Effect of Airway Pressure Release Ventilation on Dynamic Alveolar Heterogeneity

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**Importance** Ventilator-induced lung injury may arise from heterogeneous lung microanatomy, whereby some alveoli remain collapsed throughout the breath cycle while their more compliant or surfactant-replete neighbors become overdistended, and this is called dynamic alveolar heterogeneity.

**Objective** To determine how dynamic alveolar heterogeneity is influenced by 2 modes of mechanical ventilation: low tidal-volume ventilation (LTVV) and airway pressure release ventilation (APRV), using in vivo microscopy to directly measure alveolar size distributions.

**Design, Setting, and Participants** In a randomized, nonblinded laboratory animal study conducted between January 2013 and December 2014, 14 rats (450-500 g in size) were randomized to a control group with uninjured lungs (n = 4) and 2 experimental groups with surfactant deactivation induced by polysorbate lavage: the LTVV group (n = 5) and the APRV group (n = 5). For all groups, a thoracotomy and in vivo microscopy were performed. Following lung injury induced by polysorbate lavage, the LTVV group was ventilated with a tidal volume of 6 mL/kg and progressively higher positive end-expiratory pressure (PEEP) (5, 10, 16, 20, and 24 cm H2O). Following lung injury induced by polysorbate lavage, the APRV group was ventilated with a progressively shorter time at low pressure, which increased the ratio of the end-expiratory flow rate (EEFR) to the peak expiratory flow rate (PEFR; from 10% to 25% to 50% to 75%).

**Main Outcomes and Measures** Alveolar areas were quantified (using PEEP and EEFR to PEFR ratio) to determine dynamic heterogeneity.

**Results** Following lung injury induced by polysorbate lavage, a higher PEEP (20-24 cm H2O) with LTVV resulted in alveolar occupancy (reported as percentage of total frame area) at inspiration (39.9%-42.2%) and expiration (35.9%-38.7%) similar to that in the control group (inspiration 53.3%; expiration 50.3%; \(P > .01\)). Likewise, APRV with an increased EEFR to PEFR ratio (50%-75%) resulted in alveolar occupancy at inspiration (46.7%-47.9%) and expiration (40.2%-46.6%) similar to that in the control group (\(P > .01\)). At inspiration, the distribution of the alveolar area of the control group was similar to that of the APRV group (\(P > .01\)) (but not to that of the LTVV group (\(P < .01\)). A lower PEEP (5-10 cm H2O) and a decreased EEFR to PEFR ratio (\(\leq 50\%\)) demonstrated dynamic heterogeneity between inspiration and expiration (\(P < .01\) for both) with a greater percentage of large alveoli at expiration. Dynamic alveolar homogeneity between inspiration and expiration occurred with higher PEEP (16-24 cm H2O) (\(P > .01\)) and an increased EEFR to PEFR ratio (75%) (\(P > .01\)).

**Conclusions and Relevance** Increasing PEEP during LTVV increased alveolar recruitment and dynamic homogeneity but had a significantly different alveolar size distribution compared with the control group. By comparison, reducing the time at low pressure (EEFR to PEFR ratio of 75%) in the APRV group provided dynamic homogeneity and a closer approximation of the dynamics observed in the control group.

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Despite the development of improved ventilator strategies, the morbidity and mortality associated with acute respiratory distress syndrome (ARDS) remain unacceptably high.\textsuperscript{1,2} To prevent ARDS and its associated complications, it is important, first and foremost, to prevent ventilator-induced lung injury by using mechanical ventilation strategies that both maintain alveolar recruitment and avoid tissue overdistension. Protective mechanical ventilation, as it is currently used clinically, aims to avoid overdistension by reducing tidal volume ($V_t$). Nevertheless, regional overdistension of alveolar tissue can still occur when lung mechanical properties become heterogeneous because the $V_t$ delivered is then forced into tissue regions that have higher compliance. The less compliant regions either remain completely collapsed (atelectatic) or experience damaging cycles of recruitment and derecruitment with each breath.\textsuperscript{3} Furthermore, the parenchyma at the boundary between atelectatic and ventilated parenchyma may be subject to increased strain owing to geometric effects.\textsuperscript{4} Thus, ventilator-induced lung injury can arise from heterogeneous mechanical behavior at the level of the microanatomy when some alveoli remain collapsed throughout the breath cycle while their more compliant or surfactant-replete neighbors become overdistended.\textsuperscript{5} We call this phenomenon \textit{dynamic alveolar heterogeneity}.

