to obtain the overall change.

Lung dimensions were normalized to a common length of 100 points before calculating distributions of lung density while leaving the value magnitude and shape unchanged. Thus, all spatial values are given according to their relative position along the spatial axis in per cent.

The data were selectively grouped for acquisition (CT I, II, and III) and subject (the OLV group and the control pigs). Statistical analysis was performed using SPSS V. 14 (Chicago, IL, USA). Power calculations using a two-sided design at a significance level of 5% (α=0.05) and a probability of 80% (β=0.20) to detect a difference of at least 35% in the distribution of atelectasis, poorly and normally aerated lung compartments before and during OLV revealed that a minimum of three pigs was needed.

Data were tested for normal distribution with the Shapiro–Wilks W-test. Normally distributed data are presented as mean (SD) (cardiopulmonary, ventilation, and gas exchange variables). These data were analysed by a repeated-measures one-way analysis of variance (ANOVA) with post hoc Bonferroni’s correction. CT data were analysed slice-wise by two-sample t-tests and repeated-measures ANOVA. Differences were considered to be significant for all procedures if P<0.05.
Results

Cardiopulmonary and ventilation variables
OLV increased peak, plateau, and mean airway pressures in comparison with ventilation data preceding the OLV. Likewise, MPAP, PAOP, CVP, and intrapulmonary shunt increased and $P_{a_{CO_2}}$ decreased during OLV. After OLV, all variables returned to the initial values. There were no changes in haemodynamic or ventilation data in control animals over time (Tables 1–3).

Distribution of lung density in CT images
The distribution of voxels (size 1.2894 mm$^3$) with different radiological densities is depicted slice-wise in cranio-caudal direction (Fig. 3). In Tables 4 and 5, volumes of lung density compartments and their relative fractions are given separately for OLV pigs and controls. Both normally and poorly aerated lung regions dominated in apical lung zones (Fig. 3). Almost all atelectasis was localized in the dependent and dorsal lung regions (Fig. 2). The spatial lung density distribution was not affected by time as seen in the control pigs.

Lung density distribution in the non-dependent lungs of OLV pigs
In CT I, normally and poorly aerated regions were evenly distributed at end-expiration (Table 4). Atelectasis was minor and overaeration did not occur. Regional gas/tissue distribution was identical at end-inspiration and end-expiration during OLV (CT II), reflecting the absence of tidal ventilation. After resuming TLV (CT III), the amount of normal and poor aeration and atelectasis was the same as before the period of lung collapse.

Lung density distribution in the dependent lungs of OLV pigs
Before OLV, end-expiratory density distribution was dominated by poorly aerated compartments, a considerable

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**Table 1** Haemodynamic data of OLV pigs and control animals at the beginning of the study (T1), during OLV/TLV (after 90 min, T2), during TLV (90 min after OLV/after 180 min TLV, T3). Data are displayed as mean ($\pm$ sd) (*P<0.05 vs T1, $^a$P<0.05 OLV vs control)

<table>
<thead>
<tr>
<th>Variable</th>
<th>(T1) TLV before OLV</th>
<th>(T2) OLV (90 min)/TLV (90 min)</th>
<th>(T3) TLV (90/180 min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR (beats min$^{-1}$)</td>
<td>84 (9)</td>
<td>86 (11)</td>
<td>84 (9)</td>
</tr>
<tr>
<td>MAP (mm Hg)</td>
<td>80 (18)</td>
<td>80 (20)</td>
<td>80 (18)</td>
</tr>
<tr>
<td>CVP (mm Hg)</td>
<td>5 (1)</td>
<td>8 (1)$^a$</td>
<td>6 (2)</td>
</tr>
<tr>
<td>MPAP (mm Hg)</td>
<td>19 (3)</td>
<td>22 (4)$^a$</td>
<td>20 (2)</td>
</tr>
<tr>
<td>PAOP (mm Hg)</td>
<td>9 (1)</td>
<td>12 (2)$^a$</td>
<td>10 (1)</td>
</tr>
<tr>
<td>CI (litre min$^{-1}$ m$^{-2}$)</td>
<td>3.4 (0.6)</td>
<td>3.1 (0.8)</td>
<td>3.2 (0.4)</td>
</tr>
</tbody>
</table>

