AANA Journal Course
Update for Nurse Anesthetists

Anesthesia and Critical Care Ventilator Modes: Past, Present, and Future

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Mechanical ventilators have evolved from basic machines to complicated, electronic, microprocessing engines. Over the last 2 decades, ventilator capabilities and options for critical care and anesthesia ventilators have rapidly advanced. These advances in ventilator modalities—in conjunction with a better understanding of patient physiology and the effects of positive pressure ventilation on the body—have revolutionized the mechanical ventilation process. Clinicians today have a vast array of mechanical ventilator mode options designed to match the pulmonary needs of the critically ill and anesthetized patient. Modes of mechanical ventilation continue to be based on 1 of 2 variances: volume-based or pressure-based. The wording describing the standard ventilatory modes on select present-day ventilators has changed, yet the basic principles of operation have not changed compared with older ventilators. Anesthesia providers need to understand these ventilator modes to best care for patients.

This literature review encompasses a brief history of mechanical ventilation and current modes available for anesthesia and critical care ventilators, including definitions of each mode, definitions of the various descriptive labels given each mode, and techniques for optimizing and meeting the ventilator needs of the patient while avoiding complications in the surgical and critical care patient.

Keywords: Anesthesia ventilators, intensive care unit, ventilators, ventilator mode.

Objectives
At the completion of this course, the learner should be able to:
1. Describe briefly the history of assisted ventilation and the progression of ventilator modes.
2. Discuss considerations for determining initial ventilatory support.
3. Describe and discuss the 2 base modes found in all contemporary mechanical ventilators.
4. List and discuss current and future critical care and anesthesia ventilator modes.
5. Discuss optimal ventilation modalities designed to minimize barotrauma and volutrauma.

A Brief History
Assisted ventilation has been recorded in history over thousands of years. Early works by the Egyptians and Greeks note theories on aided respiration.1 Use of mouth to mouth resuscitation, a primitive form of positive-pressure ventilation, can be found in some of the earliest records in time.2 The Bible records the prophet, Elisha, providing breathing from his mouth to the mouth of a dying child.1,2 Hippocrates (460-375 BC) was credited with the first description of endotracheal intubation.1 In the 1500s, Andreas Vesalius, a Belgian professor of anatomy, used fire bellows connected to a tube in the mouth for ventilation1,2 (Figure 1). In 1776 John Hunter developed a double bellow system, which placed ambient air in and removed air out of a canine’s lungs through tubes in the trachea.2 This technology was encouraged until 1837 when chest compressions became more common as a means to artificial respiration.

Between the late 1700s and the 1900s, two basic types of ventilator systems were invented and put into practice: negative-pressure and positive-pressure ventilation. During the mid-1800s, however, it was reported to the French Academy of Science that bellow-type methods (positive-pressure ventilation) caused elevated airway
pressure complications, including ruptured alveoli, emphysema, and tension pneumothorax. Therefore, during the mid-1800s to the mid-1900s, the predominant form of mechanical ventilation was by negative-pressure systems. The negative-pressure ventilation is commonly referred to as the iron lung (Figure 2). With this system, a patient’s chest or body from the neck down was placed into an apparatus causing negative pressure around the chest. The negative-pressure method induced chest expansion and lung insufflation for the patient. The other system for mechanical ventilation was positive-pressure ventilation through a mask or endotracheal tube. During this time, several positive-pressure mechanical ventilation systems were invented. In 1911 Draeger Medical created an artificial breathing device called the Draeger Pulmator. Because of the small, suitcase size of the apparatus, it became popular in Europe and America for use by police and fire department rescue squads.

From the late 1800s to the 1950s, poliomyelitis (known as polio) affected the human population worldwide. Polio’s devastating and deadly effects on lungs and respiration motivated the evolution of mechanical respiration. The epidemic in the 1930s saw the demand for negative-pressure mechanical respirators greatly exceeding the supply. In one hospital setting, more than 200 medical students were employed for the sole purpose of providing continuous or intermittent bag ventilation because of the shortage of mechanical ventilators. Until the 1950s, positive-pressure ventilation via intubation was considered appropriate only in the operating room (OR) under the direct care of an anesthetist. However, the shortage of negative-pressure systems during the polio epidemics of the early 1950s led to a reevaluation of this paradigm. Subsequently, positive-pressure systems with endotracheal tubes began to be recognized as safe and effective for patients requiring prolonged respiratory support. Early forms of positive-pressure ventilation were noninvasive, requiring the use of a mask and bag or bellows. Their popularity increased, and with it the evolution of mechanical ventilator modes.

In the 1950s, with ventilators still primitive in development, it remained difficult to precisely adjust ventilators to control important parameters such as pressure and volume. Clinicians typically ventilated patients through uncuffed endotracheal tubes to prevent excessive tidal volumes, which left the trachea unprotected and at risk of aspiration. Two basic modes of ventilation were used in the 1950s and 1960s: pressure-limited and volume-regulated. The pressure-limited mode was also known as intermittent positive-pressure breathing. It was originally designed to administer aerosol therapy. The pressure-limited mode allowed the patient to initiate each breath, providing assistance for reduced effort known as “patient-triggered Servo-assist.” The volume-regulated mode delivered a set volume. At the time, the popular theory was to implement the pressure-limited mode first if the patient was making efforts to breathe. The volume-regulated machines required sedation and were used as a last resort. The advent and routine accessibility of blood-gas analysis and the understanding that, with pressure-limited mechanical ventilation, changes in lung compliance altered the delivered tidal volumes, diminished the appropriate application of the pressure-limited mode. Complete controlled ventilation was the mainstay until technology improved.

During the late 1950s and early 1960s the benefits of controlled automatic ventilators became recognized...
Multiple modes of ventilation have surfaced since the 1980s. In the early 1980s, pressure support ventilation (PSV) was implemented to help augment a patient’s own inspiratory effort. By 1998 it was reported that 45% of practitioners used PSV for weaning. As technology advanced during the 1990s and the impact of volutrauma on the lungs became more evident, forms of pressure-controlled ventilation were reconsidered. The advent of microprocessors in mechanical ventilators allowed for measurement of peak inspiratory pressure, mean airway pressure, and continuous positive airway pressure. Therefore, most newer modes of mechanical ventilation are derived from pressure-targeted modes.

