Effects of Mechanical Ventilation on Release of Cytokines into Systemic Circulation in Patients with Normal Pulmonary Function

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Background: Mechanical ventilation with high tidal volumes (VT) in contrast to mechanical ventilation with low VT has been shown to increase plasma levels of proinflammatory and anti-inflammatory mediators in patients with acute lung injury. The authors hypothesized that, in patients without previous lung injury, a conventional potentially injurious ventilatory strategy with high VT and zero end-expiratory pressure (ZEEP) will not cause a cytokine release into systemic circulation.

Methods: A total of 39 patients with American Society of Anesthesiologists physical status I–II and without signs of systemic infection scheduled for elective surgery with general anesthesia were randomized to receive mechanical ventilation with either (1) VT = 15 ml/kg ideal body weight on ZEEP, (2) VT = 6 ml/kg ideal body weight on ZEEP, or (3) VT = 6 ml/kg ideal body weight on positive-end-expiratory pressure of 10 cm H2O. Plasma levels of proinflammatory and anti-inflammatory mediators tumor necrosis factor, interleukin (IL)-6, IL-10, and IL-1 receptor antagonist were determined before and 1 h after the initiation of mechanical ventilation.

Results: Plasma levels of all cytokines remained low in all settings. IL-6, tumor necrosis factor, and IL-1 receptor antagonist did not change significantly after 1 h of mechanical ventilation. IL-10 was below the detection limit (10 pg/ml) in 35 of 39 patients. There were no differences between groups.

Conclusions: Initiation of mechanical ventilation for 1 h in patients without previous lung injury caused no consistent changes in plasma levels of studied mediators. Mechanical ventilation with high VT on ZEEP did not result in higher cytokine levels compared with lung-protective ventilatory strategies. Previous lung damage seems to be mandatory to cause an increase in plasma cytokines after 1 h of high VT mechanical ventilation.

(Key words: Inflammation; lung; mediators; ventilator-associated lung injury.)

POSITIVE pressure ventilation is commonly applied in patients undergoing general anesthesia to assure adequate ventilation and gas exchange. Conventional mechanical ventilation still uses low positive end-expiratory pressure (PEEP) levels with high tidal volumes (VT) ranging between 10 and 15 ml/kg ideal body weight. However, positive pressure ventilation alone or in combination with preexisting lung disease may contribute considerably to lung injury, including pneumothorax, alveolar edema, and alveolar rupture.

Mechanical ventilation with PEEP titrated above the lower inflection point of a static pressure–volume curve and low VT has been suggested to prevent tidal collapse and overdistension of lung regions during severe acute respiratory distress syndrome (ARDS). This lung-protective ventilatory strategy has been shown to improve gas exchange and outcome in patients with ARDS. Recently, Ranieri et al. observed higher systemic and intraalveolar levels of proinflammatory cytokines in ARDS patients during mechanical ventilation with low PEEP and high VT when compared with a lung-protective strategy. Therefore, it has been speculated that conventional mechanical ventilation may induce release of inflammatory mediators and thereby contribute to lung injury. In vitro experiments have demonstrated that mechanical stress to lung cells is associated with release of inflammatory mediators. However, acute lung injury or ARDS itself causes an inflammation of the lungs with increased systemic and intraalveolar concentrations of the proinflammatory cytokines. It is unclear whether mechanical ventilation alone or only in the presence of acute lung injury can release inflammatory cytokines into systemic circulation.

We hypothesized that, in patients with normal lungs, mechanical ventilation with high VT does not induce a release of cytokines into the systemic circulation. To test this hypothesis, we measured proinflammatory and anti-inflammatory cytokines in the plasma of anesthetized patients with healthy lungs while they were mechanically ventilated with lung-protective or conventional strategies.

Materials and Methods

Approval of the Bonn University Ethics Committee, Bonn, Germany, for the study protocol was obtained, and all patients gave written informed consent before inclusion in the study.