Ventilation heterogeneity can be assessed clinically during mechanical ventilation using imaging methods such as computed tomography\textsuperscript{6} and electrical impedance tomography.\textsuperscript{7} These methods, however, do not have the spatial resolution to reveal dynamic alveolar heterogeneity, so direct visualization of dynamic alveolar heterogeneity in patients is not currently possible. On the other hand, our previous computational modeling work suggests that dynamic alveolar heterogeneity can be predicted from breath-by-breath measurements of lung mechanics following the application of recruitment maneuvers.\textsuperscript{8,9} We recently used this approach in a rat model of ARDS\textsuperscript{10} to predict how the relative degrees of alveolar overdistension and intratidal derecruitment depend on ventilator settings during both conventional low tidal-volume ventilation (LTVV) and airway pressure release ventilation (APRV). Confirming these predictions experimentally would lend significant support to the validity of assessing dynamic alveolar heterogeneity via computational modeling and would allow for the design of mechanical ventilation strategies that minimize dynamic alveolar heterogeneity.

Accordingly, the purpose of the present study was to quantify dynamic alveolar heterogeneity in a rat model of acute lung injury. We used in vivo microscopy to directly measure intratidal alveolar recruitment during LTVV and APRV and to determine how dynamic alveolar heterogeneity is influenced by these 2 modes of mechanical ventilation and by the settings used with each mode.

### Methods

#### Procedure

All experiments were performed in accordance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals and approved by State University of New York Upstate Medical University Institutional Animal Care and Use Committee. Male Sprague-Dawley rats (450-500 g in size) were acclimatized to laboratory conditions for 1 week. Each rat was anesthetized with ketamine hydrochloride (90 mg/mL) and xylazine hydrochloride (10 mg/mL) dosed at 0.1 mg/kg of ketamine. Animals were intubated via tracheostomy with a 2.5-mm tracheal cannula (Harvard Apparatus) and then placed on mechanical ventilation (Dräger Evita Infinity V500) with a positive end-expiratory pressure (PEEP) of 5 cm H$_2$O, $V_t = 6$ mL/kg, a respiratory rate of 55 breaths/min, and a fraction of inspired oxygen of 21%. The carotid artery was cannulated with silastic tubing for hemodynamic monitoring, and the external jugular vein was cannulated for fluid and medication administration. The right lung was exposed via thoracotomy for in vivo assessment. A microscope coverslip was lowered onto the pleural surface, and the lung was held in place by gentle suction (5 cm H$_2$O) for in vivo videomicroscopy (epi-objective microscopy with epi-illumination; Olympus America Inc) as previously described.\textsuperscript{11} After instrumentation, the rats were randomized into a control group ($n = 4$) or 1 of 2 treatment groups (LTVV [$n = 5$] and APRV [$n = 5$]) using a random number generator (Microsoft Excel), with each group previously assigned an integer value.

#### Experimental Groups

##### Control Group

The rats in the control group were maintained on ventilation with PEEP of 5 cm H$_2$O, a $V_t$ of 6 mL/kg, a respiratory rate of 55 breaths/min, and a fraction of inspired oxygen of 21%. The in vivo microscope was placed as already described, and videos were recorded with a high-definition video camera (Allied Visions Stingray, F-145C).