In the last 20 years, mechanical ventilation has been transformed. Advances in equipment, the understanding of patient physiology, and the effects of mechanical ventilation on the body have revolutionized the mechanical ventilation process. Ventilators can be found in most clinical settings from ORs and critical care units, to radiology departments, hospital transport, emergency transport, home environments, military, and domestic field use. This literature review is designed to inform the reader of the multitude of current and future ventilator modes specific to the OR and critical care settings. Unless noted, all information regarding ventilator modes are intended to encompass both settings. Also, because ventilators are manufactured by numerous companies, multiple names have been created for similar modes of ventilation. The advancement of technology over time has also changed the meaning of some older ventilation terms. With this in mind, ventilator names have been collated when applicable in each mode review given later in the article.

**Initiation of Mechanical Ventilation**

The primary goals for mechanical support differ between the critical care and OR settings. In the surgical setting, patients vary along the full spectrum of health. Mechanical ventilatory requirements vary depending on the type of surgery, length of surgery, patient positioning, patient physical status, or any combination of these. Mechanical ventilation is typically focused on maintaining homeostasis and preventing harm or injury to the surgical patient under anesthesia and the intubated patient in the critical care setting. The advancement of technology and the understanding of how that technology relates to the physiologic status of patients and outcomes have encouraged researchers to determine best practices for mechanical ventilation.

The goal of mechanical ventilation in the critical care patient is to normalize arterial blood-gas levels and acid-base imbalances in patients unable to maintain this balance independently. Objectives of initiating mechanical ventilation include reversing hypoxemia and acute acidosis, relieving respiratory distress, and decreasing the work of breathing. Numerous factors must be accounted for when determining the needed type of ventilator support, including the patient’s physiologic status, goals of treatment, and types of ventilators and modes available. Classic indications for initiating mechanical ventilation are noted in Table 1.

**Table 1. Classic Indications for Initiating Adult Ventilatory Support**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Abbreviation</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arterial $\text{Pao}_2 &lt; 55$-$60$ mm Hg (on supplemental oxygen)</td>
<td>$\text{Pao}_2$</td>
<td>Arterial oxygen pressure $&lt; 55$-$60$ mm Hg on supplemental oxygen</td>
</tr>
<tr>
<td>Alveolar-to-arterial oxygen difference $&gt; 350$ mm Hg</td>
<td>$\text{Paco}_2$</td>
<td>Alveolar-to-arterial oxygen difference $&gt; 350$ mm Hg</td>
</tr>
<tr>
<td>Arterial $\text{Paco}_2 &gt; 50$ mm Hg (absence of chronic disease) and</td>
<td>$\text{Paco}_2$</td>
<td>$\text{Paco}_2 &gt; 50$ mm Hg (absence of chronic disease) and</td>
</tr>
<tr>
<td>$\text{pH} &lt; 7.32$</td>
<td></td>
<td>$\text{pH} &lt; 7.32$</td>
</tr>
<tr>
<td>Evidence of increased work of breathing = RR $&gt; 35$/min,</td>
<td>$\text{Vt}$</td>
<td>Evidence of increased work of breathing $= RR &gt; 35$/min,</td>
</tr>
<tr>
<td>$\text{Vt} &lt; 5$ mL/kg</td>
<td></td>
<td>$\text{Vt} &lt; 5$ mL/kg</td>
</tr>
<tr>
<td>Vital capacity $&lt; 10$-$15$ mL/L</td>
<td>$\text{FEV}_1$</td>
<td>Vital capacity $&lt; 10$-$15$ mL/L</td>
</tr>
<tr>
<td>Maximum inspiratory pressure/negative inspiratory force</td>
<td>$\text{FEV}_1$</td>
<td>Maximum inspiratory pressure/negative inspiratory force</td>
</tr>
<tr>
<td>&lt; 25 cm H$_2$O</td>
<td></td>
<td>&lt; 25 cm H$_2$O</td>
</tr>
<tr>
<td>$\text{FEV}_1 &lt; 10$ mL/kg</td>
<td>$\text{FiO}_2$</td>
<td>$\text{FEV}_1 &lt; 10$ mL/kg</td>
</tr>
<tr>
<td>Retractions/nasal flaring</td>
<td>$\text{FiO}_2$</td>
<td>Retractions/nasal flaring</td>
</tr>
<tr>
<td>Paradoxical/divergent chest motion</td>
<td></td>
<td>Paradoxical/divergent chest motion</td>
</tr>
</tbody>
</table>

Abbreviations: $\text{FEV}_1$, forced expiratory volume in 1 s; $\text{FiO}_2$, fraction of inspired oxygen; $\text{Vt}$, tidal volume. (Most of this table was reprinted with permission from Hamed et al.)
(CO₂) dissolved in arterial blood is 35 to 45 mm Hg. The normal pH, a measurement of acidity or alkalinity in the blood, is 7.35 to 7.45. Other laboratory values, such as serum bicarbonate, a value of the amount of bicarbonate in the bloodstream, may help guide ventilatory management. The alveolar-to-arterial oxygen difference (tension gradient) noted in Table 1 is another diagnostic tool. However, its interpretation and clinical significance is only relevant in limited conditions.¹¹ This tension gradient quantifies disruptions of pulmonary (alveolar) oxygen transfer into the blood (arterial) without requiring a mixed venous blood sample. It is a useful index in stable patients breathing room air, however, its value in critically ill or anesthetized patients is questionable since the value varies independently with changes in the fraction of inspired oxygen (FIO₂), the degree of oxygen bound to hemoglobin (SaO₂), and the mixed venous oxygen saturation (SVo₂).¹¹

During initiation and maintenance of assisted mechanical ventilation, an acute understanding of ventilator settings is important for the safety of the patient. They are briefly discussed as follows. The mode of ventilation should be selected to the needs of each patient, keeping in mind whether it is necessary to take control of the patient’s respirations or assist respirations, for example, volume-controlled ventilation vs PSV. Modes are listed later in the article. Respiratory rate is adjusted in correlation with other settings to achieve a common goal. Although this statement is vague, the key factor is the goal. The normal range for an adult’s respiratory rate of 8 to 12 breaths per minute may not be ideal in every situation. Whereas most patient respiratory goals may be to accomplish normal oxygen and CO₂ levels, some surgeries or critically ill patients may require a period of hyperventilation or hypoventilation to achieve desired outcomes.¹⁰ Respiratory rates are adjusted relative to tidal volumes to reach desired end-tidal CO₂ and blood-gas criteria. The goal and use of tidal volumes are discussed later. The respiratory rate also affects the inspiratory/expiratory (I:E) ratio. The normal starting ratio is 1:2, meaning expiratory time is twice that of inspiration. A longer expiratory time may be recommended in patients who need prolonged expiration to avoid air trapping (eg, obstructive airway diseases).¹⁰ Reversing the ratio to make expiratory time shorter than inspiration may be used in trials for patients unable to maintain adequate oxygenation; however, this leads to breath stacking and is not advantageous for long-term use. Inspiratory flow rate is a function of the tidal volume, I:E ratio, and respiratory rate and can be controlled through the ventilator by these settings. Some mechanical ventilators allow for independent control and may be set at a typical setting of 60 L/min.¹⁰ Higher flow rates deliver tidal volumes more quickly and allow prolonged expiration. Peak inspiratory pressure is the highest pressure noted during the inspiratory phase. In general, it is recommended to limit peak inspiratory pressures to less than 35 cm H₂O to avoid barotrauma.