Thirty-nine adult patients classified as American Society of Anesthesiologists physical status I or II scheduled for elective extrathoracic surgery with general anesthesia (table 1) were eligible to participate in the study. Patients with history or clinical signs of lung disease, history of smoking, age older than 65 yr, immunosuppression by drugs or underlying condition, elevated leu-
Table 1. Demographic and Clinical Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High VT ZEEP</th>
<th>Low VT ZEEP</th>
<th>Low VT PEEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of patients</td>
<td>13</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>46 ± 19</td>
<td>49 ± 14</td>
<td>49 ± 14</td>
</tr>
<tr>
<td>Gender (M/F)</td>
<td>7/6</td>
<td>8/5</td>
<td>7/6</td>
</tr>
<tr>
<td>Ideal body weight (kg)</td>
<td>65 ± 15</td>
<td>61 ± 8</td>
<td>63 ± 10</td>
</tr>
<tr>
<td>ASA (n)</td>
<td>5/8</td>
<td>3/10</td>
<td>3/10</td>
</tr>
<tr>
<td>Scheduled surgery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abdominal</td>
<td>5</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Bone</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Vascular</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Other</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

VT = tidal volume; ZEEP = zero end-expiratory pressure; PEEP = positive end-expiratory pressure; ASA = American Society of Anesthesiologists.

Cytokine Measurements

Venous EDTA blood samples of 5 ml were centrifuged at 1,500 g for 5 min, and the plasma was aspirated and stored at −70°C. Commercially available enzyme-linked immunosorbent assays were used to measure plasma levels of interleukin (IL)-6, tumor necrosis factor (TNF) (Biosource, Ratingen, Germany), IL-10, and IL-1 receptor antagonist (R&D Systems, Minneapolis, MN). All enzyme-linked immunosorbent assay analyses were performed with strict adherence to the manufacturers' guidelines.

Protocol

All patients remained supine throughout the study period. Baseline measurements were obtained immediately before induction of anesthesia. After induction of anesthesia, patients were randomly assigned to receive either mechanical ventilation with VT of 15 ml/kg ideal body weight and zero end-expiratory pressure (ZEEP) (high VT, ZEEP group), a VT of 6 ml/kg ideal body weight and ZEEP (low VT, ZEEP group), or VT of 6 ml/kg ideal body weight and 10 cm H₂O PEEP (low VT, PEEP group). The ventilator rate was adjusted to maintain end-tidal carbon dioxide partial pressure between 35 and 45 mmHg. After ventilation with the assigned mode was stable for 1 h, the measurements were repeated. Thereafter, data collection was concluded and the surgical procedure was allowed to commence.

Statistics

To detect differences in cytokine plasma levels between the ventilatory settings with the given two-side-tailed parallel design at a significance level of 5% (α = 0.05) with a probability of 80% (β = 0.20) based on an estimated difference of 0.85 of the parameter's mean SD, a minimum of 39 patients were to be studied.

Results are expressed as mean ± SD. All statistical analysis were performed using a statistical software package (Statistica for Windows 5.1, StatSoft, Inc., Tulsa, OK). Data were tested for normal distribution with the Shapiro-Wilks W test. Ventilatory variables were analyzed using a one-way analysis of variance. When a significant difference was found, pairwise comparisons were performed with the Tukey-Kramer test. Cytokine measurements were compared using a Student’s t-test.

Table 2. Ventilatory Variables

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High VT ZEEP</th>
<th>Low VT ZEEP</th>
<th>Low VT PEEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilatory rate (l/min)</td>
<td>6.3 ± 0.7</td>
<td>22.9 ± 4.0 †</td>
<td>22.3 ± 5.3 †</td>
</tr>
<tr>
<td>VT (ml)</td>
<td>1.024 ± 210</td>
<td>411 ± 53 †</td>
<td>430 ± 71 †</td>
</tr>
<tr>
<td>VE (l/min)</td>
<td>6.5 ± 1.3</td>
<td>9.3 ± 1.6 †</td>
<td>9.4 ± 1.9 †</td>
</tr>
<tr>
<td>TI (s)</td>
<td>4.6 ± 0.7</td>
<td>1.3 ± 0.3 †</td>
<td>1.3 ± 0.4 †</td>
</tr>
<tr>
<td>TIE (s)</td>
<td>5.0 ± 0.5</td>
<td>1.4 ± 0.2 †</td>
<td>1.5 ± 0.5 †</td>
</tr>
<tr>
<td>TV/TE</td>
<td>0.48</td>
<td>0.47</td>
<td>0.46</td>
</tr>
<tr>
<td>Pawmean (cm H₂O)</td>
<td>6.8 ± 3.5</td>
<td>5.3 ± 1.4</td>
<td>12.7 ± 0.5 †</td>
</tr>
<tr>
<td>Pawmax (cmH₂O)</td>
<td>16.1 ± 4.9</td>
<td>12.1 ± 3.3 †</td>
<td>17.9 ± 1.5 †</td>
</tr>
<tr>
<td>PETCO₂ (mmHg)</td>
<td>36 ± 3</td>
<td>41 ± 3 †</td>
<td>41 ± 5 †</td>
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</table>

