Chapter 19

Principles of Mechanical Ventilation

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**Key words:** respiratory system mechanics, pressure-targeted breaths, flow-targeted breaths, intrinsic positive end-expiratory pressure, complications of mechanical ventilation

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Mechanical ventilation is the process of using positive pressure devices to either totally or partially provide oxygen and CO₂ transport between the environment and the pulmonary capillary bed. The desired effect of mechanical ventilation is to maintain adequate levels of Po₂ and Paco₂ in arterial blood while unloading the inspiratory muscles. This process should be done in a manner that avoids injury to the lungs and other organ systems.

Over the last 2 decades, a sizeable evidence base has emerged to guide clinicians in providing safe and effective support with conventional strategies. At the same time, an array of clever innovations have been introduced, many of which await more definitive outcome studies before they can be considered standard of care. This chapter reviews the design principles underlying these devices, the physiological consequences of positive pressure ventilation, current thoughts on applying safe and effective support delivery, and some promising emerging technologies.

**DESIGN FEATURES OF POSITIVE PRESSURE MECHANICAL VENTILATION**

Most modern ventilators use piston/bellows systems or controllers of high pressure sources to drive gas flow.¹
Tidal breaths are generated by this gas flow and can be either controlled entirely by the ventilator or interactive with patient efforts. Generally, pneumatic, electronic, or microprocessor systems provide for various breath types to be available. These can be classified by what initiates the breath (trigger variable), what controls gas delivery during the breath (target or limit variable), and what terminates the breath (cycle variable).²

Trigger variables are either patient effort (detected by the ventilator as a pressure or flow change) or a set machine timer. Target or limit variables are generally either a set flow or a set inspiratory pressure. Cycle variables are generally a set volume, a set inspiratory time, or a set flow. High pressure is usually also present as a backup safety cycle variable. Together, these 3 variables can describe the 5 basic breaths available on most modern mechanical ventilators: the volume control (VC) breath, the volume assist (VA) breath, the pressure control (PC) breath, the pressure assist (PA) breath, and the pressure support (PS) breath (Table 1 on page 342). The availability and delivery logic of different breath types define the mode of mechanical ventilatory support (Table 2 on page 343).² The mode controller is an electronic, pneumatic, or microprocessor-based system that is designed to provide the proper combination of breaths according to set algorithms and feedback data.

The simplest mode is assist control ventilation (ACV), which can provide either flow-targeted, volume-cycled breaths (volume assist control) or pressure-targeted, time-cycled breaths (pressure assist control). A simple feedback system is used with ACV that guarantees a clinician-set number of positive pressure breaths. If the patient’s underlying respiratory rate exceeds this guarantee, all breaths are patient-triggered breaths (VA or PA breaths). If the patient’s respiratory rate is below this guarantee, the ventilator will make up the difference with mandatory or controlled breaths (VC or PC breaths).

Another relatively simple mode is synchronized intermittent mandatory ventilation (SIMV), which can provide either flow-targeted, volume-cycled breaths (volume SIMV) or pressure-targeted, time-cycled breaths (pressure SIMV). Like ACV, SIMV guarantees a clinician-set minimal number of positive pressure breaths. Unlike ACV, however, if the patient’s respiratory rate exceeds this guarantee, the ventilator will provide assisted breaths up to the set rate and then allow unassisted (SIMV alone) or flow-cycled, pressure-supported breaths (SIMV + PS) thereafter. If the patient’s respiratory rate is below the set guarantee, the ventilator will again make up the difference with mandatory (controlled) breaths. When pressure-targeted SIMV is applied in an inverse ratio (ie, inspiratory time is longer than expiratory time), it is often termed airway pressure release ventilation (APRV; discussed subsequently).

Pressure support breaths can be provided as a stand-alone mode without any guaranteed breaths (pressure support ventilation). When stand-alone PS (or any other purely patient-triggered mode) is used, many modern systems

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**Table 1.**

The 5 Basic Breaths Available on Most Modern Mechanical Ventilators Classified According to the Trigger, Target/Limit, and Cycle Criteria

<table>
<thead>
<tr>
<th>Breath Type</th>
<th>Trigger</th>
<th>Target/Limit</th>
<th>Cycle</th>
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<tbody>
<tr>
<td>Volume control (VC)</td>
<td>Timer</td>
<td>Flow</td>
<td>Volume</td>
</tr>
<tr>
<td>Volume assist (VA)</td>
<td>Effort</td>
<td>Flow</td>
<td>Volume</td>
</tr>
<tr>
<td>Pressure control (PC)</td>
<td>Timer</td>
<td>Pressure</td>
<td>Time</td>
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<tr>
<td>Pressure assist (PA)</td>
<td>Effort</td>
<td>Pressure</td>
<td>Time</td>
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<tr>
<td>Pressure support (PS)</td>
<td>Effort</td>
<td>Pressure</td>
<td>Flow</td>
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**Table 2.**