**Table 2** Ventilation data of OLV pigs and controls at the beginning of the study (T1), during OLV/TLV (after 90 min, T2), during TLV (90 min after OLV/after 180 min TLV, T3). Data are displayed as mean ($\pm$ sd) (*P<0.05 vs T1, $^a$P<0.05 OLV vs control)

<table>
<thead>
<tr>
<th>Variable</th>
<th>(T1) TLV before OLV</th>
<th>(T2) OLV (90 min)/TLV (90 min)</th>
<th>(T3) TLV (90/180 min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV (litre min$^{-1}$)</td>
<td>5.9 (0.6)</td>
<td>6.0 (0.5)</td>
<td>5.9 (0.6)</td>
</tr>
<tr>
<td>Ventilatory frequency (bpm)</td>
<td>19 (2.1)</td>
<td>19 (1.7)</td>
<td>19 (2.2)</td>
</tr>
<tr>
<td>$V_t$ (ml kg$^{-1}$)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$P_{AW}$ peak (cm H$_2$O)</td>
<td>21 (2)</td>
<td>27 (3)$^a$</td>
<td>21 (1)</td>
</tr>
<tr>
<td>$P_{AW}$ plateau (cm H$_2$O)</td>
<td>19 (2)</td>
<td>25 (2)$^a$</td>
<td>20 (2)</td>
</tr>
<tr>
<td>$P_{AW}$ mean (cm H$_2$O)</td>
<td>7 (1)</td>
<td>10 (1)$^a$</td>
<td>9 (0)</td>
</tr>
<tr>
<td>PEEP (cm H$_2$O)</td>
<td>4 (1)</td>
<td>5 (1)</td>
<td>5 (1)</td>
</tr>
</tbody>
</table>

**Table 3** Gas exchange data of OLV pigs and control pigs at the beginning of the study (T1, right lateral position), during OLV/TLV (after 90 min, T2), during TLV (90 min after OLV/after 180 min TLV, T3). Data are displayed as mean ($\pm$ sd) (*P<0.05 vs T1, $^a$P<0.05 OLV vs control)

<table>
<thead>
<tr>
<th>Variable</th>
<th>(T1) TLV before OLV</th>
<th>(T2) OLV (90 min)/TLV (90 min)</th>
<th>(T3) TLV (90/180 min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{a_{O_2}}$ (mm Hg)</td>
<td>160.35 (21)</td>
<td>108.92 (9.67)$^a$</td>
<td>167.55 (23.40)</td>
</tr>
<tr>
<td>$P_{a_{CO_2}}$ (mm Hg)</td>
<td>44.32 (3.45)</td>
<td>41.51 (3.15)</td>
<td>43.72 (2.70)</td>
</tr>
<tr>
<td>$k_{CO_2}$ (mm Hg)</td>
<td>40.3 (4.0)</td>
<td>35.1 (5.3)</td>
<td>38.9 (4.4)</td>
</tr>
<tr>
<td>$P_{v_{O_2}}$ (mm Hg)</td>
<td>39.30 (3.75)</td>
<td>38.47 (3.01)</td>
<td>38.55 (3.37)</td>
</tr>
<tr>
<td>$P_{v_{CO_2}}$ (mm Hg)</td>
<td>54.30 (3.78)</td>
<td>53.92 (4.20)</td>
<td>53.55 (3.00)</td>
</tr>
<tr>
<td>$aO_2$ (mm Hg)</td>
<td>160.35 (21)</td>
<td>108.92 (9.67)$^a$</td>
<td>167.55 (23.40)</td>
</tr>
<tr>
<td>$aCO_2$ (mm Hg)</td>
<td>44.32 (3.45)</td>
<td>41.51 (3.15)</td>
<td>43.72 (2.70)</td>
</tr>
</tbody>
</table>

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InspirationExpiration

CT I: TLV before OLV

CT II: OLV

CT III: TLV after OLV

Fig 2 Juxtadiaphragmatic lung CT images of a representative animal (OLV pig no. 3). Scans during TLV before OLV (CT I), during OLV (CT II), and TLV after OLV (CT III). In each image, ROI is depicted by dashed lines; overaerated (−1000 to −900 HU), normally aerated (−900 to −500 HU), poorly aerated (−500 to −100 HU), and atelectatic (−100 to +100 HU) lung regions are coded by gray scale.
amount of atelectasis, and a small fraction of normally aerated areas. At end-inspiration, atelectasis and poorly aerated regions were decreased, whereas normally aerated regions were increased (Table 5, CT I).

