Review Article

Pressure Modes of Invasive Mechanical Ventilation

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Abstract: Pressure modes of invasive mechanical ventilation generate a tidal breath by delivering pressure over time. Pressure control ventilation (PC) is the prototypical pressure mode and is patient- or time-triggered, pressure-limited, and time-cycled. Other pressure modes include pressure support ventilation (PSV), pressure-regulated volume control (PRVC, also known as volume control plus [VC+]), airway pressure release ventilation (APRV), and biphasic ventilation (also known as BiLevel). Despite their complexity, modern ventilators respond to patient effort and respiratory system mechanics in a fairly predictable fashion. No single mode has consistently demonstrated superiority in clinical trials; however, empiric management with a pressure mode may achieve the goals of patient-ventilator synchrony, effective respiratory system support, adequate gas exchange, and limited ventilator-induced lung injury.

Key Words: airway pressure release ventilation, biphasic ventilation, mechanical ventilation, pressure control, pressure-regulated volume control

In a previous review of mechanical ventilation in the *Southern Medical Journal*,[1] we outlined the basic principles of invasive ventilator support including traditional volume-controlled assist-control (AC) and synchronized intermittent mandatory ventilation (SIMV) modes. We reviewed how the mode determines the strategy by which the ventilator starts a breath (termed the trigger), delivers the breath (termed the limit), and terminates the breath (termed the cycle).

Volume-controlled modes are characterized by patient or time triggering, flow limitation, and volume cycling. The ventilator in a routine volume-controlled mode delivers gas at a set flow rate and pattern until the set tidal volume is achieved, at which time the ventilator "cycles off." The patient is then allowed to passively or actively exhale until the airway pressure reaches atmospheric pressure or a set level of positive end-expiratory pressure (PEEP).

In this review, we discuss some of the more commonly used pressure modes of mechanical ventilation including pressure control ventilation (PC), pressure support ventilation (PSV), pressure-regulated volume control (PRVC, also known at volume control plus [VC+]), airway pressure release ventilation (APRV), and biphasic ventilation (also known as BiLevel). Pressure modes, as opposed to volume-controlled modes, generate a tidal breath by delivering pressure over time. These modes employ basic principles of mechanical ventilation and utilize the powerful microprocessor technology included with modern ventilators. While use of pressure modes may improve gas exchange, decrease work of breathing, promote patient-ventilator interaction, and limit ventilator-induced lung injury on a case-by-case basis, selection of a ventilator mode often depends on institutional preference and clinician familiarity.

Pressure Control Ventilation

Pressure control ventilation (PC) is the prototypical pressure mode of mechanical ventilation.[2] In contrast to usual volume-controlled modes, PC requires the clinician to set an

Key Points

- In contrast to volume-controlled modes of invasive mechanical ventilation, pressure modes regulate pressure as the primary parameter used to deliver the tidal breath.
- Pressure control ventilation (PC) mode is the prototypical pressure mode and is patient- or time-triggered, pressure-limited, and time-cycled.
- Pressure-regulated volume control (PRVC) mode, also known as volume-control plus (VC+), responds to changes in patient mechanics by delivering the lowest possible inspiratory pressure that achieves a goal tidal volume.
- Airway pressure release ventilation (APRV) mode and biphasic ventilation (also known as BiLevel) mode effect ventilation by alternating between two levels of positive end-expiratory pressure (PEEP); the response to spontaneous breathing is determined by the ventilator settings and a computerized algorithm.
- With an understanding of how the mechanical ventilator will respond to changes in respiratory system mechanics, careful adjustment of controllable parameters can provide safe and effective mechanical ventilation using nearly any mode.

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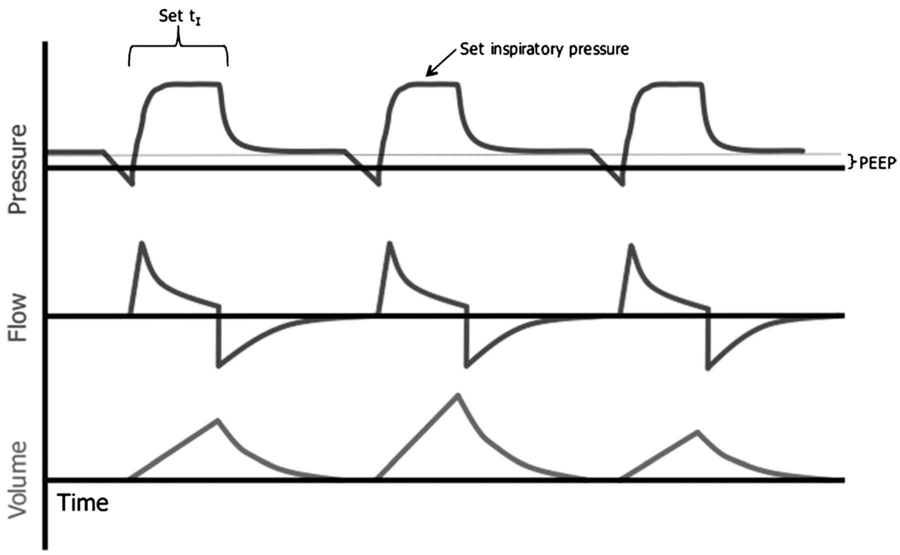