##### Injury

Surfactant deactivation was induced by intratracheal instillation of 0.2% of polysorbate 20 in normal saline (5 mL/kg), half this volume into each lung. The rats were rotated into the right and left lateral decubitus position, respectively, for bilateral polysorbate distribution. The rats were then subjected to injurious mechanical ventilation with high tidal volume ($V_t = 16$ mL/kg) and a PEEP of 0 cm H$_2$O for 10 minutes. This model of surfactant deactivation would most closely approximate a patient with a direct pulmonary insult, such as pneumonia,\textsuperscript{12} aspiration,\textsuperscript{13} or inhalation injury.\textsuperscript{14} Patients who develop extrapulmonary lung injury are susceptible to surfactant deactivation by way of an indirect injury, and this model may still be applicable; however, it does not encompass the full spectrum of pathophysiologic changes associated with indirect lung injury.\textsuperscript{15}

##### LTVV Group

Following injury induced by polysorbate lavage, the rats in this group were switched to LTVV with $V_t = 6$ mL/kg, a respiratory rate of 55 breaths/min, and a PEEP of 5 cm H$_2$O that is incrementally increased (to 10, 16, 20, and 24 cm H$_2$O). The rats were ventilated at each setting for 5 minutes to allow acclimatization. The in vivo microscope was placed as already described, and videos were recorded for 5 ventilator cycles at each ventilation setting.

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APRV Group
Following injury induced by polysorbate lavage, rats in this group were maintained at a plateau pressure ($P_{\text{high}} = 35-40 \text{ cm H}_2\text{O}$) for a time ($T_{\text{high}} = 1.9-2.0 \text{ seconds}$) that was set to occupy approximately 90% of the ventilatory cycle. The release pressure ($P_{\text{low}} = 0 \text{ cm H}_2\text{O}$) was applied for a time ($T_{\text{low}} = 0.13-0.40 \text{ seconds}$). The $T_{\text{low}}$ was adjusted so that the ratio of the end-expiratory flow rate (EEFR) to the peak expiratory flow rate (PEFR) was 10%, 25%, 50%, or 75%; larger values of the EEFR to PEFR ratio correspond to shorter $T_{\text{low}}$. This led to a reduction in the number of open alveoli at inspiration and expiration, whereas shorter expiratory durations (higher EEFR to PEFR ratio), demonstrated an increase in mean (SEM) number of alveoli at inspiration in the LTVV group increased substantially with an EEFR to PEFR ratio of 50% or lower, there was a significant difference in alveolar recruitment between the control group and the experimental groups, as well as between inspiration and expiration at each setting. All tests were 2-tailed, and $P < .01$ was considered statistically significant. We used Prism version 5.0 statistical software for analysis (GraphPad Software Inc).

Results
Plateau Pressure
Increasing PEEP from 5 to 24 cm H$_2$O led to a concomitant increase in mean (SEM) plateau pressure from 21.9 (1.4) to 40.6 (1.3) cm H$_2$O (Figure 1). The mean (SEM) plateau pressures of the higher PEEPs of 16 to 24 cm H$_2$O (31.7 (0.9) to 40.6 (1.3) cm H$_2$O) were statistically similar to those of APRV (37.1 (1.0) cm H$_2$O; $P > .01$).

Alveolar Recruitment
There were significantly fewer alveoli at inspiration for low PEEP (5 and 10 cm H$_2$O) in the 2 experimental groups compared with the control group ($P < .01$), whereas the number of alveoli per photomicrograph for all settings in the APRV group and a high PEEP (16-24 cm H$_2$O) was not significantly different from the number of alveoli per photomicrograph in the control group ($P > .01$; Table). At all settings of APRV, the number of alveoli at inspiration varied minimally with a range of mean (SEM) values of 46.0 (2.7) to 51.4 (5.4) alveoli per photomicrograph. By comparison, the mean (SEM) number of alveoli at inspiration in the LTVV group increased substantially with PEEP from 27.9 (6.5) (with a PEEP of 5 cm H$_2$O) to 49.9 (4.1) (with a PEEP of 24 cm H$_2$O) alveoli per photomicrograph. At expiration, there was a steady increase in the number of alveoli with increasing PEEP in the LTVV group, as well as with increasing EEFR to PEFR ratio in the APRV group, although it was not significantly different from the increase observed in the control group ($P > .01$). The APRV group, with a longer expiratory duration (lower EEFR to PEFR ratio), demonstrated a reduction in the number of open alveoli at inspiration and expiration, whereas shorter expiratory durations (higher EEFR to PEFR ratio) increased the number of open alveoli at expiration and inspiration.

