Mechanical ventilation is one of the most commonly used technologies in critical care. Despite the prevalence of ventilators, care planning is heavily influenced by anecdote and clinical preference. A vast array of ventilator modes and mode options exist, and claims of what works and what does not abound. Critical care nurses’ knowledge and understanding of mechanical ventilation are central to ensuring patients’ safe passage from the acute stage of ventilation to weaning. Of key importance is the use of evidence that may improve patients’ outcomes. To that end, in this article, I discuss the science related to mechanical ventilation in patients with acute respiratory distress syndrome (ARDS) and in patients who require weaning.

The Acute Stage of Ventilation: Supplying Ventilation to the Lungs in Patients With ARDS

The acute stage of ventilation is described as that stage at which the patients require a high level of ventilatory support and their hemodynamic status is often unstable. A variety of volume and pressure modes of ventilation are used in an effort to...
improve oxygenation, ventilation, and acid-base status. The results of recent research in patients with ARDS are dramatically affecting how we use mechanical ventilation in such patients and how clinical end points of mechanical ventilation are selected. The concept of “lung-protective strategies,” which include low-tidal-volume ventilation, positive end-expiratory pressure (PEEP), and prone positioning of patients, has emerged along with a renewed interest in the potential efficacy of high-frequency oscillation. A discussion focused on the evidence related to the use of such therapies follows.

**Are Volume or Pressure Modes Better for Patients With ARDS?**

Investigators have shown that animals with induced ARDS, treated with mechanical ventilation with “traditional” (ie, large) ventilator volumes experience more lung injury than do similar animals treated with mechanical ventilation with lower ventilator volumes. In these animals, plateau pressures of 35 cm H₂O or greater for 72 hours resulted in alveolar fractures and increased alveolar flooding. The term volutrauma was coined to describe injuries due to the large traditional volumes, although questions remained about whether the tidal volumes or the resultant distending (plateau) pressures were actually responsible for the lung injury. Because the potential for volutrauma in humans was recognized, recommendations for the use of smaller tidal volumes began to emerge. In a study by Hickling et al, a total of 53 patients with ARDS were treated with mechanical ventilation at low volumes (7 mL/kg) in an attempt to maintain peak airway pressures less than 30 cm H₂O. Hospital mortality for the patients was significantly lower than the mean mortality predicted on the basis of on Acute Physiology and Chronic Health Evaluation II scores. After this study, the ARDS Network reported on the results of a randomized controlled trial designed to compare clinical outcomes of patients with ARDS who were assigned to low-volume (6 mL/kg) versus traditional-volume (12 mL/kg) ventilation. The study was stopped after a preliminary analysis of 861 patients indicated that mortality in the low-tidal-volume group was significantly lower than that in the control group (31.0% vs 39.8%, P = .007). Of interest, the plateau pressures when the tidal volume of 6 mL/kg was used were in the range of 26 to 30 cm H₂O. This pressure was far lower than the plateau pressure (<35 cm H₂O) that had been suggested as potentially lung protective in the animal studies.

But, the ARDS Network’s study has been criticized. For example, some have noted that volumes between 6 and 12 mL/kg (ie, 7, 8, 9, 10, and 11 mL/kg) were not tested, yet those volumes may be more reflective of common practice patterns. Others contended that the “control” group assignment of 12 mL/kg was excessively high and that the principle of scientific equipoise (ie, that genuine uncertainty exists about what treatment is best) may have been violated. Rubenfeld et al and Weinert et al subsequently examined practice patterns in the selection of tidal volume at academic institutions where clinicians were aware of the results of the ARDS Network’s study. Their results indicated that commonly selected tidal volumes were not in the range of 6 mL/kg but were rather in a higher range, findings that somewhat dispelled the validity of the concerns.

Regardless, questions persist about the effect of tidal volumes from 7 to 11 mL/kg and about the use of pressure modes to control plateau pressures in patients with ARDS. Because pressure modes of ventilation have characteristics that make them attractive for use in patients with noncompliant lungs, many wonder if pressure-targeted ventilation might be a comparable substitute for volume-targeted ventilation in patients with ARDS. Some of the characteristics of pressure-targeted ventilation are discussed next.

