

# Prone Positioning

## Beyond Physiology

IN the current issue of ANESTHESIOLOGY, Petersson *et al.* provides us with a physiologic study describing, in anesthetized human volunteers, the effects of prone positioning and the application of 10 cm H<sub>2</sub>O positive end-expiratory pressure (PEEP) on the regional distribution of pulmonary ventilation and perfusion.<sup>1</sup> This article creates a complete formulation of the pulmonary ventilation and perfusion in the prone position.

In the supine position, at 0 cm H<sub>2</sub>O PEEP, the size of the alveolar units decreases exponentially from ventral (nondependent) to dorsal (dependent) lung regions.<sup>2</sup> This indicates that the distending forces of the lung (*i.e.*, the difference between the alveolar and the pleural pressure) decreases along the ventral-to-dorsal axis. The increase of pleural pressure close to the dependent lung regions is commonly considered the result of the push of the abdominal organs towards the lungs, which increases from the ventral to the dorsal regions.

In spontaneously breathing subjects, the engine of ventilation is the diaphragm, which displaces a huge amount in its dorsal (dependent) portion. This action is associated with a more favorable position of the dependent alveolar units along their pressure-volume curves<sup>3</sup> and accounts for the greater ventilation observed in the most dependent lung regions. During anesthesia and paralysis, however, the diaphragm acts as a passive flaccid membrane. The insufflated gas is then preferentially distributed towards the ventral and nondependent lung areas.<sup>4</sup> Because the regional distribution of lung perfusion is greater in the dependent lung regions, the final result is that mechanical ventilation, at 0 cm H<sub>2</sub>O PEEP, is associated with some degree of ventilation-to-perfusion ( $V_A/Q$ ) mismatch. This result is consistent with both the gravitational (West *et al.*<sup>5</sup>) or fractal distribution (Glenny *et al.*<sup>6</sup>) theories of lung ventilation/perfusion. The addition of PEEP partially corrects this mismatch because it progressively moves ventilation towards the dependent lung regions (as previously shown by computed tomography scanning<sup>7</sup> and in the current study<sup>1</sup>), whereas perfusion is further increased in the dependent lung regions.

In the prone position, at 0 cm H<sub>2</sub>O PEEP, the size of

alveolar units decreases with an exponential decay from dorsal (now nondependent) to ventral (now dependent) lung regions. This occurs to a much lower extent than that observed in the supine position. As a result, alveolar ventilation is more homogeneously distributed in the prone than in the supine position.<sup>2</sup> Because lung perfusion redistributes towards the dependent regions, this results in a more homogeneous  $V_A/Q$  matching at 0 cm H<sub>2</sub>O PEEP, such as shown by Petersson *et al.*<sup>1</sup> and others.<sup>8,9</sup> Surprisingly, after the addition of PEEP, Petersson *et al.* found that perfusion increased in the ventral lung regions (now dependent), whereas the distribution of alveolar ventilation remained unchanged. Consequently, the authors claimed that  $V_A/Q$  matching was decreased by the addition of PEEP in the prone position and suggested that lower PEEP levels might be preferred in the prone position compared with the levels of PEEP used in the supine position.

This conclusion may be incorrect when a patient has underlying acute lung injury. Because patients with acute lung injury often have severe hypoxemia resistant to typical therapies, Bryan<sup>10</sup> suggested that prone positioning might lead to improved oxygenation. His prediction was fully confirmed in most of the studies subsequently published, which undoubtedly showed that in approximately 70% of patients with acute respiratory distress syndrome (ARDS), prone position—always applied in association with some degree of PEEP—improves oxygenation. Therefore, there is clearly a difference between normal lungs; for example, a deterioration of  $V_A/Q$  was observed by the current authors after 10 cm H<sub>2</sub>O PEEP was added to the patients in the prone position.<sup>1</sup>

The explanation for the improvement of  $V_A/Q$  in patients with ARDS in the prone position involves understanding the distribution of edema in the diseased lungs. In patients with ARDS, the mass of the lung with the edema may be increased to 300% of that of normal lungs.<sup>11</sup> Therefore, the dependent lung regions in ARDS patients are compressed from the abnormal weight of the lung tissue above (nondependent) in the supine position.<sup>12</sup> When the ARDS patient is prone,

◆ This Editorial View accompanies the following article: Petersson J, Ax M, Frey J, Sánchez-Crespo A, Lindahl SGE, Mure M: Positive end-expiratory pressure redistributes regional blood flow and ventilation differently in supine and prone humans. ANESTHESIOLOGY 2010; 113:1361–9.

