

# The Open Lung Concept of Alveolar Recruitment Can Improve Outcome in Respiratory Failure and ARDS

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## Abstract

Respiratory failure is a common finding in the ICU and in the management of complex cases in the operating room. Over the last ten years, it has become clear that modes of mechanical ventilation and lung recruitment may play a role both in cytokine modulation and patient outcome.

Early lung recruitment and alveolar stabilization may play a very important role in the management of patients with respiratory failure and adult respiratory distress syndrome (ARDS). The open lung concept may be the key to decreasing mortality and morbidity in these patients. This technique not only improves oxygenation, but also affects surfactant function and cytokine modulation.

The open lung concept is physiologically based on the Law of Laplace. Adhering to the principles of the open lung concept, pressure-controlled ventilation may improve patient outcome by reducing the extent of irreversible structural damage to the lungs caused by mechanical ventilation.

**Key Words:** ARDS, alveolar recruitment, open lung concept, respiratory failure.

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## Introduction

MECHANICAL VENTILATION is the therapeutic technique most widely used in anesthesiology and critical care medicine for patients in intensive care units (ICU) and those undergoing routine surgery. However, over the last few years, it has become clear that mechanical ventilation with improper settings can lead to a variety of physiological effects which may affect patient outcome, including hypoxemia (1), surfactant depletion (2), cytokine release (3, 4), bacterial transmigration (5, 6), atelectasis (1, 7), and barotrauma.

The mortality rate from adult respiratory distress syndrome (ARDS) has not decreased since it was first described by Ashbaugh (8): mortality rates range from 10–90%, with an average of 50% (9). Various treatments of ARDS have not been very beneficial. These therapies include inhaled nitric oxide (10, 11)

as well as administration of antibodies (9). Recruiting and stabilizing collapsed alveoli has also been suggested as a method to prevent and treat ARDS and respiratory failure (12–14). Experimental and clinical studies have clearly shown that techniques using the open lung approach can provide marked improvements in gas exchange. Amato et al. (13) showed improvement in  $Pa_{O_2}$ , a decreased length of stay in the ICU, and decreased mortality rate. Modes of ventilation and an “open lung” recruitment strategy can reduce time spent on mechanical ventilation, with the additional benefit of decreased ICU costs (15).

## Surfactant Changes Due to Mechanical Ventilation

In 1959 Mead (16) reported that dogs that were mechanically ventilated had progressive decreases in pulmonary compliance and that these changes were related to the pulmonary surfactant system. Two primary mechanisms of surfactant failure related to mechanical ventilation have been described. In the first, mechanical ventilation enhances surfactant release from the pneumocyte type II into the alveolus (17). This material is subsequently lost into the small airways as a result of compression of the surfactant film. These changes in alveolar surfactant may affect the permeability of the alve-

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olocapillary barrier to small solutes and protein. The functional integrity of both the endothelium and the epithelium is a prerequisite for maintaining a normal fluid balance at the alveolocapillary membrane; therefore, these changes may cause the increased pulmonary leak observed in respiratory failure with the formation of edema. This breakdown of the barrier function of surfactant may also contribute to the release and modulation of inflammatory mediators (14, 18).

The second mechanism is based on the observation that the alveolar surface area changes are associated with mechanical ventilation, which result in the conversion of surface-active, large-surfactant aggregates into non-surface-active, small-surfactant aggregates (19). Surfactant changes due to mechanical ventilation are reversible as a result of a metabolically active process involving *de novo* production of surfactant. The barrier function of surfactant may collapse with disease and mechanical ventilation, and there may be transmigration of bacteria (3, 20, 21) and cytokine release. Tremblay et al. (3), using isolated lungs, investigated the effect of different ventilation strategies on lung inflammatory mediator expression and production of cytokines tumor necrosis factor (TNF), interleukin-1 (IL-1), interleukin-6 (IL-6), interleukin-10 (IL-10), platelet activating factor (PAF), and interferon-gamma in the presence and absence of a preexisting inflammatory stimulus. The use of high-peak inspiratory lung volumes and the avoidance of positive end-expiratory pressure (PEEP) during mechanical ventilation have a synergetic effort on the release of pro-inflammatory mediators from the lung tissue into the airways. Using 10 cm H<sub>2</sub>O of PEEP at comparable peak inspiratory lung volumes or lowering peak inspiratory lung volume when ventilating with zero PEEP reduced these cytokine levels. Therefore, the lung is now being regarded as an important causative part of an inflammation-induced systemic disease state that can evolve to multi-organ failure (MOF) rather than merely a pulmonary disease process. Alveolar collapse with improper mechanical ventilation has been implicated as one of the major causes of poor outcome in mechanically ventilated patients.

