Acute respiratory distress syndrome (ARDS) is a major problem in critical care medicine. The syndrome has been reported to be associated with a wide range of mortality rates of between 26 and 70% (21). Mechanical ventilation with positive end-expiratory pressure (PEEP) has long been a standard part of symptomatic therapy (18). In 1986, decreased gas content in compartmentalized dogs, lung injury was induced with oleic acid and glass bead injection. Afterward, PEEP of 10–20 cmH2O was instituted. Norepinephrine was infused at 20 cmH2O PEEP. Heterogeneity increased upon lung injury (p, 0.44 ± 0.09 vs. 0.24 ± 0.09; RD, 0.36 ± 0.06 vs. 0.64 ± 0.12; both P < 0.05), but fractal dimension remained constant. PEEP did not change p, RD, or D. Perfusion gradients were reversed after lung injury (right, −27 ± 18 vs. 196 ± 115; left, −24 ± 18 vs. 282 ± 184%; P < 0.05). PEEP (10 cmH2O) reduced gradients (116 ± 73 and 143 ± 62%, respectively; P < 0.05). Norepinephrine, in part, further reduced gradients (right, 50 ± 58%; P < 0.05; left, 102 ± 94%; P = NS). We conclude that oleic acid and glass bead-induced lung injury produces abnormal distribution of rPBF. Of these changes, application of PEEP only reverses perfusion gradients.

Supported end-expiratory pressure; acute respiratory distress syndrome; microspheres; regional blood flow; oleic acid; dogs

Kleen, M., B. Zwissler, and K. Messmer. PEEP only partly restores disturbed distribution of regional pulmonary blood flow in lung injury. Am. J. Physiol. 274 (Heart Circ. Physiol. 43): H209–H216, 1998.—The effects of lung injury, positive end-expiratory pressure (PEEP), and norepinephrine on heterogeneity of regional pulmonary blood flow (rPBF, radioactive microspheres) were investigated. We hypothesized that lung injury increases heterogeneity of rPBF and that PEEP ventilation reduces these effects. Heterogeneity of rPBF is scale dependent and was therefore assessed in detail. Local correlation (p), relative dispersion (RD), fractal dimension (D), perfusion gradients, and histograms of rPBF each measures a different aspect of heterogeneity. In eight anesthetized dogs, lung injury was induced with oleic acid and glass bead injection. Afterward, PEEP of 10–20 cmH2O was instituted. Norepinephrine was infused at 20 cmH2O PEEP. Heterogeneity increased upon lung injury (p, 0.44 ± 0.09 vs. 0.24 ± 0.09; RD, 0.36 ± 0.06 vs. 0.64 ± 0.12; both P < 0.05), but fractal dimension remained constant. PEEP did not change p, RD, or D. Perfusion gradients were reversed after lung injury (right, −27 ± 18 vs. 196 ± 115; left, −24 ± 18 vs. 282 ± 184%; P < 0.05). PEEP (10 cmH2O) reduced gradients (116 ± 73 and 143 ± 62%, respectively; P < 0.05). Norepinephrine, in part, further reduced gradients (right, 50 ± 58%; P < 0.05; left, 102 ± 94%; P = NS). We conclude that oleic acid and glass bead-induced lung injury produces abnormal distribution of rPBF. Of these changes, application of PEEP only reverses perfusion gradients.
Ceva, Bad Segeberg, Germany), 0.75 mg/kg piritramide (Dipidolor; Janssen, Neuss, Germany), and 0.25 mg/kg alcuronium (Alloferin; Roche, Grenzach-Whylen, Germany) and maintained by continuous infusion of these drugs at a rate of 5, 0.15, and 0.075 mg·kg⁻¹·h⁻¹, respectively. Fluid losses were replaced with Ringer lactate solution at 5 ml·kg⁻¹·h⁻¹. The dogs were endotracheally intubated and mechanically ventilated with 12 breaths/min and a tidal volume of 15–18 ml/kg using 100% oxygen (Servo 900C; Siemens-Elema, Solna, Sweden). Core body temperature was maintained by means of a heating pad.