Breath Types Available on Common Modes of Mechanical Ventilation

<table>
<thead>
<tr>
<th>Mode</th>
<th>Breath Types*a</th>
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<tr>
<td>Volume assist control</td>
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<tr>
<td>Pressure assist control</td>
<td>X X</td>
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<tr>
<td>Volume SIMV</td>
<td>X X</td>
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<tr>
<td>Pressure SIMV</td>
<td>X X</td>
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<tr>
<td>Pressure support</td>
<td>X</td>
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Abbreviations: PA, pressure assist; PC, pressure control; PS, pressure support; SIMV, synchronized intermittent mandatory ventilation; Sp, spontaneous unassisted; VA, volume assist; VC, volume control.

*a In addition to containing the 5 basic breaths of Figure 1 on page 347, this table also includes spontaneous unassisted and unsupported breaths.

also have so-called apnea ventilation—backup algorithms (usually a simple volume control mode setting) for safety when patient respiratory efforts are suddenly reduced or absent.

In recent years, more sophisticated feedback systems have been developed for these basic modes and are now available on many modern devices. These include pressure-regulated volume control, volume support (VS), and adaptive support ventilation (ASV).

Pressure-regulated volume control and VS are pressure-targeted modes (time cycled and flow cycled, respectively) in which the ventilator automatically adjusts the inspiratory pressure to maintain a target volume. Adaptive support ventilation is also a pressure-targeted mode with an inspiratory pressure feedback algorithm, but the inputs with ASV include a work of breathing calculation (the goal is to minimize applied work) and respiratory timing patterns. Pressure-regulated volume control, VS, and ASV have all been shown in clinical studies to perform as designed, but none have been shown in randomized trials to provide better outcomes than more conventional standard of care approaches.

Two new modes of support have been introduced over the last decade: proportional assist ventilation and neutrally adjusted ventilator assistance. Proportional assist ventilation calculates patient mechanical properties through controlled test breaths. It then monitors patient effort and delivers additional pressure, flow, and volume to offset a clinician-selected percentage of the patient’s work of breathing. Neutrally adjusted ventilator assistance uses an esophageal catheter that has an array of electromyographic electrodes. These are placed at the level of the diaphragm, and the electromyographic signal is used to trigger, adjust delivered flow, and cycle ventilator breaths. In theory, both proportional assist ventilation and neutrally adjusted ventilator assistance should enhance patient–ventilator synchrony, and in small trials these modes have been shown to behave as designed. However, randomized trials have not been conducted that show superior outcomes with these modes compared with conventional standard of care approaches.
PHYSIOLOGIC EFFECTS OF POSITIVE PRESSURE MECHANICAL VENTILATION

Respiratory System Mechanics

Equation of Motion

Lung inflation during mechanical ventilation occurs when pressure and flow are applied at the airway opening. These applied forces interact with respiratory system compliance (both lung and chest wall components), airway resistance, and, to a lesser extent, respiratory system inerstane and lung tissue resistance to effect gas flow. For simplicity, because inerstane and tissue resistance are relatively small, they can be ignored such that the interactions of pressure, flow, and volume with respiratory system mechanics can be expressed by the simplified equation of motion:

\[
\text{Driving Pressure} = (\text{Flow} \times \text{Resistance}) + (\text{Volume} / \text{System Compliance})
\]

In the mechanically ventilated patient, this relationship is expressed as

\[
dP_{\text{cir}} = (V' \times R) + (Vt / \text{CRS}),
\]

where \(dP_{\text{cir}}\) is the change in ventilator circuit pressure above baseline (peak pressure [Ppeak] minus positive end-expiratory pressure [PEEP]); \(V'\) is the flow into the patient's lungs; \(R\) is the resistance of circuit, artificial airway, and natural airways; \(Vt\) is the tidal volume; and CRS is the respiratory system compliance.

By performing an inspiratory hold at end inspiration (ie, no-flow conditions; \(V' = 0\)), the ventilator circuit pressure "plateaus" and is commonly referred to as the plateau pressure (Pplat). The components of Peir required for flow and for respiratory system distension can be separated using this inspiratory hold. Specifically, calculating the difference in ventilator circuit pressure (Pcir) during flow and during no-flow (the "peak to plateau difference") allows for a calculation of inspiratory airway resistance (\(R = \text{Ppeak} - \text{Pplat} / V'\)).