Positive end-expiratory pressure (PEEP) is the alveolar pressure above atmospheric pressure that exists at the end of expiration. There are 2 types of PEEP: (1) applied or extrinsic PEEP, which is provided by mechanical ventilation and (2) auto or intrinsic PEEP, which is secondary to incomplete expiration.¹² Extrinsic PEEP, combined with low tidal volumes, may reduce the prevalence of ventilator-induced lung injury. It may also reduce the risk of atelectasis by increasing the number of alveoli that remain open at end expiration. However, lung physiology and disease states make an ideal PEEP number target less identifiable for all alveoli.¹² Physiologic PEEP is 3 to 5 cm H₂O. According to Dr Neil MacIntyre’s article about PEEP in Medscape, there are 3 ways to determine the appropriate level of PEEP: visual, mechanical, and gas exchange.¹³ The first 2 are labor intensive and have limitations. Gas exchange, the third pathway listed, is the most clinically used and is based off FIO₂ requirements, partial pressure of oxygen in the arterial blood, or the calculated shunt fraction.¹³ The article expresses 3 research studies identifying schools of thought for levels of PEEP, aggressively high levels (generally less than 30-40 cm H₂O) and conservative PEEP levels (less than 15 cm H₂O) in relation to gas exchange.¹³ The results noted no clear benefit of one practice over the other. Dr MacIntyre summarized that both protocols were reasonable for clinical use barring new research evidence.

Another result of research, advancement in technology, and practice is the target for tidal volumes. Prevention of atelectasis, acute respiratory distress syndrome (ARDS), acute lung injury, barotrauma, and volutrauma are vital to the mechanically ventilated patient. Tidal volumes ranging from 6 mL/kg to 12 mL/kg play a major role in lung protective strategies during mechanical ventilation.¹⁴ Lower settings prevent overdistension of the alveoli and lungs and decrease injury. The ARDSNet Project from the National Heart, Lung, and Blood Institute noted that reduction of tidal volume from 12 mL/kg to 6 mL/kg also reduced mortality by more than 20% and recommended low tidal volumes and moderate levels of PEEP to prevent alveolar collapse and overdistension in patients with acute lung injury/ARDS.¹⁴ Evidence also demonstrates that low tidal volumes are beneficial in patients with normal lungs. Other than the low tidal volumes and PEEP, research has been inconsistent in determining the best ventilator modes to prevent alveolar collapse and overdistension.¹⁴,¹⁵ In other words, rather than questioning whether to use a pressure-based mode vs a volume-based mode, the more simplistic and applicable question might be, What tidal volume should be achieved under appropriate peak inspiratory pressures regardless of the mode chosen?
The Basics of Ventilation Modes

Mechanical assistance in breathing, whether complete or supportive, is provided using 2 main base pathways: volume-controlled or pressure-controlled modes. These are the target mechanisms, or how the inspiratory phase of breathing is stopped and the expiratory phase begins. Volume-controlled modes provide mechanical support primarily by attempting to obtain a set tidal volume. The ventilator targets the tidal volume regardless of the pressure generated (although safety mechanisms are set to prohibit extremely high pressures). Pressure-controlled modes assert their support through pressure settings. Tidal volumes in pressure-controlled modes are based on airway resistance, lung compliance, and/or extrapulmonary factors. All modes of mechanical ventilation are derived from one or a combination of these 2 base systems. For ease, the variances between these base modes have been provided in Table 2.

Comparing Pressure and Volume-Controlled Modes With Pressure-Volume Loops

Another venue for appreciating the differences between pressure- and volume-controlled ventilation modes is by looking at pressure-volume loops. Although a mainstay in critical care ventilators, they are becoming more

### Table 2. Differences Between Base Modes: Volume- and Pressure-Controlled Methods

<table>
<thead>
<tr>
<th>Volume-controlled modes</th>
<th>Pressure-controlled modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume constant: Attempts to achieve preset volume at expense of variable airway pressures</td>
<td>Volume variable: Attempts to achieve preset pressure with variable tidal volume</td>
</tr>
<tr>
<td>Inspiration: Ends with delivery of preset tidal volume</td>
<td>Inspiration: Ends when preset positive pressure has been achieved</td>
</tr>
<tr>
<td>Preset tidal volume delivered: Unless upper airway pressure setting is reached or if there is a leak in the system; cuff, tubing</td>
<td>Preset pressure delivered: Tidal volume varies and is determined by set pressure level, changes in airway resistance, and lung compliance</td>
</tr>
<tr>
<td>Peak airway pressure: Variable. Determined by changes in airway resistance, lung compliance, or extrapulmonary factors. The pressure increases to deliver the preset tidal volume.</td>
<td>Peak airway pressures: Fixed. Determined by preset pressure level. Volume delivered is variable and decreases with increased airway resistance, decreased lung compliance, or extrapulmonary factors.</td>
</tr>
<tr>
<td>Inspiratory flow rate: Fixed, rate set</td>
<td>Inspiratory flow rate: Variable, based on patient</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Volume-limited ventilation (also known as volume-controlled ventilation or volume-cycled ventilation)</th>
<th>Pressure-limited ventilation (also known as pressure-cycled ventilation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Clinician sets peak flow rate, flow pattern, V\textsubscript{T}, RR, PEEP, and F\textsubscript{IO\textsubscript{2}}.</td>
<td>a. Requires clinician to set the inspiratory pressure level, I:E ratio, RR, PEEP, and F\textsubscript{IO\textsubscript{2}}; inspiration ends after the set delivery of inspiratory pressure</td>
</tr>
<tr>
<td>b. Delivered via several modes: controlled mechanical ventilation (CMV), assist control (AC), intermittent mandatory ventilation (IMV), synchronized intermittent mandatory ventilation (SIMV), volume-controlled ventilation (VCV) (see descriptions in Table 3)</td>
<td>b. Variable V\textsubscript{T}, related to inspiratory pressure level, compliance, airway resistance, and tubing resistance</td>
</tr>
<tr>
<td></td>
<td>c. Can be delivered using the same modes of ventilation that deliver volume-limited ventilation: pressure-limited CMV (pressure-controlled ventilation), AC, and IMV/SIMV</td>
</tr>
<tr>
<td></td>
<td>Volume-limited vs pressure-limited ventilation:</td>
</tr>
<tr>
<td>a. Compared in randomized trial and multiple observational studies</td>
<td>a. Compared in randomized trial and multiple observational studies</td>
</tr>
<tr>
<td>b. No statistical significance in mortality, oxygenation, or work of breathing</td>
<td>b. No statistical significance in mortality, oxygenation, or work of breathing</td>
</tr>
<tr>
<td>c. Pressure-limited ventilation benefits: associated with lower peak pressures, a more homogenous gas distribution (less regional alveolar overdistension), improved patient-ventilator synchrony, and earlier weaning from ventilator than volume limited</td>
<td>c. Pressure-limited ventilation benefits: associated with lower peak pressures, a more homogenous gas distribution (less regional alveolar overdistension), improved patient-ventilator synchrony, and earlier weaning from ventilator than volume limited</td>
</tr>
</tbody>
</table>

