CHAPTER 104

Invasive Ventilatory Support Modes

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INTRODUCTION

Mechanical ventilation (MV) facilitates gas exchange by substituting, in full or in part, for the action of the respiratory muscles. MV can be provided by applying positive pressure to the proximal airway (positive pressure ventilation [PPV]) or negative pressure ventilation (NPV) to the chest wall. PPV is by far the most commonly used for acute respiratory failure, and is delivered either through an endotracheal or a tracheostomy tube (invasive ventilation), or through a face mask or similar interface applied to the upper airway (noninvasive ventilation, see Chapter 103). This chapter focuses on invasive ventilator modes; many of the principles herein illustrated can be applied to noninvasive MV as well.

PHYSICS OF VENTILATION

During spontaneous breathing, air flows into the lungs as the result of negative intrathoracic pressure generated by the respiratory muscles (PMUS). Exhalation occurs passively due to the elastic recoil pressure accrued during inspiration. PMUS is opposed by the resistance to gas flow imposed by the airways (RAW) and by the static elastance (E, stiffness) of the lungs and chest wall (1):

\[ \text{PMUS} = \text{PR} + \text{PE} \]  

where PR is the pressure required to overcome RAW and PE the pressure required to overcome E. During PPV, the driving pressure for air to flow is applied by the ventilator (PVENT) and, in certain modes, by the patient (PMUS) as well:

\[ \text{PAPPL} = \text{PMUS} + \text{PVENT} = \text{PR} + \text{PE} \]  

where PAPPL is the total pressure applied, either by the respiratory muscles (PMUS), the ventilator (PVENT), or both. PR is determined by the flow rate of gas (Vf) and the RAW:

\[ \text{PR} = \text{Vf} \times \text{RAW} \]  

VT and Vf are very closely related functions: Vf is the time derivative of VT, and volume is the time-integral of Vf, such that we only need to speak about pressure control and volume control.

This relatively simple mathematical model has two valuable practical implications: (a) it allows measurement of the patient’s respiratory mechanics at the bedside; and (b) it can be used to predict the independent variable, for example, airway pressure (PAW), for a given value of the set variable (“control”), for example, the VT (2). The first function is widely implemented in modern ventilators: we know the set variable, for example, Vf, and the ventilator measures the resulting variable, that is, PAW:

\[ \frac{\text{C}}{\text{Vf}} = \text{PAPPL} = \text{PMUS} + \text{PVENT} \]  

The second function forms the basis of the ventilator-control model used in the modern classifications of ventilatory modes (2). The equation shows that for any mode of ventilation only one variable (PAW or Vf) can be controlled at one time, that is, on volume-control ventilation (VCV) Vf is fixed, so we cannot fix the pressure. VT and Vf are very closely related functions: Vf is the time derivative of VT, and volume is the time-integral of Vf, such that we only need to speak about pressure control and volume control.

DESCRIPTION OF A VENTILATOR BREATH

There are three principal components of a ventilator breath: how inspiration begins (trigger), what limits the size of the breath (limit), and how inspiration ends (cycle).

The Trigger

Breaths are triggered either by the patient or by the ventilator (3). If the ventilator initiates the breath, the trigger is time, that is, the operator sets a respiratory rate, and the ventilator will deliver the breath at time intervals to achieve that rate. If the breath is initiated by the patient, inspiration starts when the ventilator detects a pressure or flow change at the airway (pressure trigger and flow trigger), or an electrical signal from diaphragmatic activity in neurally adjusted ventilatory assist (NAVA, later in this chapter).

With pressure trigger (Fig. 104.1) the ventilator senses a decrease of PAW relative to end-expiration, that is, 0 cm H2O or positive end-expiratory pressure (PEEP). A preset decrease of PAW, generally 0.5 to 2 cm H2O, will result in closure of the expiratory valve, opening of the inspiratory valve, and delivery of gas to the airway. With flow trigger, the ventilator...
senses a change in flow relative to a baseline continuous low flow (bias flow) of gas through the ventilator circuit that most ventilators use in conjunction with flow triggering. A decrease in this bias flow, generally 1 to 3 L/min, will result in initiation of the inspiratory phase. In the special case of NAVA, an electrode array mounted on a special nasogastric feeding tube senses the change in electrical activity of the diaphragm. The change in PAW, V, or electrical signal that triggers inspiration is usually caused by the contraction of the respiratory muscles, but can result from artifacts such as transmission of cardiac oscillations (4), air leaks in the system, or movement of the circuit from water condensate.