Also, when \(V' = 0\) at end inspiration, Pplat - PEEP reflects the static respiratory system compliance (CRS = Vt / Pplat - PEEP).

Separating chest wall compliance (CCW) and lung compliance (Ct) during a passive machine-controlled, positive pressure breath requires measurement of esophageal pressure (Pes) to approximate pleural pressure. With this measurement, the inspiratory change in Pes (dPes) can be used in the following calculations: CCW = Vt / dPes and Ct = Vt / (Pplat - PEEP - dPes). In clinical practice, because CCW usually is quite high and dPes is thus quite low, Pplat is often taken as an approximation of lung distending pressure alone. However, in situations where CCW is reduced (eg, obesity, anasarca, ascites, and surgical dressings), the stiff chest wall can have significant effect on Pplat and must therefore be considered when these measurements are used to assess lung stretch.

Pressure-Targeted Versus Flow-Targeted Breaths

The 2 basic approaches to delivering positive pressure breaths are flow targeting and pressure targeting. Changes in compliance, resistance, or patient effort will change Peir (but not flow) with a flow-targeted breath. In contrast, similar changes in compliance, resistance, or effort will cause a change of Vt (but not Peir) with the pressure-targeted breath. From a clinical perspective, both breath types can be set to deliver similar Vt and inspiratory times. However, the design features of the flow-targeted (and volume-cycled) breath can be useful in patients who need a guaranteed Vt, whereas the design features of the pressure-targeted (and either time or flow-cycled) breaths can be useful in patients with vigorous spontaneous flow demands. As noted, the feedback features of pressure-regulated volume control, PSV, and ASV conceptually provide a hybrid of these 2 breath types.

Intrinsic PEEP

Intrinsic PEEP is PEEP that develops within the alveoli when either inadequate expiratory time or collapsed airways during expiration (or both) prevent the lung from reaching its normal resting volume. Intrinsic PEEP
depends on 3 factors: minute ventilation, the expiratory time fraction, and the respiratory system expiratory time constant (the product of resistance and compliance). As minute ventilation increases, the expiratory time fraction decreases, and the time constant lengths (i.e., higher R or CRS values), the potential for intrinsic PEEP to develop increases.

The development of intrinsic PEEP will have different effects on pressure-targeted versus flow-targeted ventilation. In flow-targeted ventilation, the constant delivered flow and volume (and thus dP/eP) in the setting of an increasing intrinsic PEEP will increase both the Ppeak and the Pplat. In contrast, in pressure-targeted ventilation, the set P/eP limit coupled with an increasing intrinsic PEEP level will decrease dP/eP and thus the delivered V(t) (and minute ventilation). This can help limit the buildup of intrinsic PEEP in pressure-targeted modes.

In the passive patient, intrinsic PEEP can be assessed in 2 ways. First, when an inadequate expiratory time is producing intrinsic PEEP, analysis of the flow graphic will show that expiratory flow has not returned to zero before the next breath is given. Second, intrinsic PEEP in alveolar units that have patent airways can be quantified during an expiratory hold maneuver that permits equilibration of the intrinsic PEEP with P/eP.

In patients with active respiratory drives, the expiratory hold maneuver is impossible to perform. However, intrinsic PEEP can be assumed to be present again if the expiratory flow has not reached zero before breath initiation occurs. As noted in more detail later, intrinsic PEEP can function as an important inspiratory threshold load on patient effort. This is best quantified by using an esophageal balloon to estimate pleural pressures. With this technique, the effort-related change in Pes before P/eP change is a reflection of the threshold load imposed by intrinsic PEEP.

**Distribution of Ventilation**

A positive pressure tidal breath must distribute among the millions of alveolar units in the lung. Factors affecting this distribution include regional resistances, compliances, functional residual capacities, and the delivered flow pattern (including inspiratory pause). In general, positive pressure breaths will tend to distribute more to units with high compliance and low resistance and away from obstructed or stiff units. This creates the potential for regional overdistribution of healthier lung units, even in the face of V(t) that is considered normal.

**Alveolar Recruitment and Gas Exchange**

Parenchymal lung injury produces ventilation–perfusion (V/Q) mismatching and shunts because of alveolar inflammation, flooding, and collapse. In many of these disease processes, substantial numbers of collapsed alveoli can be recruited during a positive pressure ventilatory cycle. Additional recruitment can be provided sometimes with the use of formal recruitment maneuvers or prolongation of inspiratory time. The application of PEEP is designed to prevent derecruitment during exhalation.