OLV delivered the whole tidal volume to the dependent lung. This resulted in a reduction of atelectasis and an increase of both poorly and normally aerated compartments.

During inspiration, there was a further decrease in atelectasis, so that cyclic recruitment was even larger during OLV than during TLV before. Overaerated lung compartments covered only an insignificant fraction (Table 5, CT II).

Table 4 Non-dependent lungs: volumes of lung compartments (ml) and relative fractions (%) at expiration and inspiration hold. Data during TLV before OLV and TLV in controls, during OLV/TLV, and TLV after OLV/TLV are given as means (SD)

<table>
<thead>
<tr>
<th>CT I (TLV before OLV/TLV)</th>
<th>CT II (90 min of OLV/TLV)</th>
<th>CT III (TLV, 90 min after OLV/TLV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLV group (n=6)</td>
<td>Controls (n=3)</td>
<td>OLV group (n=6)</td>
</tr>
<tr>
<td><strong>Expiration</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lung volume (%)</td>
<td>357 (36)</td>
<td>335 (32)</td>
</tr>
<tr>
<td>Atelectasis (%)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Poorly aerated (%)</td>
<td>23 (7)</td>
<td>10 (1)</td>
</tr>
<tr>
<td>Normally aerated (%)</td>
<td>6 (2)</td>
<td>3 (1)</td>
</tr>
<tr>
<td>Overaerated (%)</td>
<td>161 (19)</td>
<td>70 (4)</td>
</tr>
</tbody>
</table>
| Table 5 Lung compartment volumes (ml) and relative fractions (%) of the dependent lungs during TLV before OLV and TLV in controls, during OLV/TLV, and TLV after OLV/TLV are displayed as means (SD). CT I was done after bronchoscopic insertion of a bronchial blocker in the left main bronchus. Correct position of the bronchial blocker was confirmed in OLV pigs by a second bronchoscopy after right lateral positioning. OLV was started by inflation of the bronchial blocker after CT I. *P<0.05 vs CT I, the OLV group; #P<0.05, OLV pigs vs controls

<table>
<thead>
<tr>
<th>CT I (TLV before OLV/TLV)</th>
<th>CT II (90 min of OLV/TLV)</th>
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<td>Controls (n=3)</td>
<td>OLV group (n=6)</td>
</tr>
<tr>
<td><strong>Expiration</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lung volume (%)</td>
<td>313 (27)</td>
<td>318 (27)</td>
</tr>
<tr>
<td>Atelectasis (%)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Poorly aerated (%)</td>
<td>92 (13)</td>
<td>15 (4)*</td>
</tr>
<tr>
<td>Poorly aerated (%)</td>
<td>29 (3)</td>
<td>5 (1)</td>
</tr>
<tr>
<td>Normally aerated (%)</td>
<td>206 (15)</td>
<td>166 (13)</td>
</tr>
<tr>
<td>Overaerated (%)</td>
<td>66 (4)</td>
<td>53 (8)</td>
</tr>
</tbody>
</table>
| Table 4 | Non-dependent lungs: volumes of lung compartments (ml) and relative fractions (%) at expiration and inspiration hold. Data during TLV before OLV and TLV in controls, during OLV/TLV, and TLV after OLV/TLV are given as means (SD)
After resuming TLV (Table 5, CT III), lung density distribution was dominated by normally/poorly aerated regions. The volume of atelectasis was decreased, but 5% remained in the dependent lungs at end-expiration.

The total volume of the dependent lungs increased during OLV, both at end-expiration and at end-inspiration. After restoration of TLV, dependent lung volumes remained increased.