In modern ventilators, both flow and pressure triggers are very sensitive (5), and if the trigger sensitivity is set correctly, both modalities are clinically effective (6). If trigger sensitivity is diminished by incorrect setting, failure to trigger spontaneous breaths may increase effort and tax the patient’s reserve. Failure to trigger is often generated by a physiologic problem such as auto-PEEP (7) or respiratory muscle weakness, and requires attention by the clinician to be detected and corrected.

The Limit

The limit variable determines the size of the breath. This is the independent or control variable—that is, the variable set and controlled by the ventilator. Within limits set by alarms and safety mechanisms, this variable is applied independently of the patient’s respiratory mechanics or inspiratory effort. When volume is the preset variable (VCV), the V̇ and V̄ are set and the PAW can vary. When pressure is the preset limit variable (pressure-control ventilation [PCV]) and pressure support ventilation [PSV]), the PAW is set, and V̇ and V̄ are variable.

The Cycle

The cycle variable is what ends the breath. This can be V̄, P̄, or time. In older ventilators, inspiration was volume-cycled when the volume was delivered from a bellows (Puritan-Bennett MA-1) or piston (Emerson Post-Operative). In modern ventilators, time is the cycle criteria with both VCV and PCV. With PSV, the cycle is usually flow: inspiration ends when the flow rate reaches a fraction of the peak flow. During VCV or PCV, pressure cycle is an alarm condition that avoids application of unsafe high pressure to the airway.

MODES OF VENTILATION

Organization

A mode of ventilation describes the pattern of breathing delivered with a ventilator. Unfortunately, a disproportionate number of proprietary designations exist for a relatively simple structure that is best explained by the equation of motion of the respiratory system Eqs. (6 through 8). That is, (a) for any mode of ventilation only one variable is controlled at one time; even in dual modes, where both pressure and volume may be targeted, this occurs in separate phases of the mechanical breath; and, (b) the result of what is set on the ventilator dependent on the setting itself and the patient’s mechanics, that is, compliance, resistance, and spontaneous effort. The updated classification of ventilator modes describes three basic components: the control variable, the breath sequence, and the targeting scheme (Fig. 104.2). The control variable is what limits the breath, and is discussed in the previous section. Hence, with VCV the PAW varies, and with PCV, the V̄ varies.

The possible breath sequences are continuous mandatory ventilation (CMV), continuous spontaneous ventilation (CSV), and intermittent mandatory ventilation (IMV). With CMV (also assist/control ventilation [ACV]), every breath is a mandatory breath type, whether initiated from the ventilator or from the patient. With CSV, every breath is a spontaneous breath type. With IMV, spontaneous breathing is allowed between mandatory breaths, so that there will be a mix of mandatory and spontaneous breaths. With CMV or IMV, a minimum rate is set on the ventilator, and the patient can trigger at a more rapid rate. With CSV, there is no set rate other than the alarm parameter (for minute volume or breaths per minute or both) set on the ventilator.

The targeting schemes represent the predetermined goals of ventilator output. The set-point scheme includes most of the traditional modes such as VCV, PCV, and PSV. More complex schemes such as servo and adaptive include proportional assist ventilation (PAV) and volume support (VS) respectively.
A complete description of the targeting schemes is available in Table 104.1.

**Continuous Mandatory Ventilation**

With CMV (also called Assist/Control, A/C) the ventilator supplies full support of the patient’s effort. Disadvantages are the possibilities of hyperventilation and of asynchrony. Hyperventilation (the patient always receives the full breath, even when triggering at a high frequency) is uncommon, because the minute ventilation (VE) is rapidly blunted by the decrease in PaCO₂ that follows hyperventilation (8). Asynchrony occurs more frequently, particularly when the level of support is insufficient (see Chapter 105). CMV A/C can be delivered in both volume- and pressure-control modes.

