Effects of Short-term Pressure-Controlled Ventilation on Gas Exchange, Airway Pressures, and Gas Distribution in Patients With Acute Lung Injury/ARDS*

Comparison With Volume-Controlled Ventilation

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Study objectives: The potential clinical benefits of pressure-controlled ventilation (PCV) over volume-controlled ventilation (VCV) in patients with acute lung injury (ALI) or ARDS still remain debated. We compared PCV with VCV in patients with ALI/ARDS with respect to the following physiologic end points: (1) gas exchange and airway pressures, and (2) CT scan intrapulmonary gas distribution at end-expiration.

Design: Prospective, observational study.

Setting: A multidisciplinary ICU in a nonuniversity, acute-care hospital.

Patients: Ten patients with ALI or ARDS (9 men and 1 woman; age range, 17 to 80 years).

Interventions: Sequential ventilation in PCV and VCV with a constant inspiratory/expiratory ratio, tidal volume, respiratory rate, and total positive end-expiratory pressure; measurement of gas exchange and airway pressures; and achievement of CT sections at lung base, hilum, and apex for the quantitative analysis of lung densities and of aerated vs nonaerated zones.

Results: PaO₂, PaCO₂, and PaO₂/fraction of inspired oxygen ratio levels did not differ between PCV and VCV. Peak airway pressure (Ppeak) was significantly lower in PCV compared with VCV (26 ± 2 cm H₂O vs 31 ± 2 cm H₂O; p < 0.001; mean ± SEM). The surface areas of the nonaerated zones as well as the total areas at each section level were unchanged in PCV compared with VCV, except at the apex level, where there was a significantly greater nonaerated area in VCV (11 ± 2 cm² vs 9 ± 2 cm²; p < 0.05). The total mean CT number of each lung (20 lungs from 10 patients) was similar in the two modes, as were the density values at the basal and apical levels; the hilum mean CT number was −442 ± 28 Hounsfield units (HU) in VCV and −430 ± 26 HU in PCV (p < 0.005).

Conclusions: These data show that PCV allows the generation of lower Ppeaks through the precise titration of the lung distending pressure, and might be applied to avoid regional overdistension by means of a more homogeneous gas distribution.

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Key words: acute lung injury; ARDS; CT; lung overdistension; mechanical ventilation; pressure-controlled ventilation

Abbreviations: ALI = acute lung injury; FIO₂ = fraction of inspired oxygen; HU = Hounsfield unit; I:E = inspiratory/expiratory; IRV = inverse-ratio ventilation; NS = not significant; PCV = pressure-controlled ventilation; PEEP = positive end-expiratory pressure; Pmean = mean airway pressure; Ppeak = peak airway pressure; RR = respiratory rate; VCV = volume-controlled ventilation; VE = minute ventilation; VT = tidal volume

In recent years, pressure-controlled ventilation (PCV) with or without inverse-ratio ventilation (IRV) has been considered a protective ventilatory strategy in patients with acute lung injury (ALI) or ARDS, as this mode prevents the uncontrolled rise in alveolar pressures and thereby may reduce the risks of lung injury.1–5 Compared with constant-flow volume-controlled ventilation (VCV), PCV has been claimed to favor gas distribution between regions with heterogeneous time constants, and to allow a more homogeneous share of tidal volume (VT) to the whole lung, through its quicker alveolar filling and more laminar flow.6 PCV has also been shown to reduce work of breathing relative to VCV in the
setting of ARDS, thanks its variable decelerating inspiratory flow pattern. However, this rapid initial flow may generate shearing and traction forces close to collapsed areas and thus induce an alveolar derecruitment.

The potential clinical benefits of PCV over classical modes of ventilation in patients with ALI or ARDS still remain debated. The present study was thus designed to compare the effects of PCV and VCV on gas exchange, airway pressures, and distribution of intrapulmonary gas. Gas distribution was analyzed at end-expiration, using the CT scan densitometric technique.