**Inspiratory Time Prolongation**

Inspiration from a positive pressure breath consists of a flow magnitude and a flow profile that can affect ventilation distribution (and thus V/Q). Prolonging inspiratory time, generally by adding a pause and often used in conjunction with a rapid decelerating flow (i.e., pressure-targeted breath), has several physiological effects. First, the longer inflation period may recruit more slowly recruitable alveoli. Second, increased gas mixing time may improve V/Q matching in parenchymal lung injury (pendelluft). Third, the development of intrinsic PEEP from consequently shorter expiratory times can have effects similar to those of applied PEEP. However, the distribution of intrinsic PEEP (most pronounced in lung units with long time constants) can be different from that of applied PEEP, and thus V/Q effects can also be different. Fourth, because these long inspiratory times significantly increase total intrathoracic pressures, cardiac output can be affected (see below). Fifth, inspiratory–expiratory (I:E) ratios that exceed 1:1 (so-called inverse ratio ventilation) are uncomfortable, and patient sedation or paralysis is often required unless a relief mechanism
allows spontaneous breathing during the inflation period (i.e., APRV).

**Positive End-Expiratory Pressure**

Positive end-expiratory pressure is defined as an elevation of transpulmonary pressures at the end of expiration. As noted previously, PEEP can be produced either by expiratory circuit valves (applied PEEP) or as a consequence of ventilator settings interacting with respiratory system mechanics and producing long expiratory time constants (intrinsic PEEP).\(^{48}\) Expiratory muscle contraction can also raise intrathoracic pressures at end expiration, but this should not be considered PEEP because it is not a transpulmonary pressure (i.e., alveolar-pleural pressure).

The ability of PEEP to prevent alveoli from being derecruited provides several potential benefits. First, recruited alveoli improve V/Q matching and gas exchange throughout the ventilatory cycle.\(^{49}\) Second, as discussed in more detail subsequently, patent alveoli throughout the ventilatory cycle are not exposed to the risk of injury from the shear stress of repeated opening and closing.\(^{50,51}\) Third, PEEP prevents surfactant breakdown in collapsing alveoli and thus improves lung compliance.\(^{52}\) This is the rationale behind applying PEEP after a recruitment maneuver: recruited alveoli are on the deflation limb of the pressure-volume relationship and thus the PEEP required to maintain recruitment is lower than that required for initial recruitment.

Positive end-expiratory pressure can be detrimental. Because the tidal breath is delivered on top of the baseline PEEP, end-inspiratory pressures are usually increased by PEEP application (although this increase may be less than the actual increased PEEP level because of PEEP-induced improved compliance). This increase must be considered if the lung is at risk for regional overdistension (discussed later). Moreover, since parenchymal lung injury is often quite heterogeneous, PEEP that is appropriate in one region can be suboptimal in another and yet excessive in another.\(^{19,20,25,29}\) Optimizing PEEP is thus a balance between recruiting the recruitable alveoli in diseased regions without overdistending already recruited alveoli in healthier regions. Another potential detrimental effect of PEEP is that it raises mean intrathoracic pressure. This can compromise cardiac filling in susceptible patients (discussed subsequently).

**PATIENT-VENTILATOR INTERACTIONS**

Mechanical ventilation modes that permit spontaneous ventilatory activity are termed interactive modes in that patients can affect various aspects of the mechanical ventilator’s functions. These interactions can range from simple triggering of mechanical breaths to more complex processes affecting delivered flow patterns and breath timing. Interactive modes allow for muscle “exercise,” which, when done at nonfatiguing or physiological levels, can prevent atrophy (ventilator-induced diaphragmatic dysfunction) and facilitate recovery from fatigue.\(^{53,54}\) Permitting spontaneous patient ventilatory activity and using comfortable interactive modes can reduce the need for the sedatives and neuromuscular blockers that are often required to prevent patients from “fighting” machine-controlled ventilation.\(^{55}\)

Interactive modes can be either synchronous or dyssynchronous with patient efforts. Synchronous interactions mean that the ventilator is sensitive to the initiation, modulation, and termination of a patient’s ventilatory effort. Dyssynchronous interactions lead to patient discomfort, unnecessary sedation, prolonged duration of mechanical ventilation, and even increased morbidity and mortality.\(^{56}\)

Synchrony is best assessed by clinical observations and analysis of airway pressure graphic over time. Clinical signs of dyssynchrony are tachypnea, dyspnea, diaphoresis, and tachycardia, and the patient is often described as “fighting” the ventilator. Graphically, trigger dyssynchrony is manifest by excessive negative airway pressure signals preceding breath triggering or the absence of any flow delivery in response to observed effort. Flow dyssynchrony is manifest by the airway pressure graphic during flow delivery.
being pulled (or “sucked”) downward during inspiration (Figure 1 on page 347). Cycle dyssynchrony is manifest by continued patient effort and sometimes double triggering if the cycle is too early. Cycle dyssynchrony can also be manifest as increases in airway pressure from expiratory muscle activity if the cycle is too long.