Abbreviations: F\textsubscript{IO\textsubscript{2}}, fraction of inspired oxygen; I:E ratio, inspiratory/expiratory ratio; PEEP, peak end-expiratory pressure; RR, respiratory rate; V\textsubscript{T}, tidal volume.

(The top half of the table was reprinted with permission from Grossbach et al.\textsuperscript{9})
commonplace in anesthesia machines as well. Pressure-volume loops essentially assess compliance, which is measured by the change in volume for a given change in pressure. They also give information about overinflation, prolonged inspiration, and leaks. On pressure-volume loops, volume is on the x-axis and pressure is on the y-axis. Inspiration is noted on the line moving up from left to right, and expiration is the line moving down from right to left. Minimum and maximum inflation are the endpoints. Drawing a line between the 2 endpoints notes static compliance for the given loop. A decrease in compliance is a hallmark of ARDS. Figure 3 is a basic diagram of the anatomy of pressure-volume loops. Note that the upper right portion of the loop is termed “beaking.” This resembles overdistension or overinflation during mechanical ventilation.17,18

Another benefit of pressure-volume loops is the assessment of PEEP during mechanical ventilation. Positive end-expiratory pressure is evaluated based on the static pressure-volume curve. Application of PEEP may increase compliance, as noted by a more vertical loop on the volume-controlled ventilation. If the loop becomes more horizontal, PEEP may need to be decreased or eliminated. The lower inflection point mainly represents the critical opening pressure of the alveoli. It has been noted that this lower inflection point suggests where PEEP should be set. However, research demonstrates that the lower inflection tends to overestimate ideal PEEP, and practitioners are inclined to vary greatly on determining the correct location of the inflection point. Also, PEEP focuses on alveoli recruitment; however, derecruitment may occur at different phases of the expiratory limb.17,18

Pressure-volume loops appear noticeably different between pressure and volume-controlled ventilation. Pressure-controlled ventilation differs from volume-controlled respiration in that the inspiratory flow is not constant; however, the pressure is more constant. Therefore, the pressure-volume loop is appreciably different and more “boxlike” in nature. As the volume stops and diminishes, pressure remains more constant to a point before returning to baseline. This reinforces a variance between pressure-controlled and volume-controlled ventilation. Also, compliance is not derived easily with pressure-controlled ventilation because of the change of flow during the inspiratory phase. Compliance is appreciable with volume-controlled ventilation. With good compliance, the line in volume-controlled ventilation forms an angle of 45 degrees or less with the volume axis. A loop that becomes more horizontal indicates a decrease in compliance.18 As noted, pressure-volume loops provide information on compliance, which is affected by extrinsic and intrinsic causes. Determining that variable of compliance change is typically easier to assess in critical care patients because extrinsic causes are less frequent. Surgery may be both extrinsic and intrinsic and demands a thorough evaluation by the anesthetic provider. In either setting, pressure-volume loops may be beneficial to evaluate the risks of high inspiratory peak pressures, overinflation, and underinflation of the lungs. Figures 4 and 5 are basic diagrams comparing pressure-volume loops of pressure- and volume-controlled mechanical ventilation. For completeness, Figures 6 and 7...
demonstrate real-time pressure-volume loops for pressure- and volume-controlled modes.

**Ventilatory Modes**

Modern ventilators offer increased accuracy and flexibility in modes of ventilation. Volume and pressure targets are controlled more accurately and reduce the risk of barotrauma, volutrauma, and atelectasis. The flexibility of modern modes and mode adjuncts, for instance, PSV for spontaneous breathing and the ability to more accurately control adjuncts like peak inspiratory pressures, allow for increased safety in the increased use of supraglottic devices, ambulatory procedures, and refined adjuncts such as regional anesthesia. Other benefits of new ventilators include single-switch activation, an ability to enter the patient's weight for recommended appropriate ventilator settings, and volume guarantee with pressure or volume modes. Assisted and controlled
ventilation is no longer limited to volume-controlled and pressure-controlled modes. Other forms of ventilation include extracorporeal membrane oxygenation (ECMO) and neurally adjusted ventilator assist (NAVA).

Extracorporeal membrane oxygenation is a form of ventilation specific to critical care and is not based on alveolar ventilation-based modes. It is an invasive procedure using wide-bore cannulae to achieve a flow rate necessary to gain adequate oxygenation (typically 3.5-5 L/min). Thus, it is likely that ECMO in this form will continue to be provided in specialty centers and remain outside the use of most critical care settings. Transfer of oxygen across the membrane is saturation dependent (mixed venous and membrane inlet being approximately 65%-70%). Carbon dioxide is predominantly carried dissolved in blood as bicarbonate. Transfer of CO₂ across the membrane is partial pressure dependent. Human CO₂ production is approximately 250 mL/min, so it is conceivable that an efficient system could achieve CO₂ clearance at considerably lower flows than conventional ECMO, thus using a system involving flows and cannulae comparable with those of renal replacement therapy. It was first used in the management of respiratory failure in the 1970s and first reported in human use in the 1980s. The first randomized controlled trial investigating the role of ECMO in adults with severe adult respiratory failure in the era of lung protective strategies (CESAR trial, or Conventional Ventilation or ECMO for Severe Adult Respiratory Failure) suggests a significant reduction in death or severe disability in those using an ECMO management vs controlled ventilation but this trial was controversial. More recently, a pumpless extracorporeal device (interventional lung assist) has been developed that uses cannulae in the femoral artery and vein, with a very-low-resistance, high-efficiency membrane for gas exchange. It uses relatively small cannulae, and the driving pressure is the arteriovenous pressure difference.