**Materials and Methods**

**Study Population**

The Cantonal Ethical Committee approved the study; for safety reasons, the grant was assigned only after confirmation that no measurements except the CT scan analysis would be carried out in the CT unit. Informed written consent was obtained from the patients’ next of kin. Ten consecutive ARDS patients admitted to our multidisciplinary ICU were considered (Table 1). Seven patients had a “secondary” ARDS (sepsis \( n = 4 \), multiple trauma \( n = 2 \), necrotizing pancreatitis \( n = 1 \)), while three patients were admitted to the ICU with a diffuse pneumonia (“primary” ARDS). ARDS was defined according to the American-European Consensus Conference diagnostic criteria.

Clinical severity was assessed by the simplified acute physiology score II, and lung severity was assessed by the Murray lung injury score. Exclusion criteria were age < 16 years, pregnancy, preexisting lung disease, chronic left ventricular failure, and immunosuppression. Considering the risks associated with a transfer to the CT scan facility, the protocol was not applied at safety reasons, the grant was assigned only after confirmation that no measurements except the CT scan analysis would be carried out in the CT unit. Informed written consent was obtained from the patients’ next of kin. Ten consecutive ARDS patients admitted to our multidisciplinary ICU were considered (Table 1). Seven patients had a “secondary” ARDS (sepsis \( n = 4 \), multiple trauma \( n = 2 \), necrotizing pancreatitis \( n = 1 \)), while three patients were admitted to the ICU with a diffuse pneumonia (“primary” ARDS). ARDS was defined according to the American-European Consensus Conference diagnostic criteria.

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**Procedure and Measurements**

The patients, fully sedated and paralyzed, were investigated in the supine position. Mechanical ventilation was provided (Siemens Servo 900 C or Siemens Servo 300; Siemens-Elema AB; Solna, Sweden). Until the onset of the procedure, the ventilator was set in the VCV mode or the PCV mode while the ventilatory parameters (\( V_t \), respiratory rate \( [R] \), minute ventilation \( [V_e] \), fraction of inspired oxygen \( [F_{IO_2}] \), and PEEP) were selected and adjusted according to patients’ needs. PCV without IRV (inspiratory/expiratory \( [I:E] \) ratio = 1:2) and constant-flow VCV were sequentially applied, beginning with the mode not selected before the protocol started. Between the two consecutive ventilatory modalities, we did not intend to return to baseline values in order to avoid the bias of a longer exposure of the patient to the ventilation technique used before the beginning of the study. The conversions from the standard ventilatory treatment to the first selected mode, and from the first selected mode to the second sequential mode, were done while exactly matching exhaled \( V_t \) and inspiratory time, keeping constant the RR, \( V_e \), and extrinsic PEEP. For each patient, all ventilatory parameters were then held constant throughout the study period; the mean values of \( V_t \), RR, \( V_e \), and extrinsic PEEP are shown in Table 2. After a period of 30 min in each ventilatory mode, gas exchange data were obtained and airway pressures recorded from the ventilator. Flow, pressure, and volume curves were reported on a three-channel recorder. End-expiratory and end-inspiratory hold maneuvers were performed to establish static pressure levels.

Immediately after collecting these data, the patients were transferred to the CT unit, where continuous monitoring and mechanical ventilation were provided with identical instrumentation as in the ICU setting. The two ventilatory modes were again applied sequentially in the same order and with the same ventilatory settings as in the ICU; after a 30-min stabilization period in each mode, CT scan data were obtained. The time elapsed between collecting the final gas exchange and lung mechanics data and performance of the first CT scan density analysis did not exceed 1 h. Before obtaining the CT exposures, the stability of the previously chosen ventilatory settings was further corroborated.

**CT Scan Methodology and Analysis**

We used a CT Systec 3000 scanner (General Electric Medical Systems; Milwaukee, WI). Exposures were obtained at 120 kilovolts, 100 mA, and within 3 s. Slice thickness was 10 mm, and the pixel dimensions of the reconstruction matrix were 0.55 mm². CT methodology and analysis were as described by Gatti.