Accepted for publication September 10, 2010. The authors are not supported by, nor maintain any financial interest in, any commercial activity that may be associated with the topic of this article.

the mass of the dorsal lung, which reinflates (*i.e.*, dorsal becomes the nondependent lung regions), is greater than the potential mass of the ventral (now dependent) lung regions, which may collapse.<sup>13</sup> When lung perfusion is substantially unmodified, the overall  $V_A/Q$  matching improves as new pulmonary units are recruited for more effective gas exchange.

This is probably the primary mechanism for the improvement in oxygenation in the prone ARDS patient, although other mechanisms (including a different shape of the diaphragm, changes of hypoxic pulmonary vasoconstriction, and a differential production of nitric oxide in different lung regions) may play a role. Sadly, there can be negative consequences to prone positioning, including a possible increase in chest wall stiffness.<sup>2</sup> The reduced chest wall compliance leads, in the case of pressure-controlled ventilation, to an initial reduction in transpulmonary pressure (*i.e.*, decreased tidal volume) or, in the case of volume-controlled ventilation, to an increase in plateau airway pressure. The overall balance of the positive and negative effects of the prone position can be observed by looking at the variation in arterial carbon dioxide. Independent of oxygenation changes, a decrease in arterial carbon dioxide indicates a recruitment of lung parenchyma, whereas an increase in arterial carbon dioxide may indicate a large increase in chest wall stiffness.

We believe that the most recent clinical trial of prone ARDS patients may provide some insights about the relationship between PEEP and the prone position.<sup>14</sup> In that study, the patients that had been randomized to the prone arm were allowed to undergo a variation in the ventilator settings aimed towards a less dangerous ventilation, if the oxygenation improved. Two maneuvers were allowed: first, a reduction of inspired oxygen fraction, and second, a reduction of PEEP, with a target arterial partial pressure of oxygen between 70–90 mmHg. The results clearly showed an identical level of PEEP between the two arms, suggesting that a decrease in PEEP was not possible in the prone ARDS patients.

These data from prone ARDS patients, contrast with the findings observed by Petersson *et al.* in normal patients.<sup>1</sup> The comparison of the results suggest that in ARDS patients, reductions of PEEP are inappropriate, at least when  $V_A/Q$  matching and systemic oxygenation are being evaluated.

Finally, although the article by Petersson *et al.*, as well as our comments, have focused on gas exchange, there may be an effect from prone positioning in ARDS patients on their survival. The survival benefit of prone positioning during ARDS is probably a result of a decrease in the harmful effects of mechanical ventilation. The prone position leads to more homogeneous lung inflation and more homogeneous alveolar ventilation, suggesting that the strain applied to the lung parenchyma and its associated stress are more homogeneously distributed than in the supine position.<sup>15</sup> This should decrease ventilator-induced lung injury. As a matter

of fact, all the meta-analyses performed on prone positioning of ARDS patients, so far, agree with two major points: (1) In all patients, a systemic oxygenation improvement is observed, and this is obviously greater in the most hypoxemic patients; and (2) in the most severe ARDS patients, when lung dishomogeneity is the greatest, prone positioning appears to provide about a 10% survival benefit.<sup>16,17</sup>

#### Luciano Gattinoni, M.D., F.R.C.P., Pietro Caironi, M.D.

Dipartimento di Anestesiologia, Terapia Intensiva e Scienze Dermatologiche, Fondazione IRCCS–Ospedale Maggiore Policlinico, Mangiagalli, Regina Elena di Milano, Università degli Studi di Milano, Milan, Italy, and Dipartimento di Anestesia, Rianimazione e Terapia del Dolore, Fondazione IRCCS–Ospedale Maggiore Policlinico, Mangiagalli, Regina Elena di Milano, Milan, Italy. gattinon@policlinico.mi.it