The decelerating flow pattern associated with pressure modes is thought to provide better gas distribution than volume ventilation does. In addition, plateau pressure can be reliably limited by using pressure modes. Although some might assume that using pressure ventilation in patients with stiff lungs (in order to ensure a low plateau pressure) might result in outcomes similar to those found in the ARDS Network’s trial, much remains to be determined. For example, volumes delivered with pressure ventilation are affected by compliance (lung and chest wall) and resistance. Using a plateau pressure to ensure lung protection may not ensure volumes comparable to the tidal volume of 6 mL/kg used in the ARDS Network’s study.

The superiority of selected “new” pressure modes, such as pressure-release ventilation, for use in ARDS also has not been established. Randomized controlled trials comparing the modes with low-volume targeted.
ventilation will be necessary before the new pressure modes can be widely endorsed.

To date, the study by the ARDS Network,\textsuperscript{16} in which tidal volumes of 6 mL/kg were used, is the only study that has demonstrated a change in mortality. Until the effects of other modes of mechanical ventilation on the outcomes of patients with ARDS are clarified, the use of low-volume targeted ventilation rather than pressure-targeted ventilation is the suggested ventilatory strategy for protecting the lungs of these patients.

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**What About PEEP Levels?**

In a randomized controlled trial of patients with ARDS, Amato et al\textsuperscript{24} studied outcomes associated with different levels of PEEP. The optimal level was determined by measuring lung compliance at increasing levels of PEEP. A level just above the lower inflection point (that level that resulted in an increase in compliance with a given level of PEEP) was selected as the lung recruitment PEEP for the intervention group. Findings of the study suggested that levels of PEEP of about 14 to 16 cm H$_2$O (ie, higher than levels generally selected) were necessary to prevent derecruitment (lung closure).

Unfortunately, measurement of the inflection point at the bedside is technically difficult, and this method is unlikely to be widely used in clinical practice. Although the results of Amato et al\textsuperscript{24} suggest that PEEP levels of 14 to 16 cm H$_2$O are required to open the lung in patients with ARDS, definitive methods for determining the appropriate level of required PEEP are unknown.

In the ARDS Network study,\textsuperscript{16} an algorithmic approach was used to assign levels of PEEP. Unfortunately, auto-PEEP (occult PEEP due to inadequate expiratory time) also occurred in many of the patients (eg, those with high respiratory rates and high minute volumes), making accurate assessment of the total level of PEEP difficult. Some have suggested that the auto-PEEP may have recruited the lung, perhaps contributing to the beneficial outcomes described by the investigators.\textsuperscript{25}

How best to apply PEEP to recruit the lung and prevent derecruitment is not yet clear. Regardless, an understanding of these concepts is helpful for focusing clinical interventions.

**Recruiting the Lungs and Keeping Them Open (Preventing Derecruitment)**

In patients with ARDS, noncompliant lungs tend to collapse, and once collapsed, high inflation pressures are necessary to reopen the lungs. Knowledge of how the lungs in patients with ARDS inflate during mechanical ventilation is essential to our understanding of recruitment.

Computed tomography scans of patients with ARDS have improved our understanding of the alveolar filling patterns associated with ARDS.\textsuperscript{26,27} Once thought to be homogeneous, the pattern of alveolar filling in ARDS is actually heterogeneous. Some areas of the lung are open and others are closed. In the areas of aerated lung, the entire brunt of a tidal volume breath is experienced by the compliant (and open) lung tissue. Unfortunately, this small area of the lung (also called “baby lung”) is at increased risk of injury from overdistention and the shear forces of repetitive opening and closing with tidal breathing. The stress on the lungs from the tidal breath may be an important mechanism associated with volutrauma.

The closed lung parenchyma of patients with ARDS cannot be recruited without applying a critical opening pressure (ie, a pressure high enough to open closed alveoli). Further, once opened, the lung tissue is at risk of closing again (derecruitment) if optimal levels of PEEP or other strategies are not applied. Thus the concepts of lung recruitment and derecruitment are integrally related.

The use of PEEP levels from 14 to 16 cm H$_2$O, as described by Amato et al,\textsuperscript{24} is suggested as one way to open the lungs. Another method is to provide periodic episodes of super-high levels of PEEP. Referred to as 40/40 or 60/60 maneuvers (eg, 40 cm H$_2$O of PEEP for 40 seconds), these techniques have been used in a number
of studies, but they are associated with a risk of barotrauma.24,27,29

**Once the Lungs Are Opened, How Are They Kept Open?**

Unfortunately, it is unclear how to select a level of PEEP to stabilize ventilation once a recruitment maneuver is completed.30,32 Although monitoring the effects of the selected settings on oxygenation and ventilation is a generally accepted way of deciding if the settings are preventing derecruitment over time, oxygenation may not be the best indicator. Oxygenation, traditionally used to assess the adequacy of PEEP, is unreliable because the increase in oxygenation may be the result of either recruitment or redistribution of blood flow to aerated areas of the lung (thus decreasing the shunt and improving oxygenation). Identification of a PEEP level that recruits lung and prevents repetitive opening injury associated with tidal breathing is thus an elusive clinical goal.