**Volume-Control Ventilation**

With VCV, the ventilator controls the inspiratory flow and time to deliver the resultant V̅ₜ. In some cases (e.g., Draeger ventilators) V̅ₜ, V̅, and Tᵢ (inspiratory time) are each set. In this case, an inspiratory breath hold occurs if the set inspiratory time is greater than that required to deliver the VT at the selected V̅. For example, for a V̅ of 0.5 L, inspiratory flow of 60 L/min, and inspiratory time 1 second, a 0.5 second breath hold will result. On other ventilators (e.g., Puritan-Bennett 840) an inspiratory hold is set separately.

For VCV, Vₚ, and Tᵢ are the independent variables, and Pₐw is the dependent variable, as dictated by the equation of motion of the respiratory system Eq. (6), (9,10). Hence, during VCV, the inspiratory pressure applied by the ventilator will increase with a higher Vₚ, higher V̅, lower C, and higher RAW. Because V̅ is fixed, a vigorous inspiratory effort will lower the inspiratory pressure, creating asynchrony (9). This can be observed by inspecting the airway pressure waveform (see Chapter 105). In patients with acute respiratory failure, who may have a high respiratory drive, V̅ should be carefully set to meet the patient’s demand in order to avoid asynchrony and increased WOB (11).

Volume-control breaths are generally delivered with a constant inspiratory flow waveform, or square wave. On most ventilators, the inspiratory flow can also be set to a descending ramp waveform. With such a flow pattern, the preset peak inspiratory flow is reached early during the breath, after which flow decreases in a linear fashion, reaching a low level at end inspiration (Fig. 104.3). Given the low inspiratory flow at end inspiration, the peak inspiratory pressure (PIP) is lower and approaches the plateau pressure (PPLAT). Note that, in order to accommodate the lower flow and deliver the same VT, the inspiratory time will be longer for a descending ramp than

<table>
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<th>Targeting Scheme</th>
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<tr>
<td>Set point</td>
<td>The ventilator will provide an output that matches a target parameter (e.g., pressure limit, V̅, inspiratory flow) set by the operator.</td>
<td>ACV, VCV, SIMV, PCV, BILevel, PSV</td>
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<tr>
<td>Dual</td>
<td>The ventilator can switch between pressure and volume signal to control the breath size in an attempt to guarantee minute ventilation.</td>
<td>Volume assured PSV, CMV with pressure limited</td>
</tr>
<tr>
<td>Servo</td>
<td>The ventilator output automatically follows a varying input (e.g., lung mechanics, diaphragmatic activity, airway resistance).</td>
<td>ATC, PAV, NAVA</td>
</tr>
<tr>
<td>Adaptive</td>
<td>One target of the ventilator is automatically adjusted to achieve another target as the patient’s condition changes.</td>
<td>Autoflow, PRVC, VS</td>
</tr>
<tr>
<td>Optimal</td>
<td>One target of the ventilator is automatically adjusted to optimize another target (using ventilatory mechanics measurements) to minimize the work of breathing.</td>
<td>ASV</td>
</tr>
<tr>
<td>Intelligent</td>
<td>Ventilator’s targets are automatically adjusted according to an artificial rule-based expert system.</td>
<td>SmartCare®</td>
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*ACV, assisted control ventilation; VCV, volume-controlled ventilation; SIMV, synchronized intermittent mandatory ventilation; PCV, pressure-controlled ventilation; PSV, pressure support ventilation; CMV, continuous mandatory ventilation; ATC, automatic tube compensation; PAV, proportionally assist ventilation; NAVA, neurally adjusted ventilatory assist; PRVC, pressure-regulated volume control; VS, volume support; ASV, adaptive support ventilation. (Adapted from Chatburn R. Classification of ventilator modes: update and proposal for implementation. Respir Care. 2007;53(3):323.)*
for a constant flow waveform. The longer inspiratory time may result in better oxygenation, but the effect is modest. The longer inspiratory time may also increase the risk or air trapping (auto-PEEP) and hemodynamic compromise.