Alveolar Diameter
The alveolar diameters at inspiration and expiration were similar between each of the experimental groups and the control group ($P > .01$). Of the experimental settings tested, APRV with an EEFR to PEFR ratio of 75% trended toward the greatest alveolar radius at both inspiration and expiration. With an increasing PEEP and an increasing EEFR to PEFR ratio, the alveolar radius at expiration increased. With an EEFR to PEFR ratio of 50% or lower, there was a significant difference in alveolar radius between inspiration and expiration ($P < .01$; Table).

Alveolar Surface Area
The lower PEEP settings (5-16 cm H$_2$O) in the 2 experimental groups had significantly less alveolar occupancy at both ins-
Airway Pressure Release Ventilation and Dynamic Alveolar Heterogeneity

Table. Comparison of Alveolar Occupancy and Recruitment Between Control and Experimental Groups

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean (SEM)</th>
<th>No. of Alveoli</th>
<th>Alveolar Diameter, μm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Alveolar Occupancy, %</td>
<td>Inspiration</td>
<td>Expiration</td>
</tr>
<tr>
<td>Control</td>
<td>53.3 (4.0)</td>
<td>60 (5.9)</td>
<td>39.0 (1.0)</td>
</tr>
<tr>
<td>APRV</td>
<td>46.2 (2.8)</td>
<td>51.4 (5.4)</td>
<td>38.4 (1.9)</td>
</tr>
<tr>
<td>EEFR to PEF ratio, %</td>
<td>35.8 (2.4,0.4)</td>
<td>32.8 (5.0)</td>
<td>26.2 (2.6,0.4)</td>
</tr>
<tr>
<td>10</td>
<td>43.5 (2.3)</td>
<td>46.0 (2.7)</td>
<td>40.2 (1.6)</td>
</tr>
<tr>
<td>25</td>
<td>46.7 (2.8)</td>
<td>49.3 (3.2)</td>
<td>41.4 (1.2)</td>
</tr>
<tr>
<td>50</td>
<td>47.9 (2.9)</td>
<td>50.6 (4.9)</td>
<td>40.1 (1.9)</td>
</tr>
<tr>
<td>75</td>
<td>24.8 (3.7)</td>
<td>27.9 (6.5)</td>
<td>39.0 (5.1)</td>
</tr>
<tr>
<td>LTG</td>
<td>39.9 (3.1)</td>
<td>40.1 (3.1)</td>
<td>37.3 (2.1)</td>
</tr>
<tr>
<td>PEEP, cm H2O</td>
<td>35.9 (3.6)</td>
<td>38.1 (3.8)</td>
<td>34.4 (2.1)</td>
</tr>
<tr>
<td>5</td>
<td>32.7 (3.9)</td>
<td>33.5 (3.9)</td>
<td>34.1 (3.0)</td>
</tr>
<tr>
<td>10</td>
<td>30.9 (3.1)</td>
<td>31.0 (4.6)</td>
<td>39.1 (4.1)</td>
</tr>
<tr>
<td>16</td>
<td>24.0 (3.8)</td>
<td>33.6 (9.3)</td>
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</tr>
<tr>
<td>20</td>
<td>29.3 (3.6)</td>
<td>35.4 (6.4)</td>
<td>31.2 (1.5)</td>
</tr>
<tr>
<td>24</td>
<td>35.9 (3.6)</td>
<td>38.1 (3.8)</td>
<td>34.4 (2.1)</td>
</tr>
</tbody>
</table>

Abbreviations: APRV, airway pressure release ventilation; EEFR, end-expiratory flow rate; LTG, low tidal-volume ventilation; PEEP, positive end-expiratory pressure; PEF, peak expiratory flow rate.

*Alveolar Occupancy represents the percentage of the photomicrograph occupied by alveolar area at inspiration and expiration. The experimental groups include the LTG group varying PEEP and the APRV group with increasing EEFR to PEF ratio.