Neurally adjusted ventilator assist is a neural-based critical care ventilator mode. Pressure and flow changes in the ventilator circuit are used in traditional modes to initiate a ventilator-supported breath. With this, there is a delay between the initiation of effort by the respiratory muscles and the ventilator delivery of support. Neurally adjusted ventilator assist attempts to discourage this delay by using neural stimulus to the muscles as the trigger for ventilator support in a simultaneous fashion with muscle effort. Bipolar electrodes on a nasogastric tube detect electrical activity of the phrenic nerve to the diaphragm. So far, NAVA has been used in neonatal and pediatric populations, adults with ARDS, acute respiratory failure postoperatively, and in conjunction with other modes such as ECMO. At high levels of NAVA, the electrical activity to the diaphragm is minimal. Therefore, pressure delivered is limited. This advantage allows for decreased injuries related to tidal volumes. Neurally adjusted ventilator assist has been assessed as having greater patient/ventilator synchrony than does PSV and without the risk of giving high tidal volumes. Studies are needed to demonstrate evidence of better outcomes with NAVA.

Today, ventilators and modes come in all shapes and sizes. Modes may have multiple names across companies, regions, and institutions. Table 3 lists ventilation modes for anesthesia and critical care ventilators. An effort to compile the various names for each mode has been attempted. When identifiable, the use of a mode to specific settings or professions has been noted. Otherwise, the modes should be considered appropriate and accessible across professions. It is important to note that not all modes are available on every ventilator machine.

Summary
Anesthesia providers need to stay current with available ventilator modes. Pressure- and volume-controlled modes are the 2 common base modes in mechanical ven-
Volume-Controlled Ventilation (VCV), Controlled Mandatory Ventilation (CMV), Continuous Mandatory Ventilation (CMV), Mandatory Minute Volume (MVV)\(^7,23-26\)

- Base mode is common in all anesthesia and critical care ventilators.
- This mode has a set VT at a constant flow; MV is determined by set RR and VT.
- Peak inspiratory pressure varies according to lung compliance and airway resistance.
- VT is adjusted to avoid atelectasis and volutrauma through VT of 6-10 mL/kg.
- Rate is adjusted to maintain ETCO\(_2\) while monitoring the peak inspiratory pressure (PIP).
- Reserved for patients under pharmacologic paralysis or heavy sedation, in a coma, or when there is lack of patient incentive to increase the minute ventilation because set MV meets or exceeds physiologic need.
- Recommendations for VCV settings in an adult: VT of 6-10 mL/kg, RR of 6/min to 12/min.

Pressure-Controlled Ventilation (PCV)\(^7,9,19,25,27\)

- Base mode, common in all anesthesia and critical care ventilators.
- Set desired pressure, inspiratory time, RR.
- With every breath, the ventilator delivers an inspiratory flow until the preset pressure is achieved.
- Controls inspiratory pressure and allows inspired volume to vary with changes in compliance and airway resistance.
- Flow is high in the initial phase of inspiration to achieve the set pressure, then decreases in the later phase of inspiration to maintain the set pressure through the inspiratory time.
- Target pressure is adjusted to achieve adequate VT without inducing atelectasis or volume trauma.
- In laparoscopic procedures, if the peak inspiratory pressure (PIP) is high for volume-controlled modes, PCV may offer increased VT at a lower PIP because of the increased flow of gas earlier in the inspiratory phase.
- If there is a concern for high PIP danger, use PCV to limit the pressure in the airway and lungs: LMA use, emphysema, and neonates/infants.
- If there is low compliance use PCV to obtain higher VT: pregnancy, laparoscopic surgery, morbid obesity, ARDS, and leak in the system (uncuffed ET tube, LMA).
- Recommended settings:
  - Pressure limit: approximately 20 cm H\(_2\)O; adjust to adequate VT.
  - RR: 6-12/min.
  - PEEP: 0 cm H\(_2\)O unless there is difficulty oxygenating or if using lower VT settings.

Synchronized Intermittent Mandatory Ventilation (SIMV)\(^7,9,16,23,25,28,29\)

- Volume- or pressure-based mode, typically for weaning from ventilator.
- VCV, which detects spontaneous breaths. Spontaneous breathing is allowed.
- A variation of intermittent mandatory ventilation (see next section).
- Ventilator delivers preset volume-controlled breaths in coordination with respiratory effort of the patient.
- Helps maintain minute ventilation while avoiding breath stacking or bucking. Synchronization of delivery breath to inspiratory effort decreases hazard of midbreath delivery.
- SIMV can provide full support to no support depending on the RR that is set.
- Some ventilators support spontaneous breaths with pressure support ventilation (PSV), resulting in a mode called SIMV-PSV.
- As a weaning mode, it was found to be inferior to spontaneous breathing trials and PSV.
- Compared with assist control (AC), it provides better synchrony and preservation of respiratory muscle function, lower airway pressures, and greater control over the level of support.
- SIMV-PSV.
- SIMV with volume-controlled breaths. Pressure support may be added to assist the patient with any spontaneous breaths.
- SIMV-PC.
- SIMV with pressure-controlled breaths. Pressure support may be added to assist the patient with any spontaneous breaths.

Intermittent Mandatory Ventilation (IMV)\(^25\)

- Volume or pressure-based mode available.
- Critical care ventilator mode.
- Similar to AC in 2 ways: clinician determines minimum MV (RR and VT), and the patient can increase MV. However, IMV differs from AC in how MV is increased. Here, patients increase MV by spontaneously breathing, rather than patient-initiated breaths. With IMV, VT differs per spontaneous breath.
- During pressure-limited IMV or SIMV, the set RR and inspiratory pressure level determine MV. Patient increases MV by initiating own spontaneous breaths.

Pressure Support Ventilation (PSV), Spontaneous Ventilation Mode, Assisted Spontaneous Breathing (ASB), Inspiratory Help System (HIS), PSV-Pro.