The main advantage of VCV is the ability to control the \( V_T \). This may be important when the \( P_\text{aCO}_2 \) must be closely controlled, such as in patients with traumatic brain injury, or when a low \( V_T \) is desired as part of a lung-protective ventilation strategy (12,13). Limitations of VCV are related to the fixed \( V_T \) and inspiratory flow pattern. This can result in asynchrony in actively breathing patients if efforts are not made to set the inspiratory flow appropriately or to provide adequate sedation (14). With VCV, a high PIP may occur with changes in lung mechanics. However, this only increases the risk of lung injury if the high PIP is associated with an increase in plateau pressure \( (P_{\text{plat}}) \). Accordingly, it is important to monitor \( P_{\text{plat}} \) regularly when VCV is used.

### Pressure-Controlled Ventilation

With PCV, inspiratory pressure and time are set on the ventilator. In some cases (e.g., Draeger ventilators), the set pressure is the total inspiratory pressure, but more commonly it is the pressure above PEEP. For PCV, inspiratory pressure and time are the independent variables. The dependent variables are inspiratory \( V \) and \( V_T \), as dictated by the equation of motion of the respiratory system Eq. (6). Hence, during PCV, inspiratory \( V \) and \( V_T \) will increase with a higher set inspiratory pressure, higher \( C \), and lower \( R_{\text{aw}} \). Also, \( V \) and \( V_T \) will increase if the patient generates a vigorous inspiratory effort (i.e., high \( P_{\text{air}} \)). Compared to VCV, this may improve patient-ventilator synchrony (15) but with an increased risk of overdistention lung injury (ventilator-induced lung injury, VILI).

During PCV, the inspiratory flow waveform is a descending ramp (Fig. 104.4). After triggering, the ventilator delivers gas to the airway at a rate dependent on the capability of the ventilator, respiratory mechanics, and patient effort. The set pressure is applied to the airway until the set time is reached. The slope of the descending portion of the inspiratory flow waveform will also depend on the lung mechanics (Fig. 104.5). The initial flow is high, flow descent rapid, and the resulting tidal volume (area under the curve of the flow trace) is unchanged.
flow pattern may improve patient–ventilator synchrony during active breathing efforts (15). It seems that in patients receiving small VT during lung-protective strategy, a variable-flow, pressure-targeted breath improves breathing effort compared to a fixed, volume-targeted breath (17).

The square pressure waveform of PCV (and of VCV with a descending ramp flow waveform) produces a higher mean airway pressure than constant flow VCV because the target pressure is reached rapidly and remains at that level throughout the breath (see Figs. 104.3 and 104.4); this may produce better alveolar recruitment for the same end-inspiratory airway pressure (18). Also, the low end-inspiratory flow with PCV may improve the distribution of ventilation, which may increase PaO₂ and decrease PCO₂, but the effect is usually modest (19).

A limitation of PCV is the inability to guarantee a VT and a stable PaCO₂. With PCV, changes in respiratory mechanics can result in hypoventilation. In particular, PCV can cause hypoventilation in the presence of dynamic hyperinflation and auto-PEEP. For example, if the inspiratory pressure is set at 15 cm H₂O and the PEEP is zero, the driving pressure is 15 cm H₂O. If the patient develops dynamic hyperinflation and auto-PEEP of 10 cm H₂O, the driving pressure is 5 cm H₂O, with consequent hypoventilation. With VCV, this will not occur because the set VT is delivered regardless of the level of auto-PEEP, albeit with a higher PIP and Pplat.

The selection of PCV or VCV is based chiefly on individual preference. If VT, Ppl, and transpulmonary distending pressure (see Chapter 105) are carefully monitored, either PCV or VCV can be used safely and effectively. Moreover current data from RCTs are insufficient to confirm or refute whether PCV or VCV offers any advantage for patients with acute respiratory failure due to ARDS (20).