Fig. 1. **Pressure control ventilation (PC) mode. In contrast to volume-controlled modes of mechanical ventilation, the ventilator in PC mode applies a set inspiratory pressure over a set inspiratory time. Thus, PC mode is patient- or time-triggered, pressure-limited, and time-cycled. Tidal volume is variable and depends in part on patient mechanics. t_I, inspiratory time.**

inspiratory pressure and inspiratory time rather than an inspiratory flow rate and tidal volume. Flow is determined by the machine; tidal volume is a consequence of the set pressure, set time, and patient mechanics (resistance and compliance). If the patient is not breathing faster than the set respiratory rate, breaths are initiated by the respiratory cycle time (i.e., time-triggering). For example, if the respiratory rate is set at 12 breaths per minute and the patient does not breathe faster than this rate, then the ventilator will initiate a breath every 5 seconds. If the patient's effort overcomes the set trigger sensitivity and initiates a breath before the cycle time has elapsed (i.e., patient-triggering), then the machine responds by delivering the prescribed inspiratory (or driving) pressure for the designated inspiratory time. The sum of the driving pressure and PEEP is peak inspiratory pressure. The patient is limited to the set inspiratory pressure, and the breath is cycled off when the inspiratory time has elapsed. Thus, PC is patient- or time-triggered, pressure-limited, and time-cycled (Fig. 1). After breath delivery, the patient is allowed to passively or actively exhale until circuit pressure returns to the set level of PEEP.

Peak inspiratory pressure is the sum of airway resistive and respiratory system distension pressures (Fig. 2). Distention pressure is measured as plateau pressure (see below). At the beginning of inspiration, peak inspiratory pressure consists mainly of airway resistive pressure, whereas at the end of inspiration peak inspiratory pressure consists mainly of respiratory system distension pressure. To achieve a constant inspiratory driving pressure the ventilator must use a decelerating flow regime that allows for the fall in airway resistive pressure to mirror the rise in respiratory system distension pressure. Thus, all modes that deliver constant inspiratory pressure are associated with decelerating inspiratory flow.

PC mode can be used to deliver fully supported breaths using an assist-control (AC) or spontaneous intermittent mandatory ventilation (SIMV) strategy. The differences between

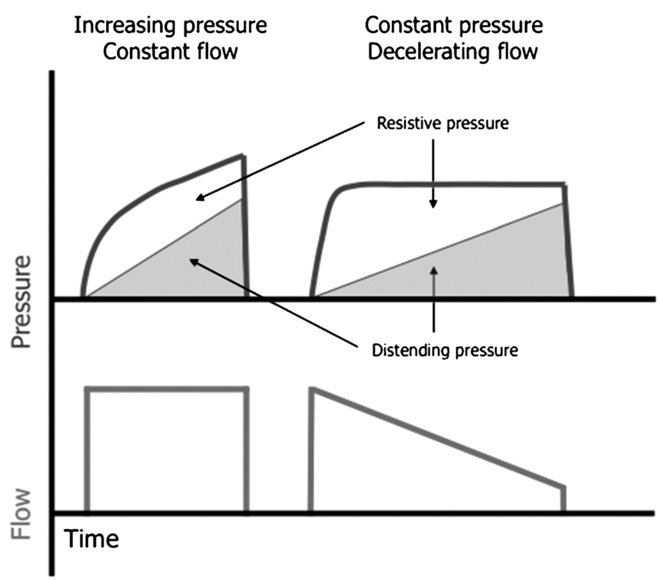

Fig. 2. **Pressure-flow waveforms. The left tracing represents a constant or square flow waveform resulting from increasing pressure during the tidal breath. When pressure is delivered at an increasing rate, resistive pressure remains fairly constant (reflecting constant flow), while distending pressure increases with delivery of the tidal breath. In the tracing on the right, a decelerating or ramp flow waveform results from constant application of pressure. Because pressure is constant, resistive pressure decreases as distending pressure increases. The net effect is decelerating flow during the tidal breath.**

traditional volume-controlled AC or SIMV modes and AC or SIMV delivered with pressure control are 1) the parameter the ventilator uses to generate supported breaths (flow-limitation versus pressure-limitation) and 2) the parameter that terminates the breath (volume-cycling versus time-cycling).[1] In both volume-controlled modes and pressure modes, an AC strategy delivers full ventilator support with every breath.[3] An SIMV strategy delivers a set number of supported breaths per minute; any breaths taken above the set rate may be unsupported or pressure-supported.[4] When SIMV and pressure support ventilation (PSV, discussed below) are combined, it is labeled as a mixed mode of mechanical ventilation.