Investigators have used computed tomography to compare lung recruitment when different ventilatory maneuvers are used.23,26 Although this method is accurate, it is impractical for use in most clinical settings and widespread use of it is unlikely. Theoretically, another way to assess recruitment is to increase the level of PEEP and monitor the difference between the plateau pressure and the PEEP level. If the addition of PEEP results in recruitment of lung, the plateau pressure should not change; however, if PEEP is adding to alveolar overdistention, the plateau pressure will increase.

Although we have learned much about the effectiveness of PEEP in treating ARDS, much remains to be elucidated. To date, definitive methods of applying PEEP to ensure lung protection and to prevent derecruitment have not been clearly identified. Regardless, arbitrary selection of a PEEP level is unlikely to accomplish the goal.

**Other Ways to Recruit the Lungs: What About High-Frequency Oscillation and Prone Positioning of Patients?**

Unlike traditional ventilatory modes, high-frequency oscillation does not require bulk movement of volume in and out of the lungs; rather, a bias flow of gases is provided and an oscillator disperses the gases throughout the lung at very high frequencies in what has been called “augmented dispersion.” The lungs are recruited and a mean airway pressure sufficient to cause a chest vibration (or “wiggle”) is maintained.34 Although some think that this mode of ventilation may recruit the lungs and prevent tidal stress (damage due to tidal volume and repetitive opening of the stiff alveoli), to date only a single randomized controlled trial has been completed. The Multicenter Oscillatory Ventilation for Acute Respiratory Distress Syndrome Trial35 was designed to test the safety and efficacy of a specific ventilator for high-frequency oscillation. The results indicated a positive but nonsignificant trend in 30-day mortality in patients receiving mechanical ventilation with high-frequency oscillation. Unfortunately, the tidal volumes in the control group were not maintained in the “protective” range, a situation that makes it difficult to interpret the results. An additional concern is that patients generally require heavy sedation and often require paralytic agents to ensure compliance with high-frequency oscillation.

Prone positioning is useful in recruiting lung tissue. Studies in animal models and patients with ARDS in the prone position have revealed a number of responsible mechanisms.36-42 Blood flow and gas distribution in the lungs are affected by gravity. When patients are supine, the alveoli in the dependent parts of the lungs (ie, the back) fill with fluid and collapse. When patients are turned to the prone position, the effect of gravity is reversed and lung tissue is recruited.35 In addition, pleural pressures are more uniform in the dorsal than in the ventral position, so lung recruitment is enhanced.34-41 The third mechanism is a mechanical one. With prone positioning, the heart rests against the sternum (rather than against the lungs) and the abdomen moves away from the lungs.38,42-44 As much as a third of the posterior part of the lungs may be recruited when patients are prone.41 Last, the anterior part of the chest, normally the most mobile part of the chest, is slightly restricted when patients are prone. Consequently, when the lungs are ventilated in a patient who is prone, the air is redistributed more evenly throughout the chest, including the dependent regions.45

The effect of prone positioning of patients on outcomes in ARDS is as yet unclear. Although our understanding of how prone positioning improves lung recruitment is fairly good, to date the only randomized controlled trial of prone positioning in patients with ARDS did not show a change in mortality.46 Patients in the study were maintained in a
prone position for at least 6 hours a day for 10 days. The study was done before the results of the ARDS study on ventilation with low lung volumes were published, however, so volumes were not controlled. Of interest, in the sickest cohort of patients in the study, patients with a ratio of PaO2 to fraction of inspired oxygen of less than 88 (a ratio <200 is defined as ARDS), those assigned to the prone position had a better 10-day survival rate than did those who remained supine.

Perhaps the most important fact associated with positioning patients prone is that it is a relatively safe intervention compared with other techniques (albeit a time- and effort-intensive one) that recruits lung and assists with drainage of secretions. Although studies are needed to definitively determine the importance of prone positioning in the management of ARDS, the use of this position may be less risky than use of some of the other recruitment maneuvers described.