Fig 3 The mean slice-wise end-expiratory and end-inspiratory distributions of lung tissue in cranio-caudal direction according to voxel density [overaerated (−1000 to −900 HU), normally aerated (−900 to −500 HU), poorly aerated (−500 to −100 HU), and atelectasis (−100 to +100 HU)] in the dependent and non-dependent lungs before (CT I, TLV before OLV), during (CT II, OLV), and after OLV (CT III, TLV after OLV).
The distribution of X-ray density in relation to the total lung volume in OLV pigs at end-inspiration and end-expiration is given in histograms (Fig. 4). Before OLV (CT I), the whole distribution shifted towards higher lung density when compared with the controls. OLV moved the spectrum to compartments with increased gas content. This OLV-induced shift of the mean dependent lung density persisted in the TLV period after OLV for at least 90 min.

Density distribution in the lungs of control pigs
Normally and poorly aerated compartments dominated in the lungs of control pigs; the fraction of atelectasis was only 3–5% of the lung volume (Tables 4 and 5). The lung CT density distribution of controls was not affected by mechanical TLV over time. Global density distribution in the dependent lungs did also not change throughout the experiment. Density distribution in the control lungs was different in comparison with the lungs of OLV pigs. The volumes of atelectasis and poorly aerated regions were minor in control pigs.

Discussion
The experimental data show significant cyclic recruitment and de-recruitment, especially in the dependent lungs during mechanical ventilation in the lateral position. Tidal recruitment was aggravated by isolated ventilation of the dependent lungs. Thus, OLV resulted in an increased dependent lung volume and a persistent shift of the lung CT density spectrum towards compartments with higher gas content. Despite temporary lung collapse, atelectasis, or poorly aerated regions in the non-dependent lungs were not increased. Lung CT data of control animals were not different over time, indicating that the experimental conditions per se were constant throughout the study period.

CT imaging allows in vivo analysis of lung aeration with a spatial resolution up to 0.2 mm³ with short scanning times. Commonly, four lung compartments are defined according to the relation of gas and tissue: over-aerated (−1000 to −900 HU), normally aerated (−900 to −500 HU), poorly aerated (−500 to −100 HU), and non-aerated (−100 to +100 HU). 8 The non-aerated regions as defined here are generally called atelectasis. 9

![Distribution histogram of lung voxels in the dependent lungs of OLV pigs and controls (mean per cent of lung volume end-expiratory and end-inspiratory) at baseline TLV, during OLV or TLV in controls, and at TLV after OLV/TLV (*P<0.05 OLV vs baseline TLV; #P<0.05 TLV after OLV vs OLV).](image-url)
physically consisting of collapsed lung tissue, cellular debris, blood, extracellular water, and <10% of air. It is impossible for methodological reasons to discriminate these fractions exactly by CT. In order to minimize systematic bias, larger extrapulmonary structures (blood vessels, trachea, and bronchi) had to be excluded by accurate drawing of ROIs.

Lung consolidation preferentially in dependent regions is observed rapidly after induction of anaesthesia and muscle paralysis in animals and humans.\textsuperscript{10–12} Several factors may influence the lung density distribution along the vertical axis. These include regional differences of transpulmonary pressure, shape and weight of lung tissue, gravity-dependent changes of pulmonary blood volume, and compression of the lungs from adjacent anatomical structures.\textsuperscript{13,14}

Pressure-dependent changes of aeration have been described on various occasions. A pleural pressure gradient\textsuperscript{15} from base to apex and from dependent to non-dependent regions could also be postulated in the present model. The lateral body position decreases functional residual capacity in dependent regions and shifts the ventilation maxima to non-dependent areas.\textsuperscript{16} A displacement of atelectasis from dorsal to the most dependent regions has been observed.

The volume of atelectasis and poorly aerated lung tissue was increased in OLV pigs when compared with controls. This difference is attributed to bronchoscopic manipulations of the airways open to the atmosphere to inflate the bronchial blocker in OLV pigs. However, the procedure is obligatory to avoid cuff herniation or blocker insufficiency.