## References

- Petersson J, Ax M, Frey J, Sánchez-Crespo A, Lindahl SGE, Mure M: Positive end-expiratory pressure redistributes regional blood flow and ventilation differently in supine and prone humans. *ANESTHESIOLOGY* 2010; 113:1361–9
- Gattinoni L, Pelosi P, Valenza F, Mascheroni D: Patient positioning in acute respiratory failure, Principles and practice of mechanical ventilation. Edited by Tobin M. New York, McGraw Hill, 2004, pp 1067–76
- Otis AB, McKerrow CB, Bartlett RA, Mead J, McIlroy MB, Selver-Stone NJ, Radford EP Jr: Mechanical factors in distribution of pulmonary ventilation. *J Appl Physiol* 1956; 8:427–43
- Froese AB, Bryan AC: Effects of anesthesia and paralysis on diaphragmatic mechanics in man. *ANESTHESIOLOGY* 1974; 41:242–55
- West JB, Dollery CT, Naimark A: Distribution of blood flow in isolated lung; relation to vascular and alveolar pressures. *J Appl Physiol* 1964; 19:713–24
- Glenny RW, Robertson HT: A computer simulation of pulmonary perfusion in three dimensions. *J Appl Physiol* 1995; 79:357–69
- Gattinoni L, Pelosi P, Crotti S, Valenza F: Effects of positive end-expiratory pressure on regional distribution of tidal volume and recruitment in adult respiratory distress syndrome. *Am J Respir Crit Care Med* 1995; 151:1807–14
- Mure M, Domino KB, Lindahl SG, Hlastala MP, Altmeier WA, Glenny RW: Regional ventilation-perfusion distribution is more uniform in the prone position. *J Appl Physiol* 2000; 88:1076–83
- Richter T, Bellani G, Scott Harris R, Vidal Melo MF, Winkler T, Venegas JG, Musch G: Effect of prone position on regional shunt, aeration, and perfusion in experimental acute lung injury. *Am J Respir Crit Care Med* 2005; 172:480–7
- Bryan AC: Conference on the scientific basis of respiratory therapy. Pulmonary physiotherapy in the pediatric age group. Comments of a devil's advocate. *Am Rev Respir Dis* 1974; 110:143–4
- Gattinoni L, Caironi P, Cressoni M, Chiumello D, Ranieri VM, Quintel M, Russo S, Patroniti N, Cornejo R, Bugedo G: Lung recruitment in patients with the acute respiratory distress syndrome. *N Engl J Med* 2006; 354:1775–86
- Pelosi P, D'Andrea L, Vitale G, Pesenti A, Gattinoni L: Vertical gradient of regional lung inflation in adult respiratory distress syndrome. *Am J Respir Crit Care Med* 1994; 149:8–13
- Gattinoni L, Pelosi P, Vitale G, Pesenti A, D'Andrea L, Mascheroni D: Body position changes redistribute lung computed-tomographic density in patients with acute respiratory failure. *ANESTHESIOLOGY* 1991; 74:15–23

14. Taccone P, Pesenti A, Latini R, Polli F, Vagginelli F, Mietto C, Caspani L, Raimondi F, Bordone G, Iapichino G, Mancebo J, Guérin C, Ayzac L, Blanch L, Fumagalli R, Tognoni G, Gattinoni L, Prone-Supine II Study Group: Prone positioning in patients with moderate and severe acute respiratory distress syndrome: A randomized controlled trial. *JAMA* 2009; 302:1977-84
15. Valenza F, Guglielmi M, Maffioletti M, Tedesco C, Maccagni P, Fossali T, Aletti G, Porro GA, Irace M, Carlesso E, Carboni N, Lazzerini M, Gattinoni L: Prone position delays the progression of ventilator-induced lung injury in rats: Does lung strain distribution play a role? *Crit Care Med* 2005; 33:361-7
16. Sud S, Friedrich JO, Taccone P, Polli F, Adhikari NK, Latini R, Pesenti A, Guérin C, Mancebo J, Curley MA, Fernandez R, Chan MC, Beuret P, Voggenreiter G, Sud M, Tognoni G, Gattinoni L: Prone ventilation reduces mortality in patients with acute respiratory failure and severe hypoxemia: Systematic review and meta-analysis. *Intensive Care Med* 2010; 36:585-99
17. Gattinoni L, Carlesso E, Taccone P, Polli F, Guérin C, Mancebo J: Prone positioning improves survival in severe ARDS: A pathophysiologic review and individual patient meta-analysis. *Minerva Anesthesiol* 2010; 76:448-54