- Pressure-based mode.
- Common in anesthesia for emergence or in cases when complete control of breathing is not necessary. In critical care settings, it is implemented as a weaning tool. In both settings, the mode is used to overcome the resistance of the machine, breathing circuit, and endotracheal tube.
- PSV senses the patient’s inspiratory effort and delivers pressure support, resulting in larger VT than the patient would produce alone.
- Used for spontaneously breathing patients and for giving patient control over inspiratory flow rate and RR.
- PSV-Pro: The Pro is an abbreviation for protect. This means that after 10-30 seconds of apnea (adjustable), the mode will revert to PCV or SIMV. In newer machines, if the patient begins breathing again in the backup mode, the ventilator will switch back to PSV-Pro.
- Useful to maintain ETCO\(_2\) and support MV during maintenance or emergence.
- Limits barotrauma and decreases work of breathing.
- Compared with assist control ventilation (ACV), patients demonstrate increased VT, MV, with decreased airway pressures.
- Recommended as adjunct to mechanical ventilation when ACV or SIMV modes are used.
- FiO\(_2\) and PEEP are set by the clinician.
- VT is dictated by the PS given, patient effort, and lung.

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compliance.
• Disadvantages: Each breath must be initiated by the patient, and central apnea may occur related to sedatives, illness, or hypocapnia. \( V_T \) and RR are variable, so MV cannot be guaranteed. Ventilatory asynchrony can occur when PSV is used for full ventilatory support. May prolong duration of MV. In the intensive care unit, PSV is associated with poorer sleep than AC and greater wakefulness. High levels of pressure support \( >20 \) cm H\(_2\)O are needed when used during full ventilatory support to prevent alveolar collapse. This can lead to atelectasis and ventilator-associated lung injury.

Pressure Control With Volume Guarantee (PC-VG)\(^7,10,19\)
• Pressure-based mode, with ventilator operating as PCV. \( V_T \) target is also set.
• Emerging mode on newer anesthesia machines; common in critical care machines
• Ventilator adjusts the PIP, staying within the set maximum pressure (Pmax) to achieve the desired \( V_T \) per breath.
• Advantages: control of PIP through the base PC mode and control of arterial CO\(_2\) through guarantee of \( V_T \), therefore minute ventilation
• An extended configuration for pressure-controlled ventilation modes such as SIMV, AC, CMV, and PSV
• Volume guarantee ensures a set \( V_T \) for all mandatory breaths with the necessary minimum pressure. If resistance or compliance changes, the pressure adapts gradually to administer the set \( V_T \).

Assist Control Ventilation (ACV), Volume Assist Control, Ventilation\(^7,16,23-25,28,29\)
• Typically volume-based mode, but pressure-based mode is also available. Critical care ventilator mode.
• Similar to SIMV-VC or SIMV-PC
• Set breaths with every inspiratory effort the patient initiates. Clinician determines minimum MV by setting RR and \( V_T \). Patient can increase MV by triggering additional breaths. Each patient-initiated breath gets the set \( V_T \) from the ventilator.
• Patient controls initiation of breath and rate. If the patient stops breathing spontaneously, the ventilator goes into backup mode with the preset rate and \( V_T \) until spontaneous inspiratory effort is sensed.
• Volume or pressure target mode provides targeted preset \( V_T \) and minimum RR. If the patient breathes, the ventilator gives set \( V_T \) with that breath.
• AC-volume advantages: Every breath receives a set \( V_T \), respiratory muscle rest.
• AC-volume risks: hyperventilation and muscle atrophy
• AC-pressure advantages: protects fragile lung tissue from overexpansion, and respiratory muscle rest.
• AC-pressure risks: hypoventilation and respiratory muscle atrophy
• Risk of auto-PEEP (breath stacking) with volume-targeted AC modes. Each mechanical breath is delivered at set \( V_T \); if the patient’s RR is high on AC, the patient may not have sufficient time to exhale between breaths, which causes air trapping (auto-PEEP/Intrinsic PEEP).
• Better suited than SIMV for patients who are critically ill and require constant volume or full or nearly maximum ventilatory support
• In pressure-limited AC, the set RR and inspiratory pressure level determine MV. Patient increases MV by triggering additional ventilator-assisted, pressure-limited breaths.

Volume Support Ventilation (VSV)\(^7\)
• Pressure-based mode in critical care ventilators
• A major pitfall of PSV is the lack of guarantee of a minimum \( V_T \).
• In VSV, the ventilator starts with a test breath to determine compliance. It then constantly adjusts the pressure support level (in increments of 3 cm H\(_2\)O) to maintain the required total volume.

Volume-Assured Pressure Support (VAPS)\(^7,29\)
• Pressure-based mode
• The ventilator initially delivers pressure support, continually comparing the inspired volume to the set \( V_T \). If the inspired volume is below target, the pressure-supported component is complemented with constant-flow volume-controlled breaths.

Pressure-Regulated Volume Control (PRVC)\(^7,16,25,29\)
• Pressure-based mode in critical care ventilators; considered the controlled form of VSV
• For patients with rapidly changing pulmonary mechanics
• Has a test breath to determine compliance, then delivers pressure-controlled breaths. The pressure limit is adjusted to maintain \( V_T \) at a preset acceptable level. Like VSV, this is achieved in increments of 3 cm H\(_2\)O.
• Similar to AC. Difference is that ventilator is able to autoregulate the inspiratory time and flow so that \( V_T \) generates a smaller rise in the plateau airway pressure.
• Advantages: Every breath receives a guaranteed \( V_T \). It improves patient-ventilator synchrony. Decreases risk of barotrauma.
• Disadvantages: Respiratory muscle atrophy may occur if in AC mode; there is a potential for unequal ventilation-perfusion distribution.

Proportional Assist Ventilation (PAV)\(^7,20,29\)
• Pressure-based mode in critical care ventilators
• Attempts to combine the patient’s inspiratory drive with the ventilator pressure output. Thus, the higher the patient’s drive, the more pressure the ventilator will generate in that particular breath.
• Flow, volume, and pressure are all proportional to patient effort. The patient is allowed to follow any comfortable breathing pattern with a level of ventilator support that follows that drive.
• The mode has been reported to improve patient-ventilator synchrony and comfort.
• Seeks to optimize the degree of ventilator support delivered according to the patient’s ventilatory drive. It uses rate and volume of gas flow in the inspiratory limb of the ventilator circuit and user-determined gain factors (to account for the elastic and resistive opposing forces) to deliver pressure support in proportion to patient effort. The ventilator support delivered to the patient can be varied in volume assist and flow assist. The support delivered can change on a breath-to-breath basis; introducing patient-controlled variability to the breathing pattern rather than having one imposed by the settings of the ventilator. If the patient generates more respiratory effort, more support will be delivered.
• Initial trials note success of unloading respiratory muscles, and decrease sensation of breathlessness in acute respiratory failure. It successfully allows patients to adapt their breathing
pattern after a hypercapnic stimulus in a manner closer to
normal physiology than those on PSV; minute ventilation is
enhanced in PAV by increasing VT rather than rate.