In patients with acute hypoxemic respiratory failure, changing from a volume-controlled (VC) mode to PC mode may result in lower peak airway pressures.[5,6] However, Munoz and colleagues found airway pressures to be equivalent when PC mode was compared with a VC mode that used a decelerating inspiratory flow pattern with matched inspiratory times, tidal volumes, and PEEP.[7] PC mode appears to be well tolerated hemodynamically.[8] It is important to note, however, that no differences in clinical outcomes have been found when comparing VC modes utilizing decelerating flow and PC mode in adult patients.

To initiate PC mode mechanical ventilation, the clinician or respiratory therapist specifies the settings listed in the Table. The Table also lists the major settings required to prescribe the other modes of mechanical ventilation discussed in this review.

As stated, the resultant tidal volume in PC mode is a consequence of the set pressure, set time, and patient mechanics (resistance and compliance). Mechanics measurements are made by performing an inspiratory hold (inspiratory pause) maneuver during which inspiratory flow is temporarily stopped, but the patient is not allowed to exhale. During the zero-flow time, the measured pressure is the plateau pressure (P_{plat}). Plateau pressure is an estimate of average end-inspiratory alveolar pressure; $P_{plat} < 30$ cm H_2O is generally recommended to avoid ventilator-induced lung injury. Importantly, because of the decelerating flow regime and negligible inspiratory flow at the end of the delivered breath, an inspiratory hold maneuver in PC mode does not allow for measurement of airways resistance. The use of constant flow with a VC mode is recommended for measurement of airways resistance.

Consider the following settings: PC mode with an AC strategy, respiratory rate of 12 breaths per minute, inspiratory driving pressure of 15 cm H_2O, and total PEEP of 5 cm H_2O. Under these conditions, peak inspiratory pressure is 20 cm H_2O. Assuming normal static compliance of the respiratory system (C_{strs}) of 60–80 mL/cm H_2O and a P_{plat} of 15 cm H_2O, tidal volume can be estimated by using the compliance formula:

$$
\begin{aligned}
C_{strs} &= \frac{V_T}{P_{plat} - PEEP_{total}} \\
V_T &= C_{strs}(P_{plat} - PEEP_{total}) \\
V_T &= 60\,mL/cm\,H_2O\,(15\,cm\,H_2O - 5\,cm\,H_2O) \\
V_T &= 600\,mL
\end{aligned}
$$

Table. Major settings required to prescribe selected modes of invasive mechanical ventilation

Mode	Main settings required for use
VC	AC or SIMV
	Respiratory rate
	Tidal volume
	Inspiratory flow rate
	Inspiratory flow pattern
	PEEP
	Fi_{O_2}
PC	AC or SIMV
	Respiratory rate
	Inspiratory driving pressure
	Inspiratory time
	PEEP
	Fi_{O_2}
PSV	Pressure support level
	PEEP
	Fi_{O_2}
PRVC	AC or SIMV
	Respiratory rate
	Goal tidal volume
	Inspiratory time
	PEEP
	Fi_{O_2}
APRV	Respiratory rate
	t_L*
	t_H
	$PEEP_L$
	$PEEP_H$
	Fi_{O_2}
Biphasic ventilation	Respiratory rate
	t_L*
	t_H
	$PEEP_L$
	$PEEP_H$
	Pressure support level
	Fi_{O_2}

**Many ventilators require setting a respiratory rate and t_H in APRV and biphasic ventilation modes. Therefore, t_L is determined implicitly and not set by the practitioner. For example, if the respiratory rate is 10 minute^{-1}, then the total cycle time is 6 seconds (60 seconds · minute^{-1}/10 minute^{-1} = 6 seconds). If t_H is set to 5.5 seconds, then t_L will automatically be 0.5 seconds. These settings thus result in an inspiratory-to-expiratory time (I:E) ratio of 11:1.*
FiO_2, fraction of inspired oxygen. See text for expansion of abbreviations.

If C_{strs} were 20 mL/cm H_2O under the same conditions, V_T would be 200 mL, likely mandating an increase in driving pressure in a normal sized adult. Note that total PEEP ($PEEP_{total}$) is the sum of set PEEP and auto-PEEP, and that tidal volume is inversely related to auto-PEEP. Note also that if inspiratory time is set at 0.6 seconds, then the average inspiratory flow rate is 60 L/minute (1000 mL/second).