Surgical Preparation

A catheter for monitoring mean arterial pressure was inserted into the left brachial artery and advanced to the descending aorta. A second catheter was advanced to the superior vena cava via the left brachial vein. A Swan-Ganz catheter (7 Fr; Edwards, Anasco, Puerto Rico) was inserted into the pulmonary artery for measurement of core body temperature and pulmonary artery pressure as well as for injection of microspheres and withdrawal of the reference sample during injection of microspheres. Both injection of microspheres and sampling of blood were performed with the distal port of the catheter in the pulmonary artery. A tip manometer was inserted into the right ventricle via the right external jugular vein for measurement of right ventricular pressures. A side-winder catheter (6 Fr; Cordis, Miami, FL) was introduced under fluoroscopic control via the right common carotid artery into the left atrium for measurement of left atrial pressure. Intrathoracic pressure was estimated using a balloon catheter (National Catheter) inserted into the esophagus and positioned at the level of the atrium. After the catheters were inserted, the dogs were placed in the left lateral decubitus position. In the lateral position, esophageal pressure reliably reflects intrathoracic pressure during PEEP (4). Blood loss due to drawing reference samples was isovolemically replaced with blood. Autologous blood was collected by isovolemic hemodilution with 6% Dextran 60 (Macrodex; Schiwa, Glandorf, Germany) to a hematocrit of 28%. The dogs were allowed to stabilize for 30 min after hemodilution. An additional 400–500 ml of blood were obtained from a premedicated, awake donor dog on the day of the experiment. Autologous and homologous blood were mixed, the absence of hemolysis was verified, and the mixture (hematocrit 28 ± 2%) was used for volume substitution and augmentation of intravascular volume during ventilation with PEEP.

Experimental Protocol

Thirty minutes after baseline measurements, the lungs were injured with OA and glass beads. After 70 min and measurements, PEEP of 10 cmH₂O was induced, and measurements were taken. Thereafter, the level of PEEP was increased by 5 cmH₂O until 20 cmH₂O was reached. After each increase, measurements were taken. Subsequently, norepinephrine was infused (PEEP at 20 cmH₂O), and a final set of measurements was made. The dose of OA was 0.01 ml/kg. Glass beads with 100-µm mean diameter were administered until mean pulmonary artery pressure reached 35–40 mmHg. Both OA and glass beads were injected into the right atrium. This technique has been shown to produce a stable ARDS-like syndrome and pulmonary hypertension (31). Norepinephrine was infused at a dose of 0.2–1.0 µg·kg⁻¹·min⁻¹. During PEEP, transmural right ventricular end-diastolic pressure was kept constant by transfusion of blood (3.6 ± 2.1, 4.5 ± 2.4, and 4.5 ± 1.1 ml/kg at 10, 15, and 20 cmH₂O PEEP, respectively). Ten minutes were allowed to elapse after each intravascular volume change. Subsequently, animals were killed by intravenous injection of saturated potassium chloride. The lungs were removed and dried in room air while being kept inflated at a pressure of 20 cmH₂O for 4 days. A time control group was not studied because the course of this experimental ARDS has been studied in detail before (31).

Measurements

Heart rate, right and left ventricular pressures, as well as intrathoracic pressures were monitored continuously on an eight-channel recorder (481, Gould-Brush, Cleveland, OH) and were evaluated at end expiration. To correct for increased absolute intrathoracic pressure during PEEP ventilation, intrathoracic pressure was subtracted from central venous pressure, mean left atrial pressure, and right ventricular pressures to yield transmural pressures. All pressures reported are transmural pressures. Intermittently, thermodilution cardiac output was measured in triplicate (SP 1435, Gould-Statham, Oxnard, CA). Blood gases were measured with an ABL 300 blood-gas analyzer (Radiometer, Copenhagen, Denmark). Stroke volume (SV) was calculated as

\[ SV = \frac{cardiac\ output}{heart\ rate} \]  (1)

Pulmonary vascular resistance (PVR) was calculated as

\[ PVR = \frac{(PAP - PCWP) \times CO}{80} \]  (2)

where PAP is pulmonary arterial pressure, PCWP is pulmonary capillary wedge pressure, and CO is cardiac output. The factor 80 in Eq. 2 transforms into the SI unit. Intrapulmonary shunt fraction (Qs/Qt) was calculated as

\[ \frac{Q_s}{Q_t} = \frac{(C_{cO_2} - C_{aO_2})}{(C_{cO_2} - C_{vO_2})} \times 100\% \]  (3)

where CcO₂ is pulmonary end-capillary oxygen content calculated as arterial hemoglobin concentration multiplied by the Hct (0.39 plus physically dissolved oxygen (0.0031 times alveolar Pao₂). Arterial (Cao₂) and mixed venous (Cvo₂) oxygen contents were calculated analogously. Microsphere injections were performed as described below at the time of hemodynamic measurements.