* Values are mean ± SD.
† P < 0.001 and † P < 0.05 compared with high tidal volume (VT) at zero end-expiratory pressure (ZEEP) mechanical ventilation group. § P < 0.001 and § P < 0.005 between low VT mechanical ventilation groups.
PEEP = positive end-expiratory pressure; VE = minute ventilation; TI = inspiratory time; TIE = expiratory time; Pawmean = mean airway pressure; Pawmax = maximum airway pressure; PETCO₂ = end-tidal partial pressure of carbon dioxide.
significant F ratio was obtained, differences between the means were isolated with the post hoc Tukey multiple comparison test. Because cytokine data were not normally distributed, a two-way analysis of variance was performed after log10 transformation to permit the application of a parametric test. Differences were considered to be statistically significant at $P$ values less than 0.05.

**Results**

There were no statistically significant differences in the demographic or clinical data between patients of the studied groups (table 1).

Ventilatory variables are shown in table 2. During mechanical ventilation with low $V_T$, a higher ventilator rate ($P < 0.001$) and a higher minute ventilation ($P < 0.001$) were required to achieve the desired end-tidal carbon dioxide partial pressure range, compared with high $V_T$ mechanical ventilation. Increase in ventilatory rate was associated with a reduction of inspiratory time and expiratory time ($P < 0.05$), whereas the inspiratory time/expiratory time ratio remained unchanged. Peak airway pressure was lowest during mechanical ventilation with low $V_T$ at ZEEP. In the presence of PEEP, mechanical ventilation with low $V_T$ resulted in the highest mean airway pressure. End-tidal carbon dioxide partial pressure was lowest during mechanical ventilation with high $V_T$ at ZEEP.

Cytokine plasma levels are shown in figures 1–3. The response of the cytokine levels to starting mechanical ventilation was neither significantly different between the three ventilatory strategies nor statistically different after 1 h of ventilation in each individual group. Plasma levels of IL-10 remained below the detection limit (10 pg/ml) in 35 of 39 patients both at baseline and after 1 h of mechanical ventilation.

**Discussion**

This study was designed to evaluate the effects of different ventilatory strategies on the release of inflammatory mediators into the systemic circulation of anesthetized patients who had healthy lungs. We were unable to detect statistically significant differences in cytokine release between potentially injurious and protective ventilatory strategies after 1 h of ventilation.

Mechanical ventilation is usually provided by using...
low PEEP levels with high V_T ranging between 10 and 15 ml/kg ideal body weight. Based on experimental data, mechanical ventilation with high V_T has been claimed to overdistend functional lung units and contribute to direct lung damage. Mechanical stress such as shear stress has been found to induce production of inflammatory cytokines in isolated endothelial, epithelial, and macrophage cells. Experimental and clinical studies have investigated the production of inflammatory mediators in injured lungs induced by various ventilatory strategies. Based on these findings, inflammatory cytokines have been implicated as contributors to ventilator-associated lung injury. A recent multicenter trial of 861 patients demonstrated a reduction in mortality by 22% and lower systemic cytokine levels when V_T was reduced from 12 to 6 ml/kg ideal body weight.

We studied the effect of different ventilatory strategies on systemic cytokine levels during anesthesia before elective surgery. Although our patients had an essentially normal pulmonary function, previous computed tomography studies have clearly demonstrated alveolar collapse and atelectasis soon after induction of anesthesia and mechanical ventilation in previously healthy patients, which can be prevented with a PEEP of 10 cm H_2O. Thus, the lung-protective ventilatory settings in this study should have prevented tidal alveolar collapse and overdistension, whereas the potentially injurious ventilatory strategy should have not. The latter has been suggested to result in shear forces with transmural pressures of up to 100 cm H_2O applied to lung cells.