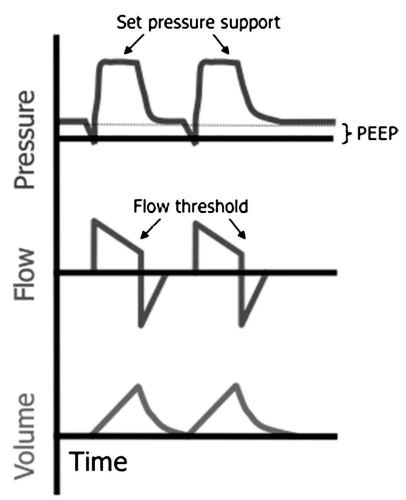

Fig. 3. **Pressure support ventilation mode. After patient effort triggers the ventilator, a set pressure is applied until flow, which is decelerating, reaches a threshold level. The ventilator then cycles off, and the patient passively or actively exhales. Thus, PSV mode is patient-triggered, pressure-limited, and flow-cycled.**

A few cautionary words are warranted regarding PC mode and ventilator adjustments in response to hypercapnia. In general, increasing tidal volume by increasing driving pressure or inspiratory time may increase minute ventilation and thereby lower P_aCO_2. However, if these changes result in auto-PEEP, tidal volume may not increase as expected and indeed may fall. Care must also be taken to avoid over-distension at end inspiration, generally by keeping P_{plat} < 30 cm H_2O.

Pressure Support Ventilation

Pressure support ventilation (PSV) is a spontaneous mode of mechanical ventilation that can be used as a stand-alone mode (Fig. 3) or added to an SIMV strategy (Fig. 4). PSV mode is patient-triggered, pressure-limited, and flow-cycled. With PSV mode, breaths are assisted by a set inspiratory pressure, which is delivered until inspiratory flow drops below a predetermined threshold (see Table). Respiratory rate and tidal volume are not set but rather determined by the patient. During SIMV with PSV mode, pressure support is applied only to spontaneous breaths, thereby increasing tidal volume and helping to overcome the resistance of the endotracheal tube. PSV can also be used as a stand-alone mode to achieve full ventilator support in a spontaneously breathing patient when other modes result in patient-ventilator dyssynchrony. Low levels of pressure support (e.g., 5 cm H_2O) may also be used during spontaneous breathing trials in patients undergoing evaluation for possible extubation.

Pressure-Regulated Volume Control

Traditional volume-controlled modes of mechanical ventilation used with an AC or SIMV strategy limit flow during inspiration, requiring the clinician to set an inspiratory flow rate and pattern that best fits patient demand. Pressure-regulated volume control (PRVC), also known as volume control plus (VC+), is a mode of mechanical ventilation that automatically adjusts inspiratory pressure in response to dynamic changes in patient mechanics. As a patient's respiratory mechanics change

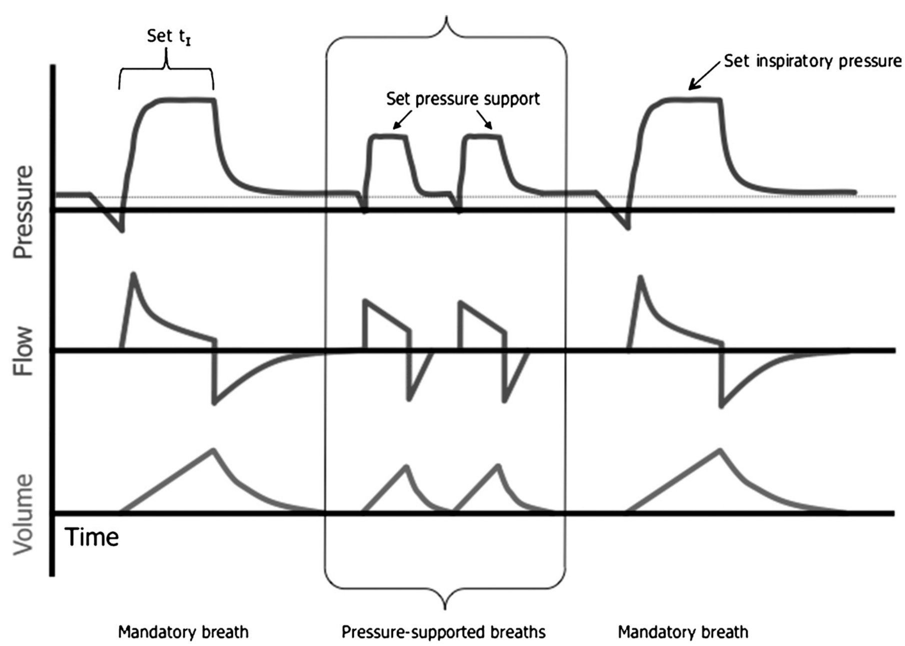

Fig. 4. **Synchronized intermittent mandatory ventilation plus pressure support ventilation (SIMV + PSV) in PC mode. The first and last breath tracings are identical to those seen in standard PC mode: patient- or time-triggered, pressure-limited, and time-cycled. However, spontaneous breaths (bracketed) are pressure-supported and thus patient-triggered, pressure-limited, and flow-cycled. t_I, inspiratory time.**

on a breath-to-breath basis, the ventilator in PRVC mode will adjust the target pressure to achieve the goal tidal volume.