- Disadvantage: PAV has a requirement to quantify the elastic
and restrictive properties of the lung in each patient before
ventilator settings can be determined. If this is not carried
out and the gain factors overcorrect these properties, a
phenomenon called “runaway” can develop, in which the
ventilator enters a positive feedback loop whereby the
pressure delivered by the ventilator generates sufficient flow
and volume delivery to trigger further increase in pressure.
As lung mechanics are not static, it has been suggested that
for PAV to be effective, continuous monitoring is necessary to
ensure runaway is avoided.

**Airway Pressure Release Ventilation (APRV)**

- Pressure-based mode in critical care ventilators. VT is
determined by driving pressure and compliance.

- A mode of ventilation that uses continuous positive airway
pressure, or CPAP (typically > 20 cm H2O, termed P_high)
with intermittent, time-cycled, transient release of pressure to a lower value (termed P_low).
Spontaneous ventilation is allowed throughout, independent of ventilator cycle. The transition from P_high
to P_low deflates the lungs and eliminates CO2. Alveolar
recruitment is maximized by the high CPAP.

- This mode couples the recruiting effects of CPAP with
superior ventilation/perfusion matching of spontaneous
breathing.

- Studies of APRV have shown favorable results on gas
gas exchange and distribution of ventilation.

- First described in 1987. It combines relatively high levels of
CPAP (typically > 20 cm H2O, termed P_high) with time cycled
“releases” at a lower pressure (usually 0 cm H2O, termed
P_low). Aim to maintain spontaneous breathing at P_high, thus
maintaining diaphragmatic ventilation of more dependent,
better perfused areas of the lung that are not usually well
ventilated during mechanical ventilation

- To aid ventilation and CO2 elimination P_high is briefly released,
typically for < 1 s. Increasing the duration of release (P_low)
risks alveolar derecruitment if long enough to allow the loss of
intrinsic PEEP.

- There are no universal indications for the use of APRV, but it
may be useful in ARDS.

- Contraindications: patients with severe obstructive
airway disease or high ventilator requirements because
hyperinflation, high alveolar pressure, and pulmonary
barotrauma may result

- APRV offers potential advantages over conventional ventilation
modes in terms of alveolar recruitment; good for acute lung
injury and ARDS

- It has not been shown to improve mortality but may decrease
peak airway pressures.

- APRV improves alveolar recruitment, increases ventilation of
the dependent lung zones, and improves oxygenation.

**Adaptive Support Ventilation (ASV)**

- Pressure-based mode in critical care ventilators; a weaning
mode with similar outcomes as SIMV

- Automatic control of respiratory parameters allows smooth
and reliable weaning. ASV is a closed-loop, pressure-controlled
ventilation mode in which the ventilator determines the RR
and VT with the least breathing effort required. When the
patient begins an inspiratory effort, the ventilator switches to
pressure support ventilation. The level of support is constantly
adjusted to the patient’s respiratory activity to attain the
adjusted minute ventilation with favorable breathing pattern
without interference of the physician, nurse, or respiratory
therapist.

- Extubation readiness may not be recognized in a timely
manner in at least 15% of patients recovering from respiratory
failure. ASV helps identify these patients and may improve
their weaning.

**High-Frequency Oscillatory Ventilation (HFOV)**

- Volume-based mode in critical care ventilators

- This mode uses rapid RRs (> 4× normal).

- At high frequencies, VT can be less than dead space. The goal
is to keep the lung in a state of recruitment while maintaining
ventilation (by facilitated diffusion).

- Complications include pneumothorax and acute respiratory
acidosis (if partial ET tube obstruction occurs).

- Considered a rescue mode in hypoxic patients noncompliant
with other methods

- Interest first arose in 1915, but the technology was not
treated until the 1970s in animal models.

- Uses an oscillating piston pump and a bias gas (flow rate)
of 20-40 L/min to generate a ventilator frequency typically
between 180/min and 900/min and a VT typically 1-2 mL/kg
(which is usually less than anatomical dead space)

- The mean pressure (Paw) and FiO2 are adjusted to maintain
oxygenation, and the oscillatory pressure amplitude (ΔP) and
frequency are adjusted to optimize CO2 removal. Alveolar
ventilation occurs predominantly through acceleration of
molecular diffusion.

- The overall effect is that mean pressure (Paw) delivered is
higher than conventional modes of ventilation, maintaining
alveolar recruitment, but plateau pressure can be maintained
below 30 cm H2O and FiO2 often can be reduced.

- Potential disadvantages of HFOV include increased
requirement for sedation and neuromuscular block, noise,
hemodynamic instability (result of increased Paw reducing
intrathoracic venous return), and a need to wean patients
using conventional ventilator modes before extubation.

**Extracorporeal Membrane Oxygenation (ECMO)**

- Critical care specific form of ventilation; not based on alveolar
ventilation-based modes

- First used in the management of respiratory failure in the
1970s and first reported in human use in the 1980s

- The first randomized controlled trial investigating the role
of ECMO in adults with severe adult respiratory failure in
the era of lung protective strategies (CESAR trial) suggests
a significant reduction in death or severe disability in those
using an ECMO management vs controlled ventilation, but
this trial was controversial.

- ECMO is an invasive procedure requiring specific skills and
personnel. Wide-bore cannulae are required to gain the flow
rate necessary to achieve adequate oxygenation (typically
3.5-5 L/min). Thus, it is likely that ECMO in this form will
continue to be provided in specialty centers and remain
outside the use of most critical care settings. Transfer of
oxygen across the membrane is saturation dependent (mixed
venous and membrane inlet being approximately 65%-70%). CO2 is predominantly carried dissolved in blood as
bicarbonate. Transfer of CO\textsubscript{2} across the membrane is partial pressure-dependent. Human CO\textsubscript{2} production is approximately 250 mL/min, so it is conceivable that an efficient system could achieve CO\textsubscript{2} clearance at considerably lower flows than conventional ECMO, thus using a system involving flows and cannulae comparable with renal replacement therapy.

- More recently, a pumpless extracorporeal device (interventional lung assist, or iLA) has been developed, which uses cannulae in the femoral artery and vein, with a very-low-resistance, high-efficiency membrane for gas exchange. It uses relatively small cannulae, and the driving pressure is the arterialvenous pressure difference.