Microsphere Methodology

All lungs were completely dissected into an average of 384 ± 77 specimens. Each tissue block was assigned x-, y-, and z-coordinates. Right and left lungs were each cut into four sagittal slices of equal thickness. The numbered slices (1–8) served as x-coordinates. Each slice was dissected into 15 horizontal blocks reaching from posterior to anterior. The blocks were numbered from bottom to top; these numbers were used as y-coordinates. The blocks were cut into 10 tissue samples (z-coordinates). Tissue specimens were prepared to have approximately equal size with the help of a grid drawn on transparent plastic. Smaller sagittal slices were cut into less blocks and smaller blocks into less final samples. Therefore, only an average of 384 samples was obtained rather than the theoretical number of 1,200 (8 slices × 15 blocks × 10 samples).

Regional perfusion was measured with the reference sample method reported by Heymann et al. (17). For injection, microspheres were transferred into glass vials and suspended in saline to give a total volume of 10 ml. Before injection, the vial was agitated for a minimum of 3 min. Microspheres were then injected over 50 s into the right atrium. During injection, the vial was continuously agitated to prevent settling of the
spheres. For every measurement of rPBF, 528,000–817,000 (mean, 700,000) microspheres labeled with a randomly selected isotope (95Nb, 114mIn, 51Cr, 141Ce, 103Ru, 46Sc, 16.5 ± 0.1-μm diameter; 46Sc, 16.5 ± 0.2-μm diameter; New England Nuclear-TRAC, Du Pont, Wilmington, DE) were injected. No cardiorespiratory changes were noted after injection of microspheres. Beginning 10 s before microspheres injection and lasting for a total of 3 min, reference samples were drawn from the pulmonary artery at a rate of 3.24 ml/min (pump model 940A; Harvard Apparatus, South Natick, MA). Reference tissue and sample radioactivity were counted for 5 min using a 1,024 channel gamma counter (model 5260; Packard Instruments, Downers Grove, IL) with a 3-in. sodium iodine (thallium drifted) detector. Data were half-life corrected, and cumulated radioactive spectra were separated to obtain activities from single nuclides using the software package MIC III (14) (Department of Surgical Research, Heidelberg, Germany). Sample flow (Qpr; ml/min) was calculated for each nuclide as

\[ Q_{pr} = Q_{pr} \times I_p \times I_{pr}^{-1} (ml/min) \]  

(4)

where \( Q_{pr} \) is withdrawal rate of the pulmonary reference sample (ml/min), \( I_p \) is counts per minute in the pulmonary reference sample, and \( I_{pr} \) is counts per minute in the tissue sample. \( Q_p \) was normalized to 100 g dry lung wt.

The number of microspheres in each sample was calculated using the specific activity per microspheres. This was determined before the experiments in vitro by assessing the activity of a specimen with a defined number of microspheres of each batch. The number of microspheres in each specimen was counted three times by microscopic examination by different persons, and the results were accepted if the difference between counts did not exceed 1% and microsphere counts were between 600 and 1,000. The gamma activity of these specimens was counted for 20 min, and the result was divided by the number of microspheres.

Analysis of Heterogeneity of rPBF

Relative dispersion. To determine global heterogeneity of rPBF, RD (standard deviation/mean) was calculated for each time point in the protocol. By dividing a measure of dispersion (SD) by a measure of central tendency (mean), one expresses the dispersion as a fraction of the mean. Thus it is possible to compare heterogeneity values from different pulmonary blood flow states. Because for calculation of RD all regional blood flow values are averaged, RD represents a global measure of heterogeneity.

Fractal dimension. Fractal properties of pulmonary blood flow heterogeneity were demonstrated by Glenny and Robertson in 1990 (10). A commonly used approach to analyze the fractal nature of pulmonary perfusion is to dissect the lung in small parts and measure the perfusion on this level. Data from these samples are then recombined to obtain information about perfusion of larger samples. If the perfusion is fractal, the natural logarithm of the decreasing heterogeneity of perfusion to larger samples is linearly related to the natural logarithm of the increasing sample size.