PRVC mode requires the clinician to set a goal tidal volume. However, in contrast to traditional volume-controlled modes, the clinician sets a defined inspiratory time rather than an inspiratory flow rate and pattern (see Table). Consider the following example: if the tidal volume is set at 600 mL and inspiratory time is set at 0.6 seconds, then the average flow (which is determined by the ventilator) will be 60 L/minute or 1000 mL/second. Thus, PRVC is a patient- or time-triggered, pressure-limited, time-cycled mode. Like PC, PRVC mode can be used to deliver fully supported breaths using an assist-control (AC) or spontaneous intermittent mandatory ventilation (SIMV) strategy.

Once these settings are entered, the ventilator will deliver a series of "test breaths" to establish the inspiratory pressure required to deliver the goal tidal volume within the chosen inspiratory time setting. The ventilator subsequently measures tidal volume on a breath-to-breath basis. If a change in respiratory system mechanics or patient effort causes the delivered tidal volume to be below goal, the ventilator will increase the inspiratory pressure on the next breath. Conversely, if the delivered tidal volume becomes too high, the ventilator will decrease the inspiratory pressure. Because inspiratory pressure is constant during each delivered breath, the machine must decelerate inspiratory flow (Fig. 5). Thus, an inspiratory hold maneuver will allow measurement of P_{plat} and C_{strs} but not airways resistance.

When compared to traditional volume-controlled modes, PRVC mode has not been shown to improve clinical outcomes but it may achieve lower airway pressures.[9,10] It is important to note that the resulting airway pressures may not be appropriate for all patients in respiratory failure and that as patient effort increases, less support is required to deliver the breath over the required time parameter.[11] PRVC mode does allow the clinician to set a fixed tidal volume and thereby respect low tidal volume lung protective strategies in patients with acute lung injury and the acute respiratory distress syndrome.

Airway Pressure Release Ventilation

Airway pressure release ventilation (APRV) is a pressure mode of mechanical ventilation that alternates between two levels of PEEP termed low PEEP ($PEEP_L$) and high PEEP ($PEEP_H$).[12–14] The time spent at $PEEP_H$, termed t_H, is generally set to be longer than the time spent at $PEEP_L$, termed t_L (see Table). We initially set $PEEP_H$ between 25–30 cm H_2O and $PEEP_L$ between 0–5 cm H_2O with an immediate assessment of the resultant tidal volume. Tidal volume is determined by the difference between $PEEP_L$ and $PEEP_H$ as well as the patient's mechanics; the practitioner should adjust the difference between $PEEP_L$ and $PEEP_H$ to achieve a tidal volume of 4–6 mL/kg in APRV mode. Ventilation and clearance of carbon dioxide are effected via transitions between $PEEP_H$ and $PEEP_L$. Transitions from $PEEP_L$ to $PEEP_H$ inflate the lungs and recruit alveoli.[13,14] Spontaneous breathing occurs mostly during t_H because the time spent at t_L is short (generally on

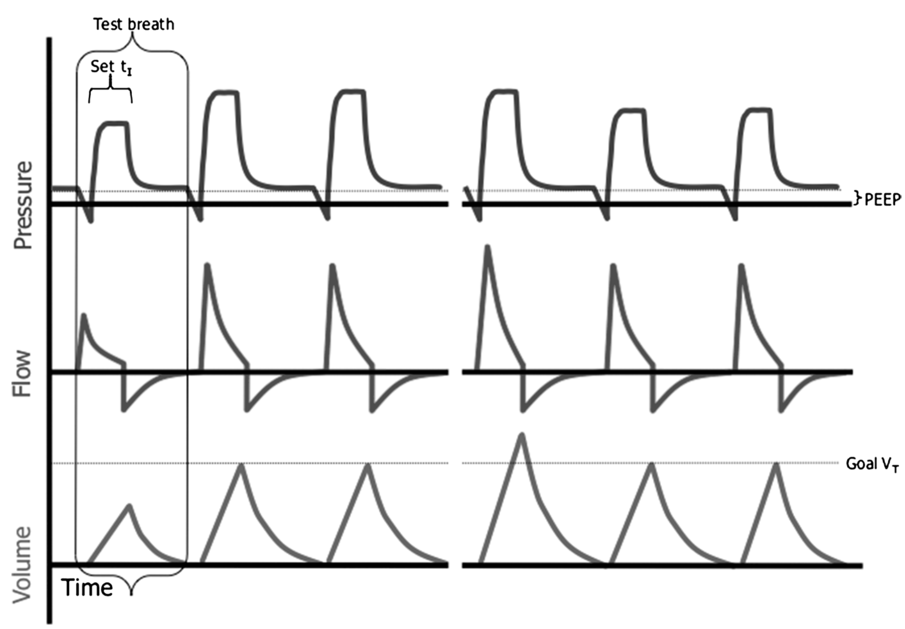

Fig. 5. **Pressure-regulated volume control mode. The ventilator in PRVC mode adjusts inspiratory pressure in response to changes in patient mechanics. Initially, the ventilator delivers a "test breath" to determine the pressure that achieves the goal tidal volume. Because the test breath shown in the tracing did not reach the goal tidal volume, a higher pressure is given in subsequent breaths. Generating higher pressure thus achieves the goal tidal volume. The fourth breath represents a favorable change in patient mechanics or increased inspiratory effort, resulting in an above-goal tidal volume. Note that the ventilator decreases the inspiratory pressure on subsequent breaths and again achieves the goal tidal volume. t_I, inspiratory time; V_T, tidal volume.**