What Ventilation, Oxygenation, and Acid–Base Thresholds Should Be Used With Protective Ventilatory Strategies?

Use of low-volume ventilation may result in significant hypercarbia. In the past, ventilator settings were adjusted to attain eucarbia and a normal pH. Because the goal is to protect the lung, such an end point may not be possible. Instead, the goal should be to ensure that volutrauma does not occur. Because low-volume ventilation results in decreased alveolar ventilation, hypercarbia is expected. Called “permissive hypercarbia,” the goal for acid-base status is to maintain a reasonable pH (approximately 7.25).

Bicarbonate infusions may be used if necessary in patients whose pH is lower and thought to be potentially harmful. Although it is generally tolerated well in most patients, permissive hypercarbia is not appropriate for all patients. Examples include patients with elevated intracranial pressures and patients with some cardiac conditions.

The Weaning Stage of Mechanical Ventilation

The weaning stage of mechanical ventilation is described as that time when the patient’s physiological status is stable and progressive liberation from mechanical ventilation is possible. Various mechanical ventilatory modes and methods are used to ensure an expeditious process. Recent research on weaning has elucidated the importance of approaches in which protocols and comprehensive multidisciplinary processes of care delivery are used.

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Mechanical Ventilation in the Weaning Stage: What Works?

To date, no mode of weaning has been shown to be superior to the others, yet how the various methods of weaning are used does seem to make a difference in clinical outcomes. In randomized controlled trials by Brochard et al and Esteban et al, patients who successfully sustained the 2-hour trial were extubated; the reintubation rate was 20%.

The protocol methods to which patients were randomly assigned included pressure-support ventilation, intermittent mandatory ventilation, and spontaneous breathing trials. Although Brochard et al found that pressure-support ventilation resulted in faster weaning and Esteban et al found that spontaneous breathing trials once per day were superior, both groups of investigators used similar protocols for assessing weaning readiness, advancing weaning trials, and defining success (tolerance) or failure (intolerance). The results of those 2 studies stimulated interest in testing the efficacy and safety of weaning protocols.

In studies by Ely et al and Kollef et al, patients were randomly assigned either to a weaning protocol managed by a nurse and respiratory
therapist or to a traditional weaning plan designed by a physician. Compared with weaning according to the physician’s plan, weaning via the protocol resulted in significantly shorter durations of mechanical ventilation in both studies and a significantly shorter stay in the intensive care unit (ICU) in the study by Kollef et al.\(^5\)

The usefulness of protocols in decreasing variation in processes of care is not restricted to weaning trials. The use of sedatives in patients receiving mechanical ventilation has been associated with prolonged duration of mechanical ventilation and prolonged stays in the ICU and hospital.\(^5\) In randomized controlled trials, the algorithmic management of sedation\(^5\) and use of a protocol to wean patients off infusions of sedatives\(^5\) resulted in significantly shorter duration of mechanical ventilation and shorter stays in the ICU and in the hospital.

The use of protocols is linked to improved outcomes. However, the results of a study by Ely et al\(^6\) suggest that protocols must be applied carefully. Ely et al sought to implement a protocol for weaning in surgical units that involved spontaneous breathing trials. The protocol had been previously tested in a study of patients in a medical ICU and coronary care unit.\(^6\) Components of the protocol included a weaning readiness screening, a spontaneous breathing trial, and end points for stopping the trial. Educational sessions were used to update clinicians about the study, and respiratory care practitioners implemented the protocol. The spontaneous breathing trials were implemented only 10% of the time initially, but implementation increased to 30% with additional educational sessions. One of the major reasons for the lack of compliance with the protocol was that the protocol was not managed by any specific person (as it had been during the original study).\(^6\)

Other methods of improving weaning outcomes for patients treated with mechanical ventilation include systematic comprehensive initiatives in which multiple evidence-based interventions are applied together in a single approach.\(^61-68\) The interventions include clinical pathways, methods for evaluating progress, specific elements of care (eg, deep vein prophylaxis, nutrition, mobility) and protocols for weaning trials. Two prospective system initiatives indicate the effectiveness of the more comprehensive approaches.

Smyrnios et al\(^6\) designed a large-scale multidisciplinary approach to care of patients receiving mechanical ventilation in a medical ICU, a surgical ICU, and a coronary care unit. The initiative consisted of using a weaning algorithm and a nurse clinician to ensure compliance with the processes of care. Duration of mechanical ventilation, length of stay in the ICU, and length of stay in the hospital all improved significantly when the care initiative was used. Financial gains also occurred; however, mortality was not affected.