**Table 1—Demographic and Clinical Characteristics of Patients**

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Diagnosis</th>
<th>Gender</th>
<th>Age, yr</th>
<th>SAPS II</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Multiple trauma</td>
<td>Male</td>
<td>25</td>
<td>31</td>
<td>Survived</td>
</tr>
<tr>
<td>2</td>
<td>Pneumonia</td>
<td>Male</td>
<td>54</td>
<td>50</td>
<td>Survived</td>
</tr>
<tr>
<td>3</td>
<td>Pneumonia</td>
<td>Male</td>
<td>66</td>
<td>55</td>
<td>Survived</td>
</tr>
<tr>
<td>4</td>
<td>Necrotizing pancreatitis</td>
<td>Female</td>
<td>47</td>
<td>41</td>
<td>Survived</td>
</tr>
<tr>
<td>5</td>
<td>Sepsis</td>
<td>Male</td>
<td>71</td>
<td>45</td>
<td>Died</td>
</tr>
<tr>
<td>6</td>
<td>Sepsis</td>
<td>Male</td>
<td>80</td>
<td>91</td>
<td>Died</td>
</tr>
<tr>
<td>7</td>
<td>Multiple trauma</td>
<td>Male</td>
<td>20</td>
<td>31</td>
<td>Survived</td>
</tr>
<tr>
<td>8</td>
<td>Sepsis</td>
<td>Male</td>
<td>39</td>
<td>45</td>
<td>Survived</td>
</tr>
<tr>
<td>9</td>
<td>Head trauma, aspiration pneumonia</td>
<td>Male</td>
<td>17</td>
<td>54</td>
<td>Survived</td>
</tr>
<tr>
<td>10</td>
<td>Sepsis</td>
<td>Male</td>
<td>49</td>
<td>77</td>
<td>Died</td>
</tr>
</tbody>
</table>

Mean ± SEM  
Mortality rate, %  

*SAPS II = simplified acute physiology score II.*
Table 1—Ventilatory Settings Throughout the Study Period*

<table>
<thead>
<tr>
<th>Variables</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>VT, ml/kg</td>
<td>9 ± 0.7</td>
</tr>
<tr>
<td>RR, cycles/min</td>
<td>14 ± 0.7</td>
</tr>
<tr>
<td>Vt, L/min</td>
<td>8 ± 0.6</td>
</tr>
<tr>
<td>Extrinsic PEEP mean, cm H$_2$O</td>
<td>7 ± 0.5</td>
</tr>
<tr>
<td>Extrinsic PEEP range, cm H$_2$O</td>
<td>6–12</td>
</tr>
<tr>
<td>Intrinsic PEEP range, cm H$_2$O</td>
<td>0–2</td>
</tr>
<tr>
<td>I:E ratio</td>
<td>1:2</td>
</tr>
</tbody>
</table>

*Data are presented as mean ± SEM unless otherwise indicated.

Results

Ten patients with ALI or ARDS were studied. The demographic and clinical characteristics of patients at the moment of intubation are summarized in Table 1. The elapsed time from tracheal intubation until onset of the trial ranged from 13 to 94 h (mean, 71 ± 8 h). At trial onset, the mean value of PaO$_2$/FiO$_2$ ratio was 182 ± 18 mm Hg (range, 132 to 278 mm Hg). The mean ventilatory parameters applied at the beginning of the protocol and kept constant in the two ventilatory modes throughout the study period are shown in Table 2. PEEP levels, individually chosen for each patient by the clinician, ranged from 6 to 12 mm Hg. The main results obtained in the ICU and in the CT scan unit are expressed in Table 3.