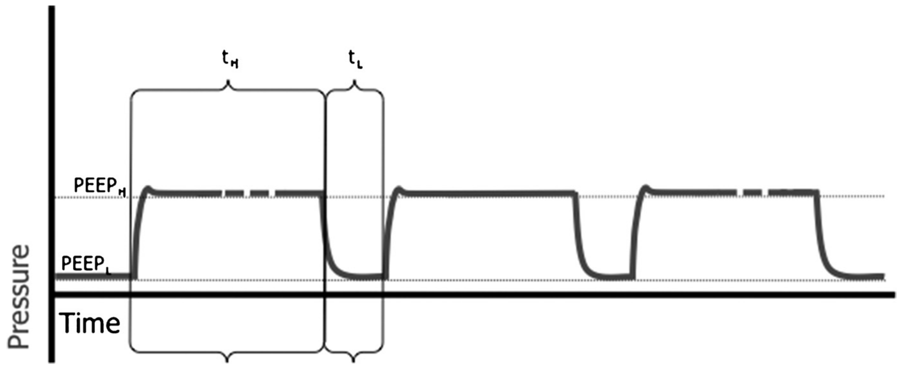

Fig. 6. **Airway pressure release ventilation mode is an inverse ratio mode of mechanical ventilation in which the time spent at high lung pressure ($PEEP_H$) exceeds that spent at low lung pressure ($PEEP_L$). Unsupported spontaneous breathing (dashed lines) is allowed and occurs mainly during t_H because of the short period of time spent at t_L.**

the order of 0.5 to 1 second). Indeed, APRV is an inverse ratio ventilation mode; that is, "inspiration" time is longer than "exhalation" time (Fig. 6).

Increasing the difference between $PEEP_L$ and $PEEP_H$ as well as increasing the number of transitions per minute will increase minute ventilation.[15] Increasing $PEEP_L$ improves oxygenation by preventing alveolar collapse and decreasing intrapulmonary shunt.[16,17]

APRV mode is generally well tolerated hemodynamically[18,19] and may improve oxygenation in patients with acute lung injury and the acute respiratory distress syndrome.[17,20–22] When compared with PC mode, APRV mode may shorten the duration of mechanical ventilation, intensive care unit length-of-stay, and utilization of sedation and pharmacologic paralysis.[23]

Minute ventilation may be highly variable in APRV mode. Close monitoring of patients ventilated with APRV mode is required to avoid extremes of P_aCO_2. Lung hyperinflation may cause barotrauma in patients with obstructive lung disease; therefore, severe obstruction is considered a relative contraindication to APRV mode.

Biphasic Ventilation

Biphasic ventilation mode, also known as BiLevel mode, is an advanced version of APRV mode in which mandatory breaths are pressure-controlled and spontaneous breaths may be pressure-supported.[24,25] Biphasic ventilation mode is similar to SIMV mode with pressure support for the spontaneous breaths. The exception is that biphasic ventilation mode alternates between $PEEP_L$ and $PEEP_H$ (Fig. 7). Recommendations for initial pressure settings are similar to those for APRV mode. Compared with APRV mode, t_L is generally longer, which allows for more spontaneous pressure-supported breaths during t_L.

The clinician determines the durations of $PEEP_L$ and $PEEP_H$ by setting the time desired at each level (see Table). These durations, again termed t_L and t_H, can vary in length to align with the patient's respiratory efforts. The ventilator accomplishes transitions between the two levels of PEEP by partitioning t_L and t_H into a spontaneous interval and a synchronous interval (Fig. 8).

The ventilator in biphasic ventilation mode will respond to patient effort in a predictable pattern. During the spontaneous interval of t_H, spontaneous breaths are allowed but not supported unless the sum of $PEEP_L$ and pressure support (PS) is greater than $PEEP_H$, in which case the spontaneous breaths at $PEEP_H$ are supported by the pressure difference between $PEEP_L + PS - PEEP_H$. As the synchronous interval of t_H begins, patient effort will trigger a transition to $PEEP_L$ and the