### **Modes of Ventilation that Will Prevent Ventilation-Induced Lung Injury**

Since its introduction in critical care medicine more than forty years ago, artificial me-

chanical ventilation has become a standard life-saving therapy. It is, however, a topic of much discussion and controversy because artificial ventilation involves a disturbance of normal physiologic function of the lung.

### **Pressure-Controlled Ventilation**

Pressure-controlled ventilation has been a mainstay in the treatment of severe lung disease since it was first described in the neonate by Colgan (22) in 1960. The keystone to proper mechanical ventilation is a pressure-controlled platform, which can be introduced into the operating room and the ICU. Basic physiological principles serve as a rationale for the use of pressure-controlled ventilation (14, 23–25). Since it is well established that artificial ventilation can both cause direct lung damage and modulate cytokine release, it is imperative that we protect the lung from ventilator-induced injury. The cycle of continuous expansion and collapse of alveoli during the respiratory cycle creates a biologic stress. This opening and closing affects structural changes via barotrauma and volutrauma, as well as surfactant function and cytokine release.

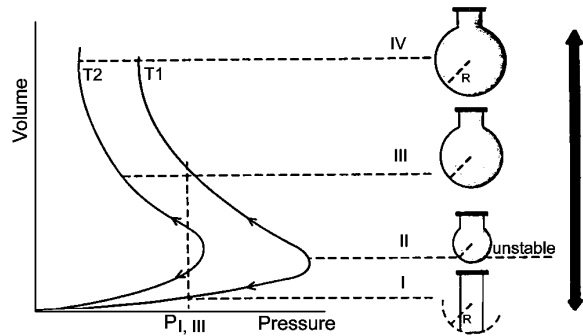
If we evaluate mechanical ventilation in light of the basic Law of Laplace, we see that utilizing modes of ventilation which can control both expiratory and inspiratory pressure may be the optimal way to ventilate the lung. The Law of Laplace links the pressure applied by the ventilator to the alveolar pressure (P), which relates surface tension (T) and radius (R):

$$P = 2T/R$$

In a healthy lung, alveolar surfactant minimizes the surface forces at the air-liquid interface, thus guaranteeing alveolar stability at all alveolar sizes. But in mechanically ventilated lungs, there may be varied levels of dysfunction of the surfactant system, because of either direct ventilator effects or the indirect effect of the systemic inflammatory response. The degree of this surfactant damage will determine the amount of pressure needed to expand alveoli from closed to open (Figure).

Pressure-controlled ventilation allows the practitioner to control ventilatory pressure throughout the cycle, in order to generate the pressure necessary to expand alveoli. In true alveolar collapse, the pressure needed for alveolar recruitment may theoretically reach values of 60–70 cm H<sub>2</sub>O (26).

Alveolar beds may be opened using a classic wave pattern of pressure control, the decel-



**Figure.** The open lung concept. Open lung units are more efficient and function at a lower pressure when alveolar radii are larger. The opening pressure is higher when surface tension is elevated (e.g., curve T1 with less effective surfactant). The pressure needed to keep the alveoli open is less when the lung volume indicated by functional residual capacity at IV is compared to that at III and is unstable at I and II. The vertical dotted line labeled  $P_{I,III}$  illustrates that it is easier for a partially opened alveolus (III) to be recruited than a closed alveolus (I) at the same pressure.  $T$  = surface tension of liquid-air interface;  $R$  = radius of alveolus; Law of Laplace:  $P = 2T/R$ .

erating wave pattern. This pattern is generated by pressure differences between the inspiratory pressure delivered by the ventilator and the pressure present inside the lung at the beginning of the inspiratory cycle, resulting in minimization of early flow. As the intrathoracic pressure increases, the difference between the ventilator and the intrathoracic pressures diminishes as does the resulting inspiratory flow. This decelerating flow pattern is in contrast to the constant flow pattern used during volume-controlled ventilation. This decelerating pattern opens alveoli better than does a constant flow pattern. The resistance of the airways influences the absolute rate of the respiratory flow; therefore, if the resistance is high, the flow will be reduced, and if the resistance is low, the flow will increase.

An important concept of pressure-controlled ventilation is fresh gas distribution in the lung. When new alveoli are recruited during an inspiratory cycle, the volume necessary to fill these alveoli comes from the ventilator, which is the source of the higher pressure, not from the adjacent lung units, because there is always equal pressure in all areas of the lung. Any reduction in alveolar size immediately results in a flow of fresh gas from the source of highest pressure, which is always the ventilator in the alveolar unit. Decelerating wave pattern ventilation also leads to better pulmonary gas exchange through better gas distribution (23,

26, 27). In contrast to volume control, pressure-controlled ventilation generates no intrapulmonary redistribution of gas from other hyperdistended lung units, the so-called "Pendelluft Effect." Pressure-controlled modes thus always generate an efficient system in which only fresh gas is entering the recruited alveoli (26, 28).