No significant differences in gas exchange were observed in the two ventilatory modes. As detected in the individual analysis, the slight trend toward a greater PaO$_2$/FiO$_2$ ratio in PCV (182 ± 18 mm Hg vs 197 ± 21 mm Hg; p = 0.1) essentially reflects the time course of two patients, whereas four patients had a decreased PaO$_2$/FiO$_2$ ratio. The only significant difference in lung mechanics between VCV and PCV was a lower peak airway pressure (Ppeak) in PCV (31 ± 2 cm H$_2$O vs 26 ± 2 cmH$_2$O; p < 0.001). This difference was found in all patients. As the plateau pressure was similar and the VT and PEEP were kept constant, the calculated quasistatic compliance of the respiratory system was identical in the two ventilatory modes (40 ± 4 mL/cm H$_2$O vs 41 ± 4 mL/cm H$_2$O; p = not significant [NS]).

Table 3 and Figures 1, 2 present the data from the CT scan analysis. The total mean CT number of each lung (20 lungs from 10 patients) was similar in the two modes (−409 ± 27 HU in VCV vs −405 ± 26 HU in PCV; p = NS), as were the density values at the basal and apical levels. The only statistically significant difference in density was found at the hilum, with a mean CT number of −442 ± 28 HU in VCV and −430 ± 26 HU in PCV (p < 0.005; Fig 1, Table 3). The surface areas of the nonaerated zones as well as the total areas at each section level were unchanged in PCV compared with VCV, except at the apex level, where there was a significantly greater nonaerated area in VCV (11 ± 2 cm$^2$ vs 9 ± 2 cm$^2$; p < 0.05; Fig 2, Table 3). Individual CT scan data at the apex and hilum are presented in Figures 3, 4; in all but two patients, the same trend was observed for the mean lung density and the nonaerated surface area in the two ventilatory modes.

Discussion

The objective of this study was to compare the effects on gas exchange, airway pressures, and gas distribution of PCV without IRV with those reported during constant-flow VCV in patients with ALI or ARDS. The level of ventilation (RR, VT, Ve, and total
PEEP) having been held constant during the entire observation period, the only differences between the two modes were the flow pattern and the generated airway pressures. Our findings indicate little influence on gas exchange when switching from one mode to the other, suggesting a lack of significant alveolar recruitment with PCV during the time schedule of our protocol. Nonetheless, we observed a lower Ppeak and, as discussed later, a pattern of more homogeneous gas distribution in PCV than in VCV, suggesting a reduction in regional overdistension.

The literature concerning the comparative effects of PCV and VCV on gas exchange in patients with ALI or ARDS has produced inconsistent results, mainly due to differences in the study populations and methodologies. Many human studies reporting an improvement in oxygenation with PCV observed a parallel increase in mean airway pressure (Pmean) or in intrinsic PEEP. At constant Pmeans, Mang et al showed, in an animal study, that the mode of ventilation does not modify oxygenation. In 27 patients with ARDS, Rappaport and coworkers also found no major PaO2/FIO2 improvement when comparing PCV and VCV over a 72-h period. More recently, Lessard et al and Esteban et al demonstrated equivalence in arterial oxygenation while comparing VCV and PCV with a normal I:E ratio. Our study agrees with these latter reports.

In spite of the elapsed time between the ICU and...
attributed to the cumulative effects of the heart weight on the underlying dependent lung regions, the differences in regional chest wall geometry and compliance, the abdominal content on regional pleural pressures, and finally the gravitational forces. In a CT scan analysis of the effect of PEEP in 71 patients with ARDS, Puybasset et al. showed that overdistension occurred only in the upper lobes, supporting the differences we found in our analysis of the three lung sections. The individual analysis shows the reproducibility of our results, with only two patients having a significantly different response to PCV (Figs 3, 4).

Thus, while our results do not support the contention that PCV may favor alveolar recruitment compared to VCV when considering the whole lung, they uphold the hypothesis that PCV might allow a more even gas distribution in the diseased lung, by directing the VT out of the overdistended lung units.