An FIO\textsubscript{2} of 1.0 commonly used during OLV is also associated with increased atelectasis formation.\textsuperscript{17} Reduction of FIO\textsubscript{2} to 0.4 will protect the lungs from re-collapse for a prolonged period.\textsuperscript{18} Inspiratory hold manoeuvres with a tidal volume of 10 ml kg\textsuperscript{-1} may recruit consolidated lung tissue, but the PEEP of 5 cm H\textsubscript{2}O and inspired oxygen concentrations of 0.4 were not sufficient to keep the dependent lung open in pigs. The large amounts of atelectasis resulted in a comparatively small intrapulmonary shunt of only 3.5%. This can be explained by the efficient hypoxic pulmonary vasoconstriction in pigs in comparison with humans.\textsuperscript{19}

OLV reduced consolidated lung compartments and increased the gas content and subsequently also the dependent lung volume by significant tidal recruitment. During OLV, atelectatic tissue was changed into poorly aerated and poorly aerated into normally aerated lung tissue resulting in a shift of the spectrum towards lower density. Tidal recruitment was thus not limited solely to atelectatic or poorly aerated lung regions.\textsuperscript{20}

About 90% of the pulmonary blood flow is delivered to the dependent lung during OLV.\textsuperscript{5} CT scans during and after OLV exposed a decrease of lung density, despite hyperperfusion. Recent experimental data suggest that pulmonary blood flow distribution is affected more by pulmonary vascular structure than by gravitational effects.\textsuperscript{21}

Although dependent lungs were ventilated with a tidal volume of 10 ml kg\textsuperscript{-1} during OLV, a significant overaeration was not observed. Overaeration is a radiological phenomenon describing a defined lung density of −1000 to −900 HU. Overstretching in contrast implies a mechanical force applied to the lung tissue that may occur at the boundaries of atelectatic, poorly, and normally aerated tissue\textsuperscript{22} and is possibly underestimated by CT.

The density distribution of the non-dependent lungs did not differ from that before OLV, despite complete lung collapse and repetitive vital capacity manoeuvres. In contrast, the dependent lungs retained an increased lung volume with higher gas content. Possible mechanisms may be decreased alveolar recoil forces or air trapping; however, these mechanisms could not be discriminated by CT imaging.

Limitations of the study include the size of the study group and the fixed ventilation setup. Major physiological differences of pigs and humans may contain the extent of HPV, intrapulmonary shunt, and atelectasis formation; nevertheless, the experimental setting was strongly related to clinical conditions. However, the control animals were not subjected to thoracotomy and lung handling. These controls were included to assess the stability of the experimental model over time.

CT imaging does not allow differentiation between lung consolidation by lung collapse or increased pulmonary blood volume; this makes it difficult to determine the underlying mechanism of atelectasis formation. In addition, mediator release by lung manipulation may have produced uncontrolled effects on lung structure independent of ventilation stress.

Cyclic recruitment of alveolar units results in shear stress to the lung parenchyma with extensively elevated transmural pressures.\textsuperscript{23} Shearing and stretching may have profound consequences on lung function and mediator release and have been detected as key factors in initiating an alveolar immune response.\textsuperscript{3,24,25} Likewise, recent histological data of pigs undergoing a similar OLV protocol attested lung injury after OLV, notably in the dependent lung.\textsuperscript{4}

Mechanical ventilation strategies may influence the local release of inflammatory mediators\textsuperscript{26} and various techniques have been advocated to minimize mechanical stress as a result of repeated collapse, reopening, and lung overdistension; however, lung injury was only partially affected. Sufficient reduction of cyclic mechanical stress may help to overcome the deleterious effects of OLV. PEEP levels above the lower inflection point\textsuperscript{27–30} and selective PEEP application\textsuperscript{31} to keep the dependent lung open may reduce alveolar injury. Accordingly, PEEP application combined with tidal volume reduction is sufficient to reduce alveolar collapse and overdistension and may decrease lung injury after experimental OLV.\textsuperscript{5}
In summary, the radiological lung density spectrum moved towards compartments with higher gas content in dependent lungs during and after OLV with tidal volumes of 10 ml kg\(^{-1}\). It remains to be evaluated whether different ventilation approaches may reduce cyclic collapse and reopening and partial overstretching of lung tissue during OLV.

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**References**