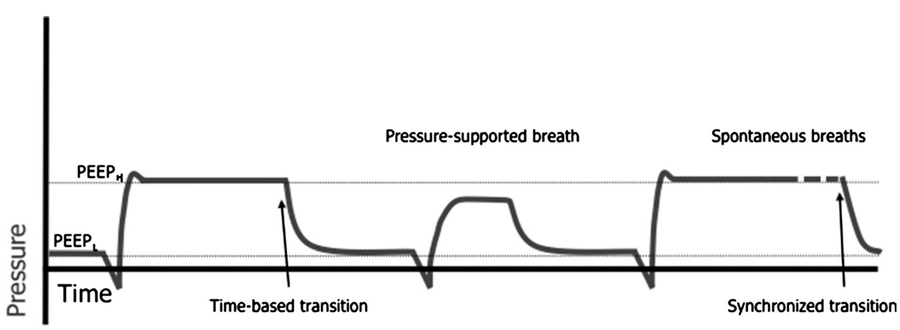

Fig. 7. **Biphasic ventilation mode. After selecting biphasic ventilation mode, 2 different levels of PEEP ($PEEP_L$ and $PEEP_H$) are chosen. Spontaneous breaths may be taken during the time when $PEEP_H$ is applied (dashed lines); pressure-supported breaths are given during the time when $PEEP_L$ is applied. The transition between the 2 levels of PEEP may be after a set time interval or synchronized with patient effort.**

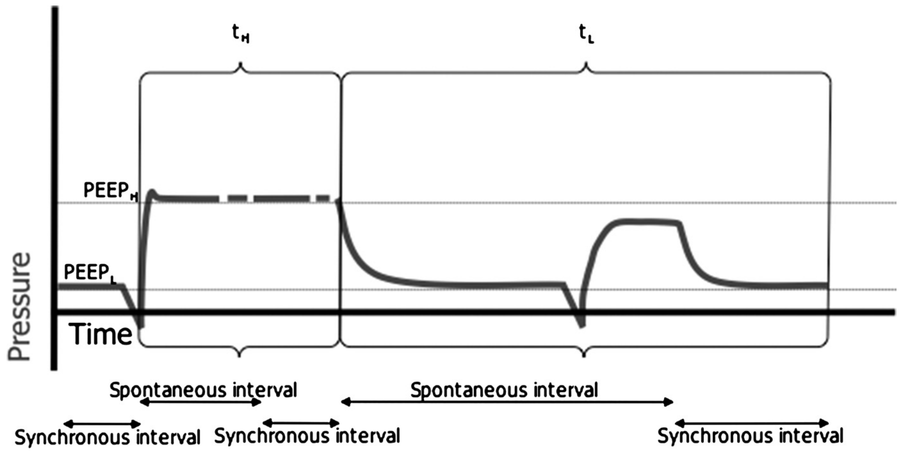

Fig. 8. **Interval partitioning in biphasic ventilation mode. Two time intervals—t_H and t_L—determine the length of time spent at $PEEP_H$ and $PEEP_L$, respectively. In addition, the ventilator partitions t_H and t_L into a spontaneous and synchronous interval. During the spontaneous interval of t_H, patient effort results in unsupported breaths (first dashed line). However, patient effort during the synchronous interval of t_H (second dashed line) results in a transition from $PEEP_H$ to $PEEP_L$. During the spontaneous interval of t_L, patient effort triggers pressure-supported breaths. Patient effort during the synchronous interval of t_L results in a transition from $PEEP_L$ to $PEEP_H$ as shown in the first breath of the tracing.**

start of t_L; if there is no patient effort by the end of t_H, the ventilator will automatically transition to $PEEP_L$ after the set t_H has elapsed. During the spontaneous interval of t_L, breaths are pressure-supported. However, during the synchronous interval of t_L an inspiratory effort will cause the ventilator to cycle from $PEEP_L$ back to $PEEP_H$. If there is no patient inspiratory effort, the ventilator will automatically transition back to $PEEP_H$ at the end of t_L.

Comparison of Modes

No single mode of mechanical ventilation has consistently demonstrated superior clinical outcomes when compared