In another study,\(^6\) all adult patients in 5 critical care units (medical ICU, coronary care unit, thoracic-cardiovascular ICU, surgical-trauma ICU, and neurological ICU) who required mechanical ventilation for more than 3 consecutive days were managed and monitored by 4 advanced practice nurses for 1 year. The process consisted of an evidence-based clinical pathway, protocols for weaning trials and sedation management, and a standardized weaning assessment tool (Burns Wean Assessment Program). Results of the intervention were compared with outcomes prospectively collected before implementation of the approach. The findings included significant reductions in duration of mechanical ventilation, lengths of stay in the ICU and hospital, and mortality in the managed group. The beneficial outcomes were attributed to the management and monitoring of the process by the advanced practice nurses and the systematic multidisciplinary evidence-based approach to care of the patients.

**Conclusions and Summary**

To achieve the best outcomes, we must have an in-depth understanding of the evidence related to appropriate use of mechanical ventilation in patients with ARDS and in patients who require weaning. We have learned much from studies conducted in such patients, yet many questions about how best to apply the therapy remain unanswered. Low-volume lung ventilation is associated with decreased mortality as applied in the ARDS Network’s study.\(^16\) Until additional studies of other modes (pressure modes and high-frequency oscillation) indicate comparable outcomes, use of low-volume ventilation in patients with ARDS should be encouraged. Unfortunately, questions still abound related to how we might best recruit the lungs and keep them open (eg, optimal levels of PEEP, prone positioning).

In the area of weaning, evidence indicates that it is not the mode used but rather the method, specifically the use of protocols, that results in improved clinical outcomes. Further,
outcomes are likely to be improved by multidisciplinary system initiatives that provide systematic evidence-based care.

References
45. Albert RK. Editorial: for every thing (turn...turn...turn...). Am J Respir Crit Care Med. 1997;155:393-394.
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Learning objectives:
1. Identify lung-protective strategies in acute respiratory distress syndrome (ARDS)
2. Describe the benefits of low-tidal-volume ventilation in ARDS
3. Discuss evidence-based guidelines of mechanical ventilation in ARDS

1. Which of the following is not a lung-protective strategy in the management of acute respiratory distress syndrome (ARDS)?
   a. Low-tidal-volume ventilation
   b. Positive end-expiratory pressure (PEEP)
   c. Lateral positioning of patients
   d. High-frequency oscillation

2. Which of the following tidal volumes contributed to a lower mortality rate in the ARDS Network’s study?
   a. 4 mL/kg
   b. 6 mL/kg
   c. 8 mL/kg
   d. 10 mL/kg

3. Which of the following PEEP levels may be beneficial in preventing alveolar closure in ARDS?
   a. 10 to 12 cm H2O
   b. 12 to 14 cm H2O
   c. 14 to 16 cm H2O
   d. 16 to 18 cm H2O

4. Which of the following mechanisms of prone positioning is beneficial in recruiting lung in ARDS?
   a. Low pleural pressure
   b. Elevation of the diaphragm
   c. Low tidal volume
   d. Reversed gravity

5. Which of the following Pao2/FiO2 ratios is indicative of ARDS?
   a. Less than 200
   b. Less than 250
   c. Less than 300
   d. Less than 350

6. Which of the following is a goal of low-tidal-volume ventilation?
   a. Increased oxygenation
   b. Eucarbia
   c. Decreased volutrauma
   d. Normal pH

7. Low-tidal-volume ventilation may result in which of the following?
   a. Hypocarbia
   b. Eucarbia
   c. Hyperventilation
   d. Hypercarbia

8. The goal for acid-base status in ARDS is to maintain a pH at which of the following levels?
   a. 7.15
   b. 7.25
   c. 7.35
   d. 7.45

9. Permissive hypercarbia should be avoided in which of the following?
   a. Increased intracranial pressure
   b. Decreased intracranial pressure
   c. Acute lung injury
   d. ARDS

10. Which of the following is not a component of a weaning protocol?
    a. Assessing weaning readiness
    b. Advancing spontaneous weaning trial
    c. Tolerance criteria
    d. Failure criteria

11. The use of a weaning protocol has been associated with which of the following?
    a. Decreased morbidity
    b. Decreased use of paralytics
    c. Decreased use of sedation
    d. Decreased ventilator days

Test answers: Mark only one box for your answer to each question. You may photocopy this form.

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