Heterogeneity of blood flow to the lung is described with the RD of regional perfusion. The scale of the applied measurement is expressed as the relative mass of the recombined tissue samples (m) in relation to a reference tissue sample mass (m0). Heterogeneity and scale of measurement of rPBF have been shown to be related according to the following equation

\[ \frac{RD_m}{RD_{m0}} = (m/m_0)^{1-D} \]  

(5)

where \( RD_m \) is the relative dispersion of regional perfusion at some resolution and \( RD_{m0} \) is relative dispersion of regional perfusion when analyzed with the reference resolution (13). The variable D in the exponent of Eq. 5 is the fractal dimension of the perfusion. The slope of the regression line through multiple data points on a plot of

\[ \ln (RD_m) vs. \ln (m/m_0) \]  

(6)

is therefore 1–D. Such plots are therefore used to determine fractal properties of perfusion of the lung (3, 11, 24).

We calculated D with a computer program developed in C/C++ (Watcom C/C++ compiler v. 10; Powersoft, Concord, MA). For calculation of D, individual samples as well as recombinations to larger tissue units comprised 4, 8, 16, 32, 64, etc., individual samples were used. Recombinations were achieved by adding the microsphere contents of the samples comprised in an aggregate sample and dividing the result by the sum of the weights of samples.

Both the program for calculating spatial correlation and the program for assessing fractal dimension were validated with computer-generated data sets with known D and p, respectively.

Spatial correlation. In 1992, Glenny (9) suggested p of regional pulmonary perfusion as a new tool for characterizing distribution of rPBF. Spatial, or three-dimensional, correlation measures the average relationship of blood flow to lung tissue pieces separated by a certain distance. We chose the smallest distance for calculation, thus obtaining spatial correlation for neighboring pieces. Spatial correlation as a measure for averaged, local heterogeneity of pulmonary blood flow has been shown to change differently upon intervention than global heterogeneity measured with RD (12). For calculation of spatial correlation, all blood flow values from tissue specimens separated by a given distance (multiples of sample size) are treated as data pairs and are used as variables for a three-dimensional extension of the standard correlation formula as reported by Glenny (9). We implemented this formula with a computer program written in C++ (Watcom C/C++ compiler v. 10; Powersoft). For analysis, we used the correlation values of adjacent samples; thus p is a measure of local gravity-independent heterogeneity of regional pulmonary perfusion.

Relative gravity-dependent perfusion gradients. Relative gravity dependent perfusion gradients (RPG) were determined separately for each lung as

\[ \text{RPG} = (\text{PBF}_{\text{bottom}} - \text{PBF}_{\text{top}})/\text{PBF}_{\text{top}} \times 100\% \]  

(7)

where \( \text{PBF}_{\text{top}} \) is mean blood flow in the uppermost quarter of the right and left lungs and \( \text{PBF}_{\text{bottom}} \) is mean blood flow in the most dependent quarter of the right and left lungs. With dogs in the left lateral decubitus position, top and bottom were defined as right and left side of the thorax, respectively.

Histograms. Histograms of pooled rPBF values from all animals were analyzed using the median as well as the 5th and 95th percentiles. rPBF was calculated as shown in Microsphere Methodology.

Statistics

All statistical analyses were performed using the software package SAS v. 6.10 (SAS Institute, Cary, NC). After a significant F value was obtained from analysis of variance, the Student-Newman-Keuls test was applied posteriori to determine differences between a time point in the protocol and the respective preceding time point. The type I error level was set to 5%.
PEEP and Lung Perfusion in Lung Injury

RESULTS

In Table 1, central hemodynamic data and blood gases are summarized. Induction of experimental ARDS resulted in significant tachycardia, a decrease of stroke volume, and increases of mean pulmonary artery pressure (MPAP), pulmonary vascular resistance, mean right ventricular pressure, and right ventricular maximal rate of pressure increase (RV dP/dtmax). Cardiac output, arterial pressure, and left atrial pressure were unchanged. Ventilation with 20 cmH2O PEEP caused a significant additional rise of MPAP.

There was a 55% rise of intrapulmonary shunt fraction (Qs/Qt) upon lung injury induction (P < 0.05), a significant acidosis (P = 0.05), a 16% fall of arterial Po2 (P < 0.05), and a 28% rise of arterial PCO2 (P < 0.05). Mixed venous Po2 (PvO2) was unchanged. Mechanical ventilation with PEEP elicited significant reduction of Qs/Qt (P < 0.05), whereas arterial pH, PaCO2, and PvO2 remained unchanged.