**POSITIVE PRESSURE VENTILATION AND CARDIAC FUNCTION**

In addition to affecting ventilation and ventilation distribution, intrathoracic pressure applications from positive pressure ventilation can affect cardiovascular function. In general, as mean intrathoracic pressure is increased, right ventricular filling is decreased and cardiac output and pulmonary perfusion consequently decrease. This is the rationale for using volume repletion to maintain

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**Figure 1.**

Flow and pressure pattern differences during dyssynchronous and synchronous breaths in a patient with a vigorous inspiratory effort. Depicted are flow (upper panel), volume (middle panel), and pressure (lower panel) for a dyssynchronous flow-targeted (left example) and more synchronous pressure-targeted (right example) breath with matched mean flow, inspiratory time, and tidal volume. Note that during the flow-targeted breaths on the left, the fixed flow does not respond to the vigorous inspiratory effort, resulting in the airway pressure graphic being “sucked” downward (solid arrow). In contrast, with the pressure-targeted breath, flow adjusts and increases to better meet the inspiratory effort (dashed arrow). Reproduced with permission from the *Journal of Critical Care.*
cardiac output in the setting of high intrathoracic pressure. Of note, however, is that positive pressure ventilation can also improve left ventricular function when elevated intrathoracic pressures reduce left ventricular afterload.\(^\text{39}\) Thus, in patients with left heart failure, the reduced cardiac filling and reduced left ventricular afterload effects of elevated intrathoracic pressure can actually improve cardiac function. Under these conditions, removal of intrathoracic pressure can produce weaning failure.\(^\text{40}\)

An interesting corollary to these concepts is the notion of using high-frequency ventilation timed to ventricular systole to augment cardiac output in patients with severe heart failure.\(^\text{41}\)

Intrathoracic pressures can influence distribution of perfusion. The relationship of alveolar pressures to perfusion pressures in the West three-zone lung model helps explain this.\(^\text{42}\) Specifically, the supine human lung is generally in a zone 3 (distension) state. As intra-alveolar pressures increase, however, zone 2 and zone 1 (dead space) regions can appear, creating high V/Q units. Indeed, increases in dead space can be a consequence of ventilatory strategies using high ventilatory pressures as well as with settings producing intrinsic PEEP buildup.

Positive pressure mechanical ventilation can affect other aspects of cardiovascular function. Specifically, dyspnea, anxiety, and discomfort from inadequate ventilatory support can lead to stress-related catechol release with resultant increases in myocardial oxygen demands and risk of dysrhythmias.\(^\text{43}\) Oxygen delivery by coronary blood vessels can be compromised by inadequate gas exchange from the lung injury coupled with low mixed venous \(\text{PO}_2\), attributable to high oxygen consumption demands by the inspiratory muscles.

**COMPLICATIONS OF MECHANICAL VENTILATION**

**Ventilator-Induced Lung Injury**

The lung can be injured when it is stretched excessively by positive pressure ventilation. The most well-recognized injury is alveolar rupture presenting as extra-alveolar air in the mediastinum (pneumomediastinum), pericardium (pneumopericardium), subcutaneous tissue (subcutaneous emphysema), pleura (pneumothorax), and vasculature (air emboli).\(^\text{43}\) The risk for extra-alveolar air increases as a function of the magnitude and duration of alveolar overdistension. Thus, interactions of respiratory system mechanics and mechanical ventilation strategies (high regional \(V_t\) and PEEP, both applied and intrinsic) that produce regions of excessive alveolar stretch (ie, transpulmonary distending pressures >40 cm H\(_2\)O) for prolonged periods create alveolar units at risk for rupture.

Parenchymal lung injury not associated with extra-alveolar air (ventilator-induced lung injury, or VILI) can be produced by mechanical ventilation strategies that stretch the lungs beyond the normal maximum (ie, transpulmonary distending pressures of 30-35 cm H\(_2\)O).\(^\text{44-45}\) This is termed *excessive lung stress* in engineering parlance.\(^\text{46-47}\) Importantly, VILI is likely more than simply a consequence of excessive end-inspiratory stretch or lung stress. Excessive tidal stretch (ie, repetitive cycling of the lung with higher than normal \(V_t\)), even in the setting of acceptable lung stress (ie, \(P_{plat} <30\) cm H\(_2\)O), can contribute to VILI.\(^\text{48}\) In engineering terms, tidal stretch, when referenced to the end-expiratory volume, is called *lung strain*.