Adaptive Pressure Control. Adaptive pressure control allows the ventilator to control pressure based on a volume feedback loop. Because the ventilator controls either pressure or volume, but not both at the same time, there is no divergence from the law of motion of the respiratory system Eq. (6). With adaptive pressure control, the ventilator delivers PCV and adjusts the pressure control in the attempt to keep VT constant.

**FIGURE 104.5** Effect of changes in respiratory mechanics on gas flow and tidal volume (VT) during pressure-control ventilation, obtained in a lung model. The left panel was obtained by setting a low compliance: 20 ml/cm H₂O, and normal resistance; the resulting VT (the area under the flow curve) was 400 ml. The right panel was obtained by setting a high airway resistance: 20 cm H₂O/L/sec and normal compliance; the VT volume was 775 ml. The inspiratory time was 1.5 seconds in both cases; note that with a low compliance (left) the inspiratory flow ends well in advance of the end of the breath, and with a high resistance flow is "cut" by the set inspiratory time, thus limiting the size of the VT.

**FIGURE 104.6** Flow and pressure waveforms obtained at increasing rise times of inspiratory flow at a pressure support of 20 cm H₂O. The fastest flow delivery (left) results in a rapid reach of the set pressure, thus favoring synchrony for high demand breaths. The slowest delivery (right) may be more comfortable during quiet, unstressed breathing. (Adapted from Gibbons FK, Hess DR. Mechanical ventilation. In: Bigatello LM, ed. Critical Care Handbook of the Massachusetts General Hospital. 4th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2006.)
Pressure-regulated volume control (PRVC) (21–27) (Maquet, CareFusion), AutoFlow (Draeger), VC+ (Puritan-Bennett), PCV-Volume Guaranteed (PCV-VG, GE), Adaptive pressure ventilation (Hamilton, Galileo) are trade names of gas delivery that function in a similar manner. Each mode increases or decreases the pressure breath-to-breath by no more than 3 cm H₂O per breath to deliver the desired VT. The pressure limit fluctuates between PEEP and 5 cm H₂O below the upper pressure alarm setting, as illustrated by the example in Figure 104.7. An alarm occurs if the VT and maximum pressure settings are incompatible. The proposed advantage of dual control is the ability of the ventilator to meet patient demand (an advantage of PCV) while maintaining a constant VE (an advantage of VCV). However, the VT and transpulmonary distending pressure during PRVC can potentially exceed safe limits, as illustrated by the example in Figure 104.8 (24). This is of particular concern if these modes are utilized to limit the size of the VT to avoid VILI, suggesting that these modes

**Figure 104.7** Adaptive pressure control with a set tidal volume of 600 mL. Left: effects of an increase in lung compliance. The first four breaths are at steady state; with the fifth and sixth breaths the tidal volume (VT) is higher due to an increase in compliance as indicated by the steady airway pressure (Paw). From the sixth breath, Paw starts decreasing, and the original VT is restored. Right panel: effects of a decrease in lung compliance. The first four breaths are at steady state; with the fifth breath the VT is lower due to a decrease in compliance as indicated by a steady Paw. From the sixth breath the Paw is increasing, and the original VT is restored. (Adapted from Branson RD, Johannigman JA. The role of ventilator graphics when setting dual-control modes. Respir Care. 2005;50:187, with permission.)

**Figure 104.8** Airway pressure (Paw), flow, and volume waveforms demonstrating the response of a dual-control algorithm over a 2-minute period with varying patient effort. The tidal volume varies above and below the target (500 mL) by as much as 150 mL. (From Branson RD, Johannigman JA. The role of ventilator graphics when setting dual-control modes. Respir Care. 2005;50:187, with permission.)
may not be as safe as traditional VCV when used as part of a lung-protective ventilation strategy. Moreover, if patient effort increases, the level of support decreases, which could result in asynchrony and discomfort (28). Additionally, as the pressure level is reduced, mean airway pressure will fall, potentially resulting in a fall in PaO₂. Because this mode depends on the measured V̇_{\text{T}}, any errors in measurement will also result in decision errors.