Alveolar Heterogeneity

Qualitatively, there appeared to be greater dynamic heterogeneity with a PEEP of 5 cm H2O and an EEFR to PEF ratio of 10%, whereas there was more dynamic homogeneity with a PEEP of 20 cm H2O and an EEFR to PEF ratio of 75%, as shown for representative rats in Figure 2. At inspiration, the distribution of alveolar area also appeared to be similar between an EEFR to PEF ratio of 10% and an EEFR to PEF ratio of 75%. Using the χ2 test, we compared the expected distribution of alveolar areas with the actual distribution. All groups failed the normality test. Using the Kolmogorov-Smirnov test, we compared the distributions of alveolar areas in the 2 experimental groups with the distribution of alveolar areas in the control group to determine whether the distributions were similar at both inspiration and expiration. At inspiration, all of the settings in the APRV group demonstrated an alveolar distribution similar to that observed in the control group (P > .01; Figure 3A), whereas none of the settings in the LTG group demonstrated distributions that were similar to the distribution observed in the control group (P < .01; Figure 3B). At expiration, neither of the experimental groups had an alveolar distribution similar to that of the control group (P < .01; Figure 3C and D).

The Kolmogorov-Smirnov test was performed to determine dynamic heterogeneity, which reflects whether the alveolar size distributions significantly changed between inspiration and expiration in each group. In the control group, there was dynamic homogeneity (P > .01), which indicates that there was not a significant change in the alveolar size distribution between inspiration and expiration as depicted in Figure 4A. In addition, there was minimal skew, with the median alveolar sizes at inspiration and expiration closely approximating the corresponding mean values. Likewise, the alveolar size distribution for all APRV settings at inspiration was characterized by low skew, with the median values closely approximating the alveolar mean values (Figure 4B–E). At expiration, there was positive skewness in the APRV group with EEFR to PEF ratios of 10% (Figure 4B), which lessened with increasing EEFR to PEF ratios. In the APRV group with low EEFR to PEF ratios (<50%) there was dynamic heterogeneity between inspiration and expiration (P < .01), but there was dynamic homogeneity with an EEFR to PEF ratio of 75% (P > .01). In the LTG group, the low PEEP settings (5 and 10 cm H2O; Figure 4F–G) also demonstrated positive skewness at expiration, which lessened with increasing PEEP (16-24 cm H2O; Figure 4H–J). The low PEEP settings (5 and 10 cm H2O) demonstrated dynamic heterogeneity between inspiration and expiration (P < .01), but with increasing PEEP (16-24 cm H2O), there was a closer ap-
proximation of both the alveolar mean and median values between inspiration and expiration, which indicates dynamic homogeneity ($P > .01$).

**Discussion**

In most investigations into the pathogenesis of ventilator-induced lung injury, the assessment of heterogeneity is made at the level of the whole lung.6,7 This represents a length scale several orders of magnitude larger than that of the alveoli, which are directly affected by the stresses and strains of mechanical ventilation16 and, therefore, might not accurately reflect the alveolar heterogeneity that occurs in the injured lung.17 Applying a mechanical breath to a heterogeneous population of alveoli might result in localized regions of high stress without a significant increase in the overall stress of the whole lung.6 Likewise, the changes in alveolar size distribution at inspiration vs expiration that occur when dynamic heterogeneity is present are indicative of abnormal alveolar microstrain5 and intratidal derecruitment, which are known to accelerate the progression of lung injury. Thus, to truly identify the protective benefits of a ventilation strategy, the spatiotemporal alveolar heterogeneity that it causes must be assessed. Using computational modeling,10 we have recently shown evidence that both alveolar microstrain and intratidal derecruitment depend markedly on ventilator settings for both LTVV and APRV. The results of the present study directly corroborate these previous modeling results and confirm the importance of ventilating the injured lung in a manner that minimizes the heterogeneous mechanical behavior of the lung at the level of individual alveoli.