Figure 1 shows RD of rPBF (global heterogeneity), D of rPBF (scale-independent global heterogeneity), and r of the perfusion of adjacent pulmonary tissue samples (local heterogeneity of rPBF). Global heterogeneity of rPBF was altered by lung injury: RD was 0.36 ± 0.06 at baseline and 0.64 ± 0.12 upon induction of lung injury (P < 0.05). Neither administration of PEEP nor therapy with norepinephrine induced any rehomogenization (Fig. 1). D was stable after lung injury (1.25 ± 0.06 vs. 1.34 ± 0.08; P = NS) and was not influenced by PEEP or therapy. Induction of lung injury decreased r from 0.44 ± 0.09 at baseline to 0.24 ± 0.09 (P < 0.05). Therapy with 10, 15, and 20 cmH2O PEEP and additional administration of norepinephrine did not change r (Fig. 1).

Figure 2 shows the RPG separately for each lung. At baseline, there was a preferential perfusion of the uppermost quarter of both lungs (right, −27 ± 18%; left, −24 ± 18%). Upon embolization, there was a reversal of this distribution. The RPGs changed to 196 ± 115 and 282 ± 184% for the right and left lung, respectively (P < 0.05). PEEP of 10 cmH2O lowered the gradients of both lungs significantly to 116 ± 73 and 143 ± 62%, respectively, for right and left lungs (P < 0.05). PEEP of 15 and 20 cmH2O did not induce further significant decrease of RPG for both lungs (PEEP 15 cmH2O: right, 103 ± 78%; left, 90 ± 52%; PEEP 20 cmH2O: right, 109 ± 105%, left, 124 ± 58%; P = NS). Infusion of norepinephrine, however, lowered the RPG to 50 ± 58% (P < 0.05) in the right lung, which was not significantly different from baseline. In the dependent left lung, the RPG remained at 102 ± 94% with infusion of the vasoconstricting agent. In Fig. 4, the mean

Table 1. Cardiovascular and gas exchange parameters

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Lung Injury</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>20 + NE</th>
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</thead>
<tbody>
<tr>
<td><strong>HR, min⁻¹</strong></td>
<td>72 ± 19</td>
<td>107 ± 17*</td>
<td>99 ± 16</td>
<td>109 ± 19</td>
<td>124 ± 10</td>
<td>135 ± 31</td>
</tr>
<tr>
<td><strong>MAP, Torr</strong></td>
<td>102 ± 9</td>
<td>102 ± 8</td>
<td>108 ± 13</td>
<td>112 ± 17</td>
<td>102 ± 13</td>
<td>110 ± 19</td>
</tr>
<tr>
<td><strong>CO, l/min</strong></td>
<td>31.0 ± 7</td>
<td>2.8 ± 0.8</td>
<td>2.5 ± 0.7</td>
<td>2.4 ± 0.5</td>
<td>2.1 ± 0.6</td>
<td>2.5 ± 1.0</td>
</tr>
<tr>
<td><strong>SV, ml</strong></td>
<td>44 ± 13</td>
<td>27 ± 8*</td>
<td>25 ± 5</td>
<td>22 ± 5</td>
<td>17 ± 5</td>
<td>20 ± 12</td>
</tr>
<tr>
<td><strong>MLAP, Torr</strong></td>
<td>45.3 ± 3</td>
<td>2.6 ± 2.5</td>
<td>2.8 ± 1.9</td>
<td>2.3 ± 1.9</td>
<td>1.8 ± 2.1</td>
<td>0.9 ± 2.6</td>
</tr>
<tr>
<td><strong>MPAP, Torr</strong></td>
<td>11 ± 3</td>
<td>32 ± 5*</td>
<td>31 ± 4</td>
<td>32 ± 3</td>
<td>37 ± 3*</td>
<td>38 ± 3</td>
</tr>
<tr>
<td><strong>MRVP, Torr</strong></td>
<td>6 ± 2</td>
<td>16 ± 3*</td>
<td>15 ± 3</td>
<td>15 ± 2</td>
<td>17 ± 2</td>
<td>16 ± 2</td>
</tr>
<tr>
<td><strong>RVEDP, Torr</strong></td>
<td>1.4 ± 2.5</td>
<td>2.2 ± 2.8</td>
<td>3.0 ± 2.6</td>
<td>1.6 ± 2.0</td>
<td>1.0 ± 1.1</td>
<td>−0.5 ± 2.1</td>
</tr>
<tr>
<td><strong>RV dP/dtmax, Torr/s</strong></td>
<td>370 ± 92</td>
<td>590 ± 174*</td>
<td>505 ± 136</td>
<td>536 ± 136</td>
<td>567 ± 66</td>
<td>1,276 ± 207</td>
</tr>
<tr>
<td><strong>PVR, dyn·s·cm⁻⁵</strong></td>
<td>156 ± 81</td>
<td>907 ± 350*</td>
<td>947 ± 321</td>
<td>1,081 ± 378</td>
<td>1,461 ± 549</td>
<td>1,458 ± 728</td>
</tr>
<tr>
<td><strong>Qs/Qt</strong></td>
<td>0.09 ± 0.04</td>
<td>0.14 ± 0.03*</td>
<td>0.10 ± 0.04*</td>
<td>0.07 ± 0.03*</td>
<td>0.05 ± 0.03</td>
<td>0.05 ± 0.03</td>
</tr>
<tr>
<td><strong>pH</strong></td>
<td>7.35 ± 0.04</td>
<td>7.26 ± 0.03*</td>
<td>7.27 ± 0.03</td>
<td>7.27 ± 0.04</td>
<td>7.26 ± 0.04</td>
<td>7.23 ± 0.04</td>
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<tr>
<td><strong>PaO₂, Torr</strong></td>
<td>584 ± 39</td>
<td>491 ± 34*</td>
<td>536 ± 34*</td>
<td>579 ± 33*</td>
<td>590 ± 38*</td>
<td>587 ± 35</td>
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<td><strong>PaCO₂, Torr</strong></td>
<td>36 ± 4</td>
<td>46 ± 6*</td>
<td>45 ± 4</td>
<td>45 ± 6</td>
<td>46 ± 5</td>
<td>47 ± 6</td>
</tr>
<tr>
<td><strong>PvO₂, Torr</strong></td>
<td>68 ± 15</td>
<td>62 ± 9</td>
<td>60 ± 10</td>
<td>57 ± 10</td>
<td>52 ± 12</td>
<td>54 ± 14</td>
</tr>
</tbody>
</table>