### The Open Lung Concept

Gattinoni et al. showed that patients with early ARDS have multiple areas of atelectasis, most commonly in the dependent lung regions, and that this resulted in a reduced volume of the aerated lung (29). Even with the new guidelines of smaller tidal volumes (5–7 mL/kg for body weight), we can see that these will generate both barotrauma and biotrauma (cytokine release) in a non-open lung (30, 31). The importance of early lung recruitment and stabilization cannot be stressed enough, for this will affect all aspects of ventilatory physiology; therefore, we must use an "open lung" approach in all mechanically ventilated patients.

The "open lung" concept was first coined by Lachmann (12) and has since been discussed many times. The open lung is one in which there is little or no atelectasis and an optimal gas exchange. Intrapulmonary shunt ideally should be less than 10%, corresponding to a  $Pa_{O_2}$  of more than 450 mm Hg, when breathing 100% oxygen at sea level (32).

This concept has led in the last few years to an "open lung" procedure, in which the lung is opened and kept open to minimize cyclic forces of alveolar opening and closing. The goal of this technique is to minimize cyclic alveolar collapse and reopening. Pressure-controlled ventilation is used with a peak pressure of 40–60 cm  $H_2O$  and a ratio of the duration of inspiration to that of expiration of 1:1 to 2:1 (Table — I:E ratio). Recruitment success should be checked with a graphic analysis of the pressure volume curve or with blood gas analysis. The peak inspiratory pressure (PIP) is adjusted to the lowest pressure which keeps the lung open. This lowest pressure is realized when the tidal volume remains stable and the arterial blood gases are constant. The ideal pressure is generally 15–30 cm  $H_2O$  lower than the required recruitment pressure. The positive end-expiratory pressure (PEEP) is set at 10–20 cm of  $H_2O$  for PEEP to avoid alveolar collapse. This has been used in critical care medicine and in the operating room with great success (13, 33).

**TABLE**  
*Open Lung Concept*

The goal of the open lung concept procedure is to recruit alveoli and maintain them "open" with the least changes in pressure to minimize alveolar shear forces.

**Open Lung Procedure**

Place on Pressure Control  
Raise peak inspiratory pressure to 40 – 60 cm H<sub>2</sub>O  
10 breaths minimal  
Range 10 – 30 breaths

*I:E Ratio 1:1 or 2:1  
PEEP to 10–20 cm H<sub>2</sub>O*

Adjust peak inspiratory pressure to lowest pressure  
without loss of recruitment

*Keep PEEP in range of  
10 – 20 cm H<sub>2</sub>O*

**Lung Protective Strategy**

Titrate ventilator peak inspiratory pressure and  
mean inspiratory pressure to the smallest  
possible difference

I:E Ratio – durations of inspiration and expiration  
PEEP – positive end-expiratory pressure

Amato et al. (13) demonstrated an improved outcome in critically ill patients who had been placed on pressure-controlled modes if they had their lungs opened as compared to those using conventional modes. This group was the first to show a higher weaning rate based on the mode of ventilation used. Amato et al. were very careful to construct a pressure-volume curve for each patient and used it as the keystone in the management of the patient. Preliminary results of our study, monitored by the Food and Drug Administration (FDA), in which the open lung concept was used with patients soon after admission to the critical care units of the University of Rochester, indicated that the mortality rate was 10% in a group of 22 patients with severe ARDS (Pa<sub>O</sub><sub>2</sub>/FiO<sub>2</sub> ratios of less than 150). We also noted that the incidence of multiple organ dysfunction syndrome (MODS) in this patient population was less than that of historical controls (34). These studies may support the ap-

proach that it is wise to spend extra time at the onset of mechanical ventilation to find physiologically based ventilation settings, as opposed to using standard settings for every patient (35).

The results of studies using open lung may be due to decreased barotrauma and biotrauma (cytokine) modulation. The open lung concept suggests that barotrauma and biotrauma are more dependent on swings in airway pressures that are generated when alveoli open and close, rather than on the absolute peak inspiratory pressure (37). This ability of alveoli to remain open modulates the surfactant system and does not allow for ongoing collapse due to loss of surfactant as the result of cyclic changes with inspiration and expiration (14). Finally, the most important contribution may be that an open lung may be less likely to produce biotrauma to itself and other organ systems, thus decreasing cytokine load and the systemic inflammatory response.

**Summary**

The use of the open lung concept may favorably alter a variety of physiologic responses to improve patient outcome in the operating room and in the ICU. The core of this strategy is the understanding that alveolar atelectasis is detrimental and can promote a systemic inflammatory response. Maintaining alveolar beds and keeping them open during mechanical ventilation is an important therapeutic goal.

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