The normal lung is homogenously expanded near total lung capacity.18 Accordingly, the inspiratory pressure used in APRV is conventionally set to produce lung volumes at a point on the steep portion of the pressure-volume curve that is well above functional residual capacity but still less than total lung capacity. This avoids alveolar overdistension and encourages spon-

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**Figure 2. Qualitative Comparison of Dynamic Alveolar Heterogeneity Between Inspiration and Expiration at Low Tidal-Volume Ventilation (LTVV) and at Airway Pressure Release Ventilation (APRV)**

- **LTVV with PEEP of 5 cm H$_2$O**
- **LTVV with PEEP of 20 cm H$_2$O**
- **APRV with EEFR to PEFR**
  - ratio of 10%
  - ratio of 75%

Alveoli from in vivo photomicrograph are ordered from largest to smallest area. EEFR indicates end-expiratory flow rate; PEEP, positive end-expiratory pressure; and PEFR, peak expiratory flow rate.
taneous breathing by patients while, at the same time, promoting alveolar recruitment. The ability of APRV to maintain alveolar homogeneity thus arises because the majority (approximately 90%) of the ventilation cycle is spent at the upper pressure ($P_{\text{high}}$). The sustained greater lung volume that this produces results in alveolar size distributions for APRV at inspiration that are independent of the value of $T_{\text{low}}$, as shown in Figures 2 and 3. These size distributions are also similar to those observed in control animals randomly assigned to LTVV, which show that APRV did not cause additional alveolar overdistension. In contrast, the alveolar size distribution for APRV at expiration is highly dependent on $T_{\text{low}}$. In particular, an EEFR to PEFR ratio of 50% or lower caused a marked decrease in the median alveolar size, increased derecruitment, and resulted in a positive skew of the size distribution similar to that of decreasing PEEP with LTVV (Figure 4). In other words, longer durations at $P_{\text{low}} = 0$ cm H$_2$O allowed sufficient time for significant derecruitment to occur with each expiration. The benefits of APRV in terms of increased homogeneity and decreased intratidal derecruitment that have been reported in human studies and in animal models of ARDS thus require that $T_{\text{low}}$ be set appropriately such that the EEFR to PEFR ratio is 75%. These findings are supported by an experimental study demonstrating that a prolonged inspiratory time at the plateau pressure requires either an expiratory phase of a brief duration to a low pressure or an expiratory phase of a longer duration to a high pressure in order to stabilize oleic-acid-injured lungs.

Manipulating the parameters of conventional LTVV in the injured rats also had a substantial effect on dynamic alveolar heterogeneity. For example, a low PEEP decreased the median alveolar size in a manner similar to prolonged $T_{\text{low}}$ in APRV (Figure 4). The positive skew in the alveolar distributions at low PEEPs indicates that the rats that underwent ventilator-induced lung injury by polysorbate-induced surfactant deactivation required increased airway pressures in order to maintain the presumably normal alveolar architecture exhibited by the uninjured rats in the control group. Furthermore, the significantly lower number of patent alveoli observed in the rats ventilated with low PEEP indicate that the resulting low ventilation pressures were not sufficient to maintain recruitment following lung injury. Increasing PEEP, which resulted in increased inspiratory pressures due to the fixed...
Comparison of alveolar distributions between inspiration and expiration in the control group (A), the airway pressure release ventilation group with increasing ratio of end-expiratory flow rate (EEFR) to peak expiratory flow rate (PEFR) (B-E), and the low tidal-volume ventilation group with increasing positive end-expiratory pressure (PEEP) (F-J). Alveolar distribution at inspiration (solid curve) is compared with alveolar distribution at expiration (dotted curve). Median values are represented by the 2 vertical lines (solid line = median at inspiration; dotted line = median at expiration). P < .01 indicates statistical significance for dynamic heterogeneity (dissimilar alveolar distributions between inspiration and expiration), and P > .01 indicates dynamic homogeneity.
V_t, reduced the skewness of the alveolar distributions at inspiration and promoted dynamic alveolar homogeneity (Figure 4). Therefore, the improvements in homogeneity with PEEP might have been due to a combination of increased plateau and end-expiratory pressures (Figure 1) that would have induced alveolar recruitment and prevented derecruitment.

Another interesting possible effect of PEEP, suggested by Namati et al, is that it might facilitate recruitment via the pores of Kohn. Opening the pores of Kohn, therefore, might enable collateral ventilation and allow for the redistribution of alveolar volume from more compliant to adjacent, less-compliant alveoli, thereby promoting alveolar homogeneity. Corroborating this hypothesis, Wellman et al, using positron emission tomography, established that increasing PEEP in a sheep nitrogen washout model improved specific ventilation homogeneity. The present study, increasing the end-expiratory lung volume by either increasing PEEP or increasing the EEFR to PEFR ratio increased alveolar occupancy at expiration and decreased alveolar derecruitment (Table). Increasing PEEP also led to an increase in alveolar occupancy, although not to the same degree as APRV at inspiration, likely because the prolonged T_high in APRV allowed time for nearly complete recruitment of alveoli.