Values are means ± SD. HR, heart rate; MAP, mean arterial pressure; CO, cardiac output; SV, stroke volume; MLAP, mean left atrial pressure; MPAP, mean pulmonary artery pressure; RV, right ventricular; MRVP, mean RV pressure; RVEDP, RV end-diastolic pressure; RV dP/dtmax, maximal rate of RV pressure increase; PVR, pulmonary vascular resistance; Qs/Qt, intrapulmonary shunt fraction; pH, arterial pH; PaO₂, arterial Po2; PaCO₂, arterial PCO2; PvO₂, mixed venous Po2; PEEP, positive end-expiratory pressure; NE, norepinephrine. To convert Torr to kPa, multiply by 1.33. *P ≤ 0.05 vs. preceding time point.
perfusion values of each slice of both lungs are depicted. The perfusion gradients from dependent to nondependent parts of the lungs, and vice versa, can be deduced from Fig. 4.

The cumulated histograms of rPBF from all animals values are shown in Figure 3. The median blood flow was $3.8 \pm 0.6 \text{l} \cdot \text{min}^{-1} \cdot 100 \text{g}^{-1}$ at baseline and $3.7 \pm 0.9 \text{l} \cdot \text{min}^{-1} \cdot 100 \text{g}^{-1}$ upon lung injury induction ($P = \text{NS}$). Ventilation with PEEP of 10 cmH$_2$O elevated median blood flow to $4.2 \pm 2.8 \text{l} \cdot \text{min}^{-1} \cdot 100 \text{g}^{-1}$ ($P < 0.05$).

PEEP of 15 and 20 cmH$_2$O each reduced perfusion ($2.6 \pm 0.4$ and $2.3 \pm 0.3 \text{l} \cdot \text{min}^{-1} \cdot 100 \text{g}^{-1}$, respectively; $P \leq 0.05$). Infusion of norepinephrine did not further change blood flow ($2.1 \pm 0.8 \text{l} \cdot \text{min}^{-1} \cdot 100 \text{g}^{-1}$; $P = \text{NS}$). The configuration of the rPBF histograms was distorted with lung injury (Fig. 3). The 5th percentile (P5) of rPBF was lowered by lung injury. Application of PEEP did not reverse this, but PEEP of 20 cmH$_2$O further reduced the lower border of the histograms. Additional application of norepinephrine increased P5 slightly but consistently. The median lung blood flow was not altered by lung injury. PEEP of 10 cmH$_2$O increased the median blood flow by $0.46 \text{l} \cdot \text{min}^{-1} \cdot 100 \text{g}^{-1}$, Increasing PEEP then reduced median perfusion to a minimum of $2.09 \text{l} \cdot \text{min}^{-1} \cdot 100 \text{g}^{-1}$ as compared with $3.74 \text{l} \cdot \text{min}^{-1} \cdot 100 \text{g}^{-1}$ at baseline. The upper border of the histograms, the 95th percentile, was significantly reduced by 15 cmH$_2$O after an insignificant increase upon lung injury.