Other ventilatory pattern factors can be involved in the development of VILI. These include frequency of stretch\(^\text{49}\) and the acceleration and velocity of stretch.\(^\text{49}\) Although VILI may not be affected by fixed atelectasis, it does appear to be potentiated by a shear stress phenomenon that occurs when injured alveoli are repetitively opened and collapsed during the ventilatory cycle (ie, cyclical atelectasis).\(^\text{50,51}\) Vascular pressure elevations can also contribute to VILI.\(^\text{52}\)

Ventilator-induced lung injury is manifest pathologically as diffuse alveolar damage.\(^\text{53,54}\) Moreover, VILI is associated with cytokine release\(^\text{55,56}\) and bacterial translocation\(^\text{57}\) that are implicated in the systemic inflammatory response with multiple-organ dysfunction that results in VILI-associated mortality.
Ventilator-induced lung injury likely develops regionally when low-resistance/high-compliance units receive a disproportionately high regional Vt in the setting of high alveolar distending pressures. Regional protection of these healthier lung units is the rationale for using lung-protective ventilator strategies that accept less than normal values for pH and Po2 in exchange for lower (and safer) distending pressures (discussed subsequently).

**Oxygen Toxicity**

Oxygen concentrations approaching 100% are known to cause oxidant injuries in airways and lung parenchyma.57 Much of the data supporting this concept, however, have come from animals that often have quite different tolerances to oxygen than humans. It is thus not clear what the “safe” oxygen concentration or duration of exposure is in sick humans. Most consensus groups have argued that fraction of inspired oxygen (Fio2) less than 0.4 is safe for prolonged periods of time and that Fio2 greater than 0.80 should be avoided if at all possible.

**Pulmonary Infectious Complications**

Mechanically ventilated patients are at risk for pulmonary infections for several reasons.58 First, the natural glottic closure protective mechanism is compromised by an endotracheal tube. This permits continuous seepage of oropharyngeal material into the airways. Second, the endotracheal tube itself impairs the cough reflex and serves as an additional potential portal for pathogens to enter the lungs. This is particularly important if the circuit is contaminated. Third, airway and parenchymal injury from the underlying disease and from management complications makes the lung prone to infections. Fourth, the ICU environment with its heavy antibiotic use and presence of very sick patients in close proximity presents a risk for a variety of infections.

Preventing ventilator-associated pneumonias is critical because they greatly affect length of stay and mortality.58-60 Hand washing, elevation of the head of the bed, oral care, and carefully chosen antibiotic regimens for other infections are beneficial. Management strategies that avoid breaking the integrity of the circuit (ie, changing the circuit only when it is visibly contaminated) also appear to be helpful. Continuous drainage of subglottic secretions is another simple way of reducing lung contamination with oropharyngeal material. Finally, aerosolized antibiotics in patients with purulent secretions can reduce the progression of tracheobronchitis to ventilator-associated pneumonia.61

**APPLYING MECHANICAL VENTILATORY SUPPORT**

**Mechanical Ventilatory Support Involves Tradeoffs**

To provide adequate support yet minimize VILI, mechanical ventilation goals must involve tradeoffs. Specifically, the need for potentially injurious pressures, volumes, and supplemental oxygen must be weighed against the benefits of gas exchange support. To this end, gas exchange goals have been examined over the last decade, and now pH goals as low as 7.15 and Po2 goals as low as 55 mm Hg are often considered acceptable if this allows the lung to be protected from VILI.62 Together, these concepts embody “lung-protective” mechanical ventilation and guide current recommendations for the specific management of various forms of respiratory failure.63-65

**Considerations in Choosing Ventilator Settings for Different Forms of Respiratory Failure**

**Acute Lung Injury**

Gas exchange abnormalities in acute lung injury (parenchymal injury) are a consequence of alveolar flooding or collapse, producing a maldistribution of ventilation that results in V/Q mismatching and shunts. Because dead space (V/Q = ∞) is not a major manifestation of parenchymal lung disease unless there is very severe or end-stage injury, hypoxemia tends to be more of a problem than is CO2 clearance in parenchymal lung disease.
Frequency–V̇t settings for supporting parenchymal lung injury must focus on limiting end-inspiratory and tidal stretch. The importance of this in improving outcome has been shown in numerous clinical trials, and this has led to widespread recommendations that in patients with acute lung injury, the default V̇t should be 6 mL/kg of ideal body weight (IBW) and the end-inspiratory lung distending pressure (Pplat corrected for any chest wall effects) should be less than 30 cm H₂O. Increases in V̇t settings might be considered if there is marked patient discomfort or suboptimal gas exchange, provided that the subsequent Pplat values do not exceed 30 cm H₂O. Respiratory rate settings are then adjusted to control pH, and the I:E times are generally set in the physiological 1:2 to 1:4 range to ensure comfort and minimize air trapping.