The distributions of alveolar areas observed in the control and experimental groups were non-Gaussian. Mazzuca et al hypothesized that such non-Gaussian distributions are artifacts because in vivo microscopy does not evaluate each alveolus in the plane of the alveolar centroid. Alternatively, Namati et al suggested that non-Gaussian distributions observed using a laser-scanning confocal technique were the result of evaluating 3 types of alveoli: those that change with tidal inflation, those that do not, and those that collapse at expiration. These effects are exaggerated in lung injuries associated with the loss of surfactant function due to elevated rates and magnitudes of derecruitment. In any case, the alveolar size distributions in the present study were significantly positively skewed at low pressures (Figure 4), similar to the skewed size distributions observed using in vivo microscopy in open-chest rabbits at 3 cm H_2O. Likewise, our distributions at high PEEP (20 and 24 cm H_2O; Figure 4) demonstrate the same decrease in kurtosis (or flattening of the curve) as observed by Mazzuca et al at a pressure of 16.5 cm H_2O.

The experimental findings of the present study thus provide direct evidence that alveolar heterogeneity is reduced by increases in lung inflation pressure. Nevertheless, these findings must still be viewed in the context of the limitations of the in vivo microscopy technique and the region of the lung studied. Ventilation heterogeneity exists across the lung, and our assessment was limited to zone I, or the anterior surface, of the lung and therefore may not necessarily be generalized to the whole lung. One other potential issue is that suction is required to stabilize the lung tissue on the microscope coverslip during imaging, and this is known to increase both alveolar stability and size. These effects appear, however, to be subtle. Another potentially significant limitation is that in vivo microscopy can only evaluate subpleural alveoli to a depth of approximately 70 μm. This restricts investigation essentially to 2 dimensions and does not allow for the characterization of the gas distribution to the conducting air spaces. However, the normalization of the alveolar size distribution with increasing airway pressure, as we found in the present study (Figure 4), has also been found using a laser-scanning confocal technique capable of looking deeper into excised mouse lungs. Furthermore, similar improvements in lung homogeneity with increasing PEEP and plateau pressure have been observed using computed tomography in patients with ARDS, so it seems reasonable to propose that the behavior of subpleural alveoli, as observed by in vivo microscopy, provides a suitable approximation of whole-lung alveolar dynamics. Finally, it must be remembered that the mechanics of lungs in a patient with ARDS is influenced by the presence of an intact chest wall, diaphragm, and abdomen. In the present study, the chest wall was removed, as necessitated by the use of in vivo microscopy, so conditions were not identical to those encountered clinically.

Conclusions

The alveolar size distributions observed using in vivo microscopy in lung-injured rats demonstrate the importance of both the magnitude and the duration of the applied pressures during mechanical ventilation. The extended durations of APRV at the inspiratory pressure (T_high) provide alveolar size distributions at inspiration that closely approximate noninjured rats ventilated at low tidal volumes (P > .01). For long durations of T_low (EEFR to PEFR ratio of ≤50%), significant changes in the alveolar size distribution occur from inspiration to expiration, which reflect dynamic alveolar heterogeneity. Reducing the APRV T_low duration (EEFR to PEFR ratio of 75%) eliminates this dynamic heterogeneity and reduces intratidal derecruitment, providing a close approximation of the dynamics observed in the control group. Likewise, increasing PEEP during LTVV increases recruitment, alveolar occupancy, and dynamic homogeneity. However, even at a PEEP of 24 cm H_2O, the alveolar size distributions at inspiration are significantly different from the alveolar size distribution observed in the control group. Our findings indicate that the alveolar dynamics during APRV with an EEFR to PEFR ratio of 75% more closely resembles the dynamics of a healthy lung than does the alveolar dynamics during LTVV with a PEEP of up to 24 cm H_2O.
REFERENCES