DISCUSSION

The main results of the present study are as follows: 1) lung injury caused an increase of both global and local heterogeneity of rPBF, reversal of gravity-dependent blood flow gradients, and alterations of statistical measures of histograms of rPBF. 2) PEEP and, partly, norepinephrine counteracted changes of perfusion gradients and blood flow histograms. However, injury-induced heterogeneity remained high. Neither the global, resolution-dependent RD nor global, resolution-independent fractal D were influenced by PEEP therapy. Local correlation of blood flow was also unchanged.

Fig. 2. Effects of lung injury, different levels of PEEP, and PEEP plus NE on relative perfusion gradients (RPG) of rPBF. Data are means ± SD. Definitions are as in Fig. 1. *$P \leq 0.05$ vs. preceding time point in protocol for left lung. #$P \leq 0.05$ vs. preceding time point in protocol for right lung.

Fig. 3. Effects of lung injury, PEEP, and PEEP plus norepinephrine on histograms of rPBF. Data are cumulated regional blood flow values from 8 dogs. M, median of histogram; P5, 5th percentile of histogram; P95, 95th percentile of histogram. *$P \leq 0.05$ vs. preceding time point in protocol.
Data on heterogeneity of regional pulmonary perfusion during respiratory failure are limited. The prone position has been shown to reduce gravitational gradients of regional pulmonary perfusion (30) and reduce venous admixture (1) in dogs with OA edema. High-level PEEP was demonstrated to improve gas exchange in lavage-induced lung injury (2) and to homogenize density distribution in computed tomography images in ARDS patients (7). In 1994, Schuster and Howard (25) showed with indirect perfusion measurements (positron emission tomography) that PEEP reverses OA-induced redistribution of pulmonary perfusion to edematous tissue. Using the multiple inert gas elimination technique, Matamis et al. (22) noted beneficial effects of 17 ± 2 cmH2O PEEP on ventilation-perfusion distribution in patients with acute respiratory failure. Hedenstierna and co-workers (15, 16) reported on the effects of 20 cmH2O PEEP on gravitational gradients in healthy dog lungs by analyzing representative samples rather than whole lungs. In their studies, decreased right ventricular preload was not compensated for, but reduced cardiac output without PEEP did not produce similar patterns of perfusion redistribution (15, 16).

There is one study dealing with distribution of rPBF in OA injury in dogs (27). The authors have calculated peripheral to central perfusion gradients. Early after OA infusion they found a reduction of peripheral perfusion. This seems to be in contrast to our data. We observed an increase in peripheral perfusion in the dependent lung and a decrease of peripheral blood flow in the nondependent lung (Fig. 4). Tarver and colleagues (27) studied only representative samples of one lobe of one lung. We studied the complete lung and observed heterogeneous distribution changes including effects similar to those observed by Tarver et al. We therefore cannot definitely conclude whether our results are in contrast to or in agreement with those of the cited study. Another important difference between our study and that of Tarver et al. is that in the former, animals were placed in the left lateral decubitus posi-

![Fig. 4. rPBF gradients at baseline, lung injury, PEEP of 10–20 cmH₂O, and PEEP plus norepinephrine. Each lung was separated in 4 sagittal slices (dogs were in left lateral decubitus position). Average blood flow to each slice is plotted against its vertical position in lying dog. Data are cumulated from 8 dogs.](http://ajpheart.physiology.org/)

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tion and in the latter the prone position was used. The time frame in both studies is very different. We induced OA-glass bead lung injury over a time that was certainly much longer than the time used in Tarver’s study. The latter study was explicitly designed to investigate early effects of OA infusion, whereas we established a more chronic form of lung injury. In conclusion, we think that our results are not necessarily in contrast to those published by Tarver and colleagues.