There are both mechanical and gas exchange approaches to setting the PEEP/Fio₂ combination to support oxygenation while minimizing overstretch injury and oxygen toxicity. Mechanical approaches rely on the respiratory system pressure–volume relationships to set the PEEP and V̇t. This can be assessed with a traditional static pressure–volume plot, a “slow-flow” single breath pressure–volume plot, a “best compliance” PEEP titration, or an airway pressure profile analysis during a constant flow breath (“stress index”). Conceptually, the goal is to provide ventilator settings between the overdistension and collapse–reopening points in the pressure–volume relationship. Unfortunately, these techniques are technically challenging and time consuming and thus are not used routinely in most patients.

Gas exchange criteria to guide PEEP/Fio₂ settings generally involve algorithms designed to provide adequate values for Pao₂ (eg. 55-80 mm Hg) while minimizing PEEP and Fio₂. Constructing a PEEP/Fio₂ algorithm is usually an empirical exercise in balancing pressure, Pao₂ (arterial oxygen saturation or oxygen saturation as measured by pulse oximetry), and Fio₂ and depends on the clinician’s perception of the relative toxicities of high thoracic pressures, high Fio₂, and low arterial oxygen saturation. Several recent trials have compared a number of PEEP/Fio₂ algorithms in conjunction with low-V̇t/limited-Pplat strategies (Table 3 on page 350). Taken together, these studies found that more aggressive PEEP strategies (ie, average 13-15 cm H₂O) can improve outcome in more severe disease with high recruitability potential, whereas more conservative PEEP strategies (ie, average 7-9 cm H₂O) are sufficient in less severely injured lungs with less recruitability.

In acute lung injury when gas exchange goals are not being met with conventional lung-protective strategies, 2 other approaches have received considerable attention in the last decade: (1) inverse ratio ventilation (I:E ratios of 2:4:1) with airway pressure release ventilation (APRV) and (2) high-frequency ventilation (HFV).

The concept underlying APRV is that the long inflation phase recruits more slowly filling alveoli and raises mean airway pressure without increasing applied PEEP (although intrinsic PEEP can develop with short deflation periods). Because spontaneous breathing can occur,

| Table 3. |
| The PEEP/Fio₂ Table Used in the NIH ARDS Network Study⁷ a |

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Abbreviation: ARDS, acute respiratory distress syndrome; NIH, National Institutes of Health; PEEP, positive end-expiratory pressure.

a The clinical target is a Pao₂ of 55 to 80 mm Hg or oxygen saturation (as measured by pulse oximetry) of 88% to 95%. If the patient’s value is below these target values, move up the table to the right. If the patient’s value is above these targets, move down the table to the left.
matching. Regions of air trapping and intrinsic PEEP also function as a threshold load to trigger mechanical breaths.\(^{83}\)

Setting the frequency–\(V_t\) pattern in obstructive diseases involves many considerations that are similar to those used in setting these parameters in parenchymal lung injury.\(^{84}\) Specifically, \(V_t\) should be sufficiently low (eg, 6 mL/kg IBW) to ensure that Pplat values are less than 30 cm H\(_2\)O. As with parenchymal lung injury, \(V_t\) reductions should be considered to meet Pplat goals, and increases in \(V_t\) can be considered for comfort or gas exchange provided that Pplat values do not exceed 30 cm H\(_2\)O. The set rate is used to control pH. Unlike parenchymal disease, however, obstructive disease involves elevated airway resistance (and often the low recoil pressures of emphysema) that greatly increase the potential for air trapping, and this limits the range of breath rates available. Permissive hypercapnia may be an appropriate tradeoff to limit overdistension.

Because alveolar recruitment is less of an issue and overdistension is more of an issue in obstructive lung injury compared with parenchymal lung injury, the PEEP/Fio\(_2\) steps in Table 3 on page 350 should probably be shifted to emphasize Fio\(_2\), more for oxygenation support. A specific role for PEEP in the obstructed patient occurs when intrinsic PEEP serves as an inspiratory threshold load in the patient attempting to trigger a breath. Under these conditions, judicious application of circuit PEEP (up to 85% of intrinsic PEEP) can balance expiratory pressure throughout the ventilator circuitry to reduce this triggering load and facilitate the triggering process.\(^{85}\)

**Obstructive Airway Disease**

Respiratory failure from airflow obstruction is a direct consequence of increases in airway resistance. This leads to 2 important physiological changes.\(^{86}\) First, the increased pressures required for airflow can overload inspiratory muscles, producing a ventilatory pump failure with spontaneous minute ventilation inadequate for gas exchange (hypercapnic respiratory failure). Second, the narrowed airways create regions of lung that cannot properly empty and return to their normal resting volume, and intrinsic PEEP is produced. These regions of overinflation create dead space and put inspiratory muscles at a substantial mechanical disadvantage, which further worsens muscle function. Overinflated regions can compress more healthy regions of the lung, impairing V/O