**Neurally Adjusted Ventilator Assist (NAVA)**

- Neural-based critical care ventilator mode
- Pressures and flow changes are traditionally used within the ventilator circuit to initiate a ventilator-supported breath. With this, there is a delay between the initiation of effort by the respiratory muscles and the ventilator delivery of support. NAVA attempts to deter this delay by using a neural stimulus to those muscles as the trigger for ventilator support in a simultaneous fashion with muscle effort. Bipolar electrodes on a nasogastric tube detect electrical activity of the phrenic nerve to the diaphragm.
- Has been used in neonatal and pediatric populations, adults with ARDS, acute respiratory failure postoperatively, and in conjunction with other modes such as ECMO.
- At high NAVA levels, the electrical activity to the diaphragm is minimal. Therefore, pressure delivered is limited. This advantage allows for decreased injuries related to V\textsubscript{T}.
- Presents as having greater patient-ventilator synchrony than PSV and does not have the risk of giving high V\textsubscript{T}.
- Remains relatively new. Studies are needed to demonstrate evidence of better outcomes with NAVA.

PEEP, CPAP, BPAP

- Adjunct or assistive pressure-based modes
- PEEP: level of positive pressure maintained in airways at end expiration
- CPAP: Actual mode. Used with some level of patient spontaneous breathing
- Placement of an ET tube opens the epiglottis and knocks out physiologic PEEP (normal range, 3-8 cm H\textsubscript{2}O). Therefore, 5 cm H\textsubscript{2}O is recommended with PEEP/CPAP to avoid atelectasis.
- In patients with increased shunt fraction and hypoxemia, PEEP improves gas exchange, possibly by the following: stabilizing small airways, increasing lymphatic drainage, decreasing transmural pressure with resultant decrease of net fluid filtration across capillary membrane.
- Chronic obstructive pulmonary disease characterized by dynamic hyperinflation and intrinsic PEEP (PEEPi). External PEEP (PEEPi) counteracts PEEPi on ventilator triggering and may improve the patient’s comfort.
- CPAP: delivery of a continuous level of positive airway pressure
- CPAP is functionally similar to PEEP. Ventilator does not cycle during CPAP, no additional pressure above the level of CPAP is provided, and the patient initiates all breaths.
- CPAP is commonly used in the management of sleep-related breathing disorders, cardiogenic pulmonary edema, and obesity hypoventilation syndrome.
- BPAP: Mode used during noninvasive positive pressure ventilation. Delivers preset inspiratory positive airway pressure (IPAP) and expiratory positive airway pressure (EPAP). V\textsubscript{T} correlates with the difference in IPAP and EPAP. For example, V\textsubscript{T} is greater using an IPAP of 15 cm H\textsubscript{2}O and an EPAP of 5 cm H\textsubscript{2}O (difference of 10 cm H\textsubscript{2}O). Bilevel positive airway pressure, or “BiPAP” is typically often miss-noted as BPAP mode. BiPAP is the name of a portable ventilator manufactured by Philips Respironics; it is just one of many ventilators that can deliver BPAP.

**Inverse Ratio Ventilation (IRV)**

- Adjunct strategy on critical care and anesthesia ventilators
- Not a mode but a strategy employed during volume- or pressure-limited mechanical ventilation
- Inspiratory time exceeds expiratory time during IRV (I:E ratio is inversed), increasing the mean airway pressure and potentially improving oxygenation. When a patient is severely hypoxemic while receiving maximum PEEP and Fi\textsubscript{O\textsubscript{2}}, this setting may be successful as a trial.
- Risks: increases auto-PEEP and its adverse issues: pulmonary barotrauma and hypotension

**Table 3. Ventilator Modes for Anesthesia and Intensive Care Environments**

<table>
<thead>
<tr>
<th>Abbreviations: ARDS, acute respiratory distress syndrome; CESAR, Conventional Ventilation or ECMO for Severe Adult Respiratory Failure; CO\textsubscript{2}, carbon dioxide; ET, endotracheal; ETCO\textsubscript{2}, end-tidal carbon dioxide; LMA, laryngeal mask airway; PEEP, positive end-expiratory pressure; RR, respiratory rate.</th>
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<tbody>
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<td><strong>Table 3 continued from page 397</strong></td>
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<tr>
<td><strong>Risks:</strong> increases auto-PEEP and its adverse issues: pulmonary barotrauma and hypotension</td>
</tr>
</tbody>
</table>

Anesthesia and critical care providers must also be aware of ventilator modes in development that may be on future anesthesia machines. The future of ventilators, especially in long-term settings such as critical care, focuses on NAVA technology, in an attempt to decrease the delay of the brain stimulating breathing and respiratory muscles creating the breath. Ventilators continue to advance in a rapidly changing environment. Each improvement focuses on safety while providing another option in delivering the best form of ventilation based on the patient’s condition and need.
 volume breaths are greater than the preceding volumes inhaled and has not had sufficient time to completely distend the lungs.

- Peak flow rate or peak inspiratory flow: The highest flow or speed set to deliver the tidal volume during inspiration. Higher flow rates mean faster delivery and shorter inspiratory times.

- Inspiratory (I) and expiratory (E) time and I:E ratio: The speed of delivery for inspiration VT. The average adult inspiratory time is 0.7 to 1.0 seconds. The I:E ratio is typically 1:2 or 1:3.

- Peak airway pressures (Paw): Total pressure needed to deliver the tidal volume. It is dependent on airway resistance, lung compliance, and chest wall factors.

- Plateau pressure (Pplat): The pressure needed to distend the lungs.

- Sensitivity or trigger sensitivity: Effort or negative pressure required by the patient to trigger a machine breath. Common minimal effort setting is −1 to −2 cm H₂O.

- Recruitment maneuvers (RM): The intentional process of increasing transpulmonary pressures aimed at opening alveoli. The most common maneuver is to use sustained inflation with a continuous pressure of 40 cm H₂O for up to 60 seconds. RM added to PEEP compared with PEEP alone in the obese patient improved intraoperative PaO₂/Fio₂ ratio and increased respiratory system compliance. It improved intraoperative oxygenation and compliance without adverse effects.

- Intermittent positive-pressure ventilation (IPPV): This term defines both pressure- and volume-controlled ventilation. In pediatric or neonatal care, this term is specific to pressure-controlled ventilation. In anesthesia or critical care environments, the term may be specific to volume-controlled ventilation.

- Breath stacking: Occurs when a patient has already inhaled and has not had sufficient time to completely exhale or exhale greater than or equal to the subsequent mechanical breaths. Essentially the subsequent tidal volume breaths are greater than the preceding volumes of exhalation, causing intrinsic PEEP, barotrauma, and volutrauma.

A sign or symptom of respiratory distress when the ventilator is not appropriately configured to meet the patient’s inspiratory and expiratory demands. The patient’s breathing and the ventilator on not in synchrony.

**REFERENCES**


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