Spatial Correlation, Relative Dispersion, and Fractal Dimension

Spatial correlation ($\rho$) of perfusion of adjacent lung tissue samples is a measure of local similarity of blood flow (9). Lung injury decreased $\rho$ notably ($0.44 \pm 0.09$ vs. $0.24 \pm 0.09$) (Fig. 1). This is in contrast to findings of Schuster and Howard (25) who reported a redistribution of perfusion to the most edematous lung regions induced by OA after application of 10 cmH2O PEEP. Global heterogeneity of rPBF greatly increased upon lung injury ($RD = 0.36 \pm 0.06$ vs. $0.64 \pm 0.12$) (Fig. 1) and was influenced neither by PEEP nor by infusion of norepinephrine. The lack of effect of the treatment on these three parameters of heterogeneity is an important finding. From previous data on OA edema, a positive effect of PEEP on distribution of rPBF should have been expected (25). When assessed with more specific methods, however, heterogeneity proved uninfluenced. Therefore, RD and $\rho$ are valuable parameters of rPBF distribution in this model of lung injury. For testing other therapeutic strategies, it may be useful to use them to show superiority of new concepts.

Relative Perfusion Gradients

At baseline, we found preferential perfusion of the nondependent parts of the lung, which is in agreement with recent findings by Hlastala et al. in horses (19). Relative perfusion gradients were calculated separately for each lung. The dependent part of the left lung was the part adjacent to the lateral thoracic wall, and the nondependent parts were mediastinal regions. For the right lung (superior to the left lung because of the left lateral decubitus position), the dependent part was the mediastinal part and the nondependent part corresponded to those regions next to right lateral thoracic wall. Induction of lung injury reversed RPGs and greatly enhanced the extent of gravity-dependent perfusion inhomogeneity in both lungs (Fig. 2). The difference of the bottom and top parts (left lateral decubitus position of the dogs) of the lungs amounted to two to three times the blood flow in the uppermost parts of the lungs. PEEP of 10 cmH2O counteracted these gradients significantly. This is in contrast to the reported effects of PEEP on the noninjured lung in dogs in which 20 cmH2O PEEP resulted in marked reduction of perfusion of the uppermost regions of the lung (15, 16). Similarly, PEEP (10 cmH2O) redirected perfusion to dependent regions of the lung in a model of OA-induced single-lung injury (20).

In the right (nondependent) lung, norepinephrine further redistributed perfusion to nondependent areas of the lung, thus rendering the resulting RPG not significantly different from baseline values despite the presence of lung injury and 20 cmH2O PEEP. The catecholamine was infused in a central vein. The lung is known to clear 30% of this drug during a single passage (8, 26); however, this may or may not be the case in the injured lung. As can be concluded from unchanged values for pulmonary vascular resistance (Table 1), norepinephrine did not vasoconstrict pulmonary vessels. There was, however, a trend toward increased right ventricular contractility (RV $dP/dt_{max}$ see Table 1) and increased cardiac output. The effects of norepinephrine on RPGs may therefore probably be explained by a recruitment of pulmonary vessels. Norepinephrine might be of benefit when combined with PEEP in attempts to normalize disturbed gradients of pulmonary blood flow in ARDS. However, norepinephrine failed to further improve $Q_v/Q_a$ or $Pa_O_2$ in our study and may also cause increased cardiovascular stress, which may be undesirable in critically ill patients.

Histograms of rPBF Values

At baseline, the histogram of rPBF values (Fig. 3) was close to a Gaussian distribution as judged by inspection. Such a normal distribution was also found by Walther et al. (29) in awake sheep. Upon lung injury, the number of values close to zero and the number of extremely high values were increased, which resulted in a left-shifted and skewed histogram. The most prominent change upon ventilation with PEEP (15 cmH2O) was the reduced frequency of extremely high values. Thus the rPBF histogram approached prelung injury configuration upon therapy with PEEP. It appears that PEEP therapy removed the tail from the rPBF distribution and added to the frequency of values close to the mean. The median value was reduced by higher levels of PEEP, but the fifth percentile was not greatly reduced; thus the lower median seems due to less high values. Considering improved gas exchange and reduced shunt fraction, we interpret these changes upon PEEP as improvement of distribution of rPBF in this model of lung injury.

Conclusion

In the present study, we provide the first data on spatial correlation and fractal dimension of regional pulmonary blood flow in a model of acute lung injury and PEEP therapy. Our data show that most parameters of heterogeneity are greatly changed by lung injury. PEEP therapy normalizes only the perturbations of perfusion gradients and some of the statistical measures of rPBF histograms. However, neither of the new parameters of blood flow distribution (fractal dimension, spatial correlation) that were changed by lung injury were normalized by PEEP therapy. In addition to restoring ventilation to collapsed or fluid-filled alveoli that are still perfused, PEEP may contribute to improved oxygenation in patients with ARDS by improving disturbed perfusion gradients.
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REFERENCES