**Neuromuscular Respiratory Failure**

Many of the principles of lung-protective strategies described here also apply to the patient with neuromuscular respiratory failure. However, the risk of VILI is generally less in a patient with neuromuscular failure because lung mechanics are often near normal and regional overdistension is thus less likely to occur. More generous \(V_t\) of perhaps 8 to 10 mL/kg IBW can be used as necessary to improve comfort, maintain recruitment, prevent atelectasis, and avoid levels of hypercarbia that can
adversely affect central nervous system function. At the same time, however, maximal distending pressures should be kept as low as possible (and certainly <30 cm H₂O). Low levels of PEEP are often beneficial at preventing derecruitment (atelectasis) in these patients, who are often supine and incapable of secretion clearance or spontaneous sigh breaths.

**Recovering Respiratory Failure: Weaning and Discontinuation**

As respiratory failure stabilizes and begins to reverse, clinical attention shifts to ventilator withdrawal. Unfortunately, a number of large clinical trials have clearly demonstrated that current assessment and management strategies are not optimal and result in considerable undue delay in ventilator withdrawal. Increased length of stay, costs, exposure to pressure, and risk of infection result. Attempts to increase withdrawal aggressiveness, however, must be balanced against the risk of premature withdrawal with consequent airway loss, aspiration, and inspiratory muscle fatigue.

An evidence-based task force has recommended a daily assessment process for most patients requiring at least 24 hours of mechanical ventilator support:

1. Consider a patient a candidate for withdrawal if (a) the lung injury is stable and resolving; (b) gas exchange is adequate with low PEEP/Fio₂ requirements; (c) hemodynamics are stable without a need for pressors; and (d) the patient can initiate spontaneous breaths.

2. In these patients, perform a spontaneous breathing trial (SBT, using t-piece, continuous positive airway pressure, or 5 cm H₂O PS) for 30 to 120 minutes. Assessments should include the ventilatory pattern, gas exchange, hemodynamics, and comfort. Patients who pass this trial should be considered for ventilator withdrawal.

3. Couple these efforts with aggressive strategies to reduce sedation.

In patients who pass the SBT, separate assessments are required to determine whether the artificial airway can be removed. These involve the evaluation of cough strength, suctioning frequency, and, to a certain extent, the ability to follow commands. Exubation failures can be expected in 10% to 20% of all extubations. Many of these involve airway protection, and thus prompt reintubation is indicated. However, in some patients, especially patients with chronic obstructive pulmonary disease, an exubation failure caused by increasing inspiratory muscle overload might be managed by noninvasive ventilation.

In patients who fail the SBT, a stable and comfortable level of interactive support should be provided until the next SBT. Frequent (eg, every 2-12 hours) support reductions between daily SBT considerations are usually not necessary. Indeed, support reduction strategies not only do not speed up the withdrawal process but also appear to excessively consume resources and unnecessarily expose the patient to muscle overload risks.

Over the years, a number of attempts have been made to automate the weaning process with feedback control algorithms designed to progressively reduce support. Approaches include mandatory minute ventilation (an SIMV mode with feedback reductions in mandatory breath rates), volume support, and adaptive support ventilation as described previously. The most recent approach also uses a volume support feedback strategy but incorporates respiratory frequency, end-tidal CO₂, and an SBT reminder into the algorithm.

All of these strategies are based on the premise that support reduction between SBTs improves outcomes—a premise that, as noted, has no supporting evidence. Because of this, studies evaluating these approaches have only been able to show that support reduction strategies can effectively be automated (with consequently less clinician work). However, no study has shown that any of these approaches shorten the duration of mechanical ventilation compared with strategies that mandate regular SBTs. The lone exception to this generalization might be in the postoperative setting where patient recovery is rapid and automated tools to assess this recovery might be helpful.
SUMMARY

Mechanical ventilatory support is a critical component of the management of patients with respiratory failure. However, this technology is supportive—not therapeutic. It cannot cure lung injury. Indeed, the best we can hope for is that ventilatory support will buy time by supporting gas exchange without harming the lungs.

There are exciting innovations on the horizon, but they must be assessed properly. This is particularly important for innovations with significant risks or costs. Only with properly conducted studies that include such clinically relevant outcomes as mortality, ventilator-free days, barotrauma, and costs can we effectively assess the sometimes bewildering array of new approaches to this vital life support technology.

REFERENCES