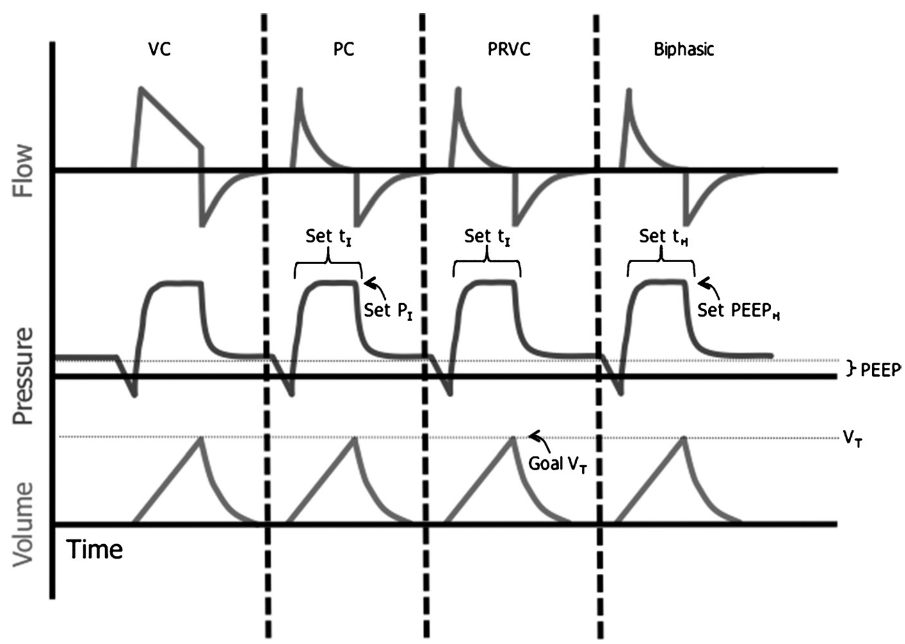

Fig. 9. **Waveform comparison of selected modes. In an individual patient, identical pressure and volume tracings can be achieved in most modes of mechanical ventilation. In a traditional volume-controlled (VC) mode using a decelerating waveform, a square pressure wave is often generated. A similar square pressure wave can be achieved in pressure modes including PC mode (second tracing) by setting the inspiratory pressure (P_I) and time (t_I) to match those of the first tracing. The third tracing shows the how the same pressure waveform can be generated in PRVC mode by setting the inspiratory time (t_I) and goal tidal volume (V_T). Likewise, manipulating the high-PEEP level ($PEEP_H$) and high-PEEP time (t_H) in biphasic mode will generate a pressure waveform (fourth tracing) that replicates the others.**

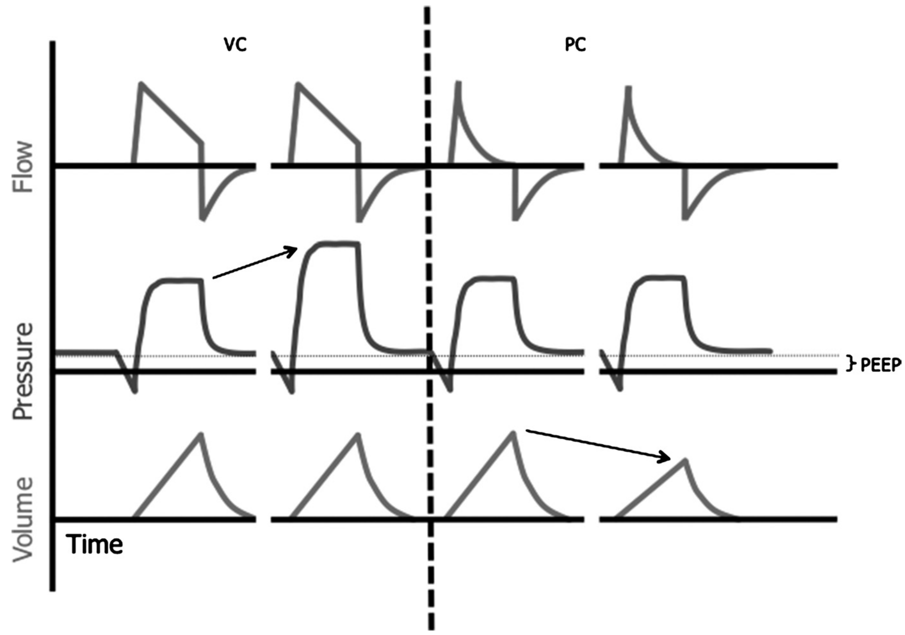

Fig. 10. **Responses to changes in respiratory system compliance. When faced with a decrease in respiratory system compliance, the ventilator in a volume-controlled mode will continue to deliver a set tidal volume at the expense of increased pressure (first and second tracings). Pressure modes such as PC maintain a set inspiratory pressure, which results in a decreased tidal volume as compliance decreases (third and fourth tracings).**

head-to-head,[2] although rigorous comparative effectiveness studies are lacking. Careful manipulation of the controllable parameters in any mode can generally achieve the goals of safe and synchronous respiratory system support in an appropriately sedated patient. Indeed, by applying the concepts outlined in this review, pressure and volume waveforms can be made almost identical using select volume or pressure modes (Fig. 9).

Appropriate management presupposes an understanding of how the ventilator will respond to changes in respiratory system mechanics (Fig. 10). Volume-controlled modes guarantee a set tidal volume on all fully supported breaths. A decrease in respiratory system compliance will cause an increase in circuit pressure that maintains the set tidal volume. In contrast, pressure modes such as PC, APRV, and biphasic ventilation modes guarantee an inspiratory pressure given over a set inspiratory time. The resultant tidal volume is determined by the patient's respiratory system mechanics and effort. Therefore, a decrease in compliance will cause a drop in tidal volume. As described earlier, the ventilator in PRVC mode will respond in a predictable fashion to changes in respiratory system compliance (see Fig. 5).

Conclusion

The main goals of invasive mechanical ventilation are adequate gas exchange and patient-ventilator synchrony while avoiding ventilator-induced lung injury and minimizing, but not eliminating, work of breathing. Although pressure modes may achieve these goals for a given patient, it is premature to conclude that any mode is superior in terms of clinical outcomes. However, on a case-by-case basis, an empiric trial of a mode may provide effective and safe mechanical ventilation.

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