This potential advantage of PCV may be explained by its flow characteristics (more laminar) and by its ability to generate lower Ppeaks, as shown in our analysis of the ventilatory mechanics. The association between PCV and lower Ppeak has been demonstrated in previous trials. This decrease in Ppeak reflects in part the lower flow resistance generated by the decelerating flow pattern, but most of all, it defines the set level that cannot be exceeded in alveolar pressure under conditions of passive ventilation. However, even if the plateau pressure is kept constant in the two ventilatory modes, at constant-flow VCV some noncollapsed alveoli may receive higher pressures during inspiration, thus favoring overdistension in lungs with marked heterogeneous lesions.

Considering the small and heterogeneous sample size of our patients and the large variety of factors influencing alveolar recruitment, our results may not necessarily apply to other ALI or ARDS groups of patients and need to be substantiated in a larger number of patients. However, the reproducibility of our individual CT data gives strength to our results even with a sample size of only 20 lungs (Figs 3, 4). Taking 5 days as the cutoff duration, all our subjects were studied in the early phase of ALI/ARDS, characterized by a severe permeability pulmonary edema and no signs of pulmonary fibrosis or emphysematous changes, discerned on CT scan images in the chronic phase of the disease, were observed in our patients. Another possible limit of our study is the length of the stabilization period before the CT scan procedure, which was restricted to 30 min. This period of time was decided in order to minimize the duration of the patient’s stay outside the ICU. However, it seems unlikely that a longer application of PCV or VCV would have revealed

The homogenization of VT in PCV thus followed a caudocephalic gradient: no gas movement at the base and the greatest redistribution process at the apex. These findings are consistent with the cephalocaudal distribution of lung tissue and gas revealed by CT studies on patients with ARDS and commonly
changes not recorded in the present condition; indeed, lung volume and arterial blood gas modifications after changes in ventilatory pattern have been observed within minutes in patients with ARDS, as demonstrated in studies on the effects of PEEP,16 IRV,31 and periodic hyperinflations.32

A third limitation might be the sequential application of the two studied ventilatory modes without an effective return to baseline values. We cannot exclude the possibility that the first applied modality has influenced the other in a different way, but this possibility appears remote in view of the homogeneity of our CT scan data (Figs 3, 4).

The application of an individualized level of PEEP for each patient might also have influenced lungs mechanics during the study protocol. Any difference in alveolar recruitment between PCV and VCV might have been more marked and therefore easier to detect in patients with a high amount of collapsed but recruitable parenchyma, and the latter obviously depends on PEEP. Moreover, PEEP-induced alveolar recruitment may also be associated with overdistension of previously aerated lung regions,33,34 which seems to favor a more even distribution of gas volume.24 Thus, while PCV may homogenize ventilation by directing the VT out of the overdistended areas, PEEP has been shown to act by changing regional compliance. As these two different mechanisms might have influenced each other, we looked for a possible relationship between PEEP level and our individual CT data, but could not find any statistically significant correlation (data not shown).

Finally we considered only CT scan sections performed at end-expiration. An analysis of the CT scan images at end-inspiration would add a dynamic view of the gas distribution, revealing these lung areas that inflate at plateau pressure and collapse again at PEEP. In conclusion, our results suggest that in patients with ARDS or ALI, PCV might be applied to avoid regional overdistension through its more homogeneous gas distribution and the precise titration of the lung distending pressure.

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REFERENCES


4 Amato MB, Barbas CS, Medeiros DM, et al. Beneficial effects of the “open lung approach” with low distending pressure in


7 Kallet RH, Alonzo JA, Morabito DJ. The effects of PC vs VC assisted ventilation in acute lung injury and ARDS. Respir Care 2000; 45:1085–1096


10 Le Gall JR, Lemeshow ST, Saulnier F. A new simplified acute physiology score (SAPS II) based on a European/North American multicenter study. JAMA 1993; 270:2957–2963


28 MacIntyre NR. Clinically available new strategies for mechanical ventilatory support. Chest 1993; 104:560–565