In our patients, we did not observe consistent differences in proinflammatory and antiinflammatory cytokine plasma levels depending on different ventilatory strategies, and all levels were still within the variability observed in healthy volunteers. Therefore, our findings appear to be in contrast with previous experimental and clinical observations, indicating a marked systemic inflammatory response in the presence of an injurious ventilatory strategy using low PEEP and high V_T. Variation in the systemic cytokine concentrations observed during injurious mechanical ventilation may be attributed to the difference in the design and the experimental conditions of the individual studies. Tremblay et al. found pronounced production of cytokines induced by injurious mechanical ventilation in animals pretreated with intravenous lipopolysaccharides, whereas pressure stretching of cultivated alveolar macrophages in absence of lipopolysaccharides as an inflammatory costimulus could not induce TNF and IL-6 expression. These findings support our observation that mechanical ventilation seems to induce no inflammation in normal lungs, but may well augment lung inflammation to clinically important levels in preinjured or infected lungs. In agreement with our findings, in rats without lung injury, mechanical ventilation with V_T set at 10 ml/kg did not affect bronchoalveolar lavage fluid content of IL-1α, IL-1β, IL-6, macrophage inflammatory protein-2, and TNF when compared with spontaneous breathing, whereas in a rat model with hydrochloric acid instillation–induced lung injury, mechanical ventilation with V_T of 16 ml and ZEEP resulted in a marked increase in TNF and macrophage inflammatory protein when compared with V_T of 9 ml and PEEP of 5 cm H_2O.

Unfortunately, we cannot draw conclusions on lung tissue cytokine concentrations on the basis of plasma cytokine levels. Previous studies suggest that an increase in alveolar–capillary permeability is required for translocation of mediators, including cytokines, from the lungs into the circulation. Because inflammatory mediators cause an increase in vascular and alveolar permeability, a relevant accumulation of cytokines in the lungs should have resulted in an increased release of cytokines into the blood and alveolar fluid.

It is also important to note that we tested each ventilatory strategy only for 1 h. Experimental data have demonstrated that intraalveolar expression of TNF gene and increased TNF levels in the systemic circulation can be found after 1 h of injurious mechanical ventilation in lung injury models. Preliminary clinical data in patients with injured lungs indicate that maximal

Fig. 3. Plasma levels of interleukin (IL)-1 receptor antagonist before and after 1 h of mechanical ventilation with high-tidal-volume (V_T) or two different low-tidal-volume mechanical ventilation settings. ZEEP = zero end-expiratory pressure; PEEP = positive end-expiratory pressure.
increase in alveolar and systemic cytokine concentrations occurs within 1 h after initiating mechanical ventilation with low PEEP and high $V_{T}$. Therefore, the lack of an increase in plasma cytokines during injurious mechanical ventilation in our patients should not be attributed to a time-related component on the cytokine release. However, we did not study long-term effects of mechanical ventilation on cytokine production in healthy lungs or the effects of mechanical ventilation combined with a surgical intervention, which itself may cause an inflammatory response or even bacteremia.

General anesthesia itself has been suggested to modulate the inflammatory response during mechanical ventilation. Recent experimental data suggest that inflammatory response to mechanical ventilation may be aggravated by inhalation of volatile anesthetics after 2 h. Studies comparing the immune response to standardized elective surgery in patients during propofol versus isoflurane anesthesia have revealed no differences or a minimally diminished systemic inflammatory response with propofol and alfentanil when compared with isoflurane and nitrous oxide anesthesia. Anesthesia in all of our patients was provided with isoflurane and fentanyl. Therefore, it is unlikely that anesthesia has a major influence on our results after a study period of only 1 h.

Our data suggest that in essentially normal lungs of anesthetized patients, short-term mechanical ventilation with high $V_{T}$ in the presence or absence of PEEP induces no clinical relevant increase in systemic proinflammatory and anti-inflammatory cytokines. This observation is indirect evidence that mechanical ventilation seems to induce no inflammation in normal lungs, but may well augment lung inflammation to clinically important levels in preinjured or infected lungs as previously shown.

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References