**Pressure Control Inverse Ratio Ventilation.** With PCIRV the T_{\text{i}} is set longer than the expiratory time T_{\text{e}}. The result is a higher mean airway pressure (see Chapter 105) and enhanced lung recruitment, but also a higher potential for air trapping and hemodynamic compromise. In the past, this ventilatory strategy was used with the rationale that it improves lung recruitment (e.g., ARDS) (29,30). However, this approach likely results in little additional alveolar recruitment unless auto-PEEP results from the short expiratory time.

**BiLevel Positive Airway Pressure (BiLevel) Ventilation and Airway Pressure Release Ventilation.** Current-generation expiratory valves that are used with PCV allow the delivery of additional inspiratory flow if the P_{aw} decreases below the set value, thereby permitting spontaneous breathing during the inspiratory phase of the ventilator. This happens with modes of ventilation such as BiLevel and APRV (31,32). Ambiguity exists in the nomenclature of these modes (7), in part because of proprietary technology used by different manufacturers. For example, BiLevel (Covidien), Biphasic (CareFusion), BiVent (Maquet), and BiPAP and APRV by Draeger and GE. For clarity, in this section we will use the terms BiLevel and APRV.

During fully controlled ventilation, BiLevel is identical to PCV, and APRV is BiLevel with extreme inverse I:E ratio. The patient can breathe spontaneously at the two set levels of pressure (P-high and P-low; Fig. 104.9). P-high is equivalent to a continuous positive airway pressure (CPAP) level that is held for a set time (T-high). The CPAP phase is intermittently released to a set P-low level (CPAP at a lower pressure) generally of brief duration (T-low), and the high CPAP is then reestablished. Spontaneous breathing may be superimposed at both pressure levels, and is independent of time cycling. Spontaneous breathing can be supported with PSV. With APRV, the set duration of P-high is extreme, and the short time at P-low is intended to deliver a mandatory breath in reverse from a traditional positive pressure breath. The minute ventilation during both these modes results from the amount of spontaneous breathing, the difference between the two pressure levels, and the frequency at which the pressure is released to the lower level. The P-high level is the main determinant of arterial oxygenation, but the additional spontaneous breaths may further improve gas exchange by preferentially recruiting the dependent lung regions (33,34). The duration of T-low is set sufficiently short to interrupt expiratory flow and maintain alveolar recruitment due to air trapping.

The potential advantage of these modes is lung recruitment and improved oxygenation at a relatively low airway pressure (the P-high) and possibly higher mean airway pressure. In addition, maintaining spontaneous breathing provides further recruitment to lung segments adjacent to the diaphragm, and may decrease the need for sedation. On the other hand, a long inspiratory time may prove uncomfortable in some patients. A concern with APRV is the high transpulmonary pressure that can be generated during spontaneous breathing at P-high, as this could potentially result in injuries distending pressures. The use of these modes in clinical practice is limited by the lack of evidence for improved outcomes. APRV improves oxygenation through lung recruitment (35) while maintaining spontaneous breathing, attractive features in diseases like ARDS. However, it may also increase ventilator days and ICU length of stay (36), possibly due to the complexity of implementation.

**Synchronized Intermittent Mandatory Ventilation**

With SIMV, the ventilator provides a mandatory breath rate. If the patient breathes at a higher rate, the additional breaths are unsupported (Fig. 104.10). If the patient has no spontaneous breathing efforts, SIMV, CMV, and A/CV are synonymous. The mandatory breaths are synchronized to patient trigger effort, and can be volume control, pressure control, or adaptive pressure control. It has been traditionally taught that during SIMV the ventilator does the work for the mandatory breaths, and the patient does the work for the spontaneous breaths, thus integrating effort and support. As such, weaning from the ventilator would occur by progressively decreasing the mandatory breath rate. However, this has not been confirmed by either physiologic or outcome studies (37,38). Inspiratory effort may be as great during mandatory breaths as during spontaneous breaths, as shown in Figure 104.10, thus denying the purpose of unloading the work of breathing with the mandatory breath. The combination of mandatory and spontaneous breaths can also lead to asynchrony (39).
Part of the SIMV shortcomings can be resolved by supporting spontaneous breathing with PSV (Fig. 104.11); this has become a routine addition when SIMV is used. A particular way to accomplish this goal of supporting the spontaneous breaths with SIMV is with BiLevel (Covidien) (PCV+ in the Draeger). This mode allows delivering PSV as the primary mode with a low number (typically 1–4) of BiLevel mandatory breaths that can be thought of as sighs (40). The mandatory breaths are set at relative high $P_{aw}$ to provide recruitment, for example, 25 to 30 cm H$_2$O, and a relatively long inspiratory time, for example, 3 to 4 seconds (Fig. 104.12). With the PCV+ mode, these mandatory breaths are BiLevel breaths that allow spontaneous breathing during the sigh, thus further enhancing recruitment (40).

**FIGURE 104.10** Synchronized intermittent mandatory ventilation (SIMV). Flow, volume, airway pressure, and esophageal pressure waveforms are shown. Note the persistence of the patient's own negative intrathoracic pressure during the mandatory breath. (Adapted from Hess D, Branson RD. Ventilators and weaning modes. *Respir Care Clin North Am*. 2000;6(9):407, with permission.)

**FIGURE 104.11** Synchronized intermittent mandatory ventilation (SIMV). Flow, airway pressure, and volume waveforms obtained in a lung model. The mandatory breaths are constant flow, volume-controlled ventilation, and the spontaneous breaths are pressure support ventilation.
Continuous Spontaneous Ventilation

Continuous Positive Airway Pressure

CPAP provides positive $P_{aw}$ throughout the respiratory cycle, promoting recruitment and possibly decreasing work of breathing (41). This is traditionally accomplished by maintaining $V$ at the airway higher than the patient’s inspiratory $V$. Such a system is still occasionally employed without the support of a ventilator, with the high gas flow coming directly from a regulator at the gas source (42). When delivered by a mechanical ventilator, the need to supply very high $V$ is generally circumvented by substituting CPAP with PSV, for example, 2 cm H$_2$O (Fig. 104.13). This is possible in modern ventilators by virtue of very

![Figure 104.12 Using a sigh breath in conjunction with pressure support ventilation. The patient is ventilated with a Draeger Evita 4 in PCV+ mode. Paw is airway pressure. (Adapted from Patroniti N, Foti G, Cortinovis B, et al. Sigh improves gas exchange and lung volume in patients with acute respiratory distress syndrome undergoing pressure support ventilation. Anesthesiology. 2002;96:788, with permission.)](image1.png)

![Figure 104.13 Flow, pressure, and volume waveforms during continuous positive airway pressure (CPAP) by a ventilator. The airway pressure fluctuates above and below the set CPAP level of 5 cm H$_2$O (see text for explanation).](image2.png)
low-resistance exhalation valves and minimal time delay for triggering and cycling.

CPAP is used to treat hypoxemia by maintaining alveolar recruitment throughout the respiratory cycle, to treat acute cardiogenic pulmonary edema by raising intrathoracic pressure, and to counterbalance auto-PEEP in patients with obstructive lung disease.

**Pressure Support Ventilation**

With PSV, the ventilator applies a set inspiratory pressure to assist each patient-initiated breath (Fig. 104.14) (43). The early part of inspiration is similar to PCV. Once the patient triggers the ventilator, inspiratory $V$ is delivered at a variable rate, and the rise time can be adjusted (44,45). When the set inspiratory pressure is reached, $V$ decreases with a variable decay (see above: PCV). The size of the $V_F$ is the result of the set inspiratory pressure, the patient's mechanics, and the patient's inspiratory effort (see Chapter 105). Differently from PCV, where inspiration ends by time, with PSV inspiration ends when the inspiratory flow falls to a ventilator-preset value, such as 25% of the peak flow. Most current ventilators allow the clinician to adjust the fraction of the inspiratory flow at which inspiration ends—the expiratory sensitivity (Fig. 104.15) (46–50). Setting a high expiratory sensitivity (e.g., 50% of the peak rate) will shorten the duration of the breath, which may be desirable in situations of expiratory flow limitation and slow flow decay such as COPD. A low expiratory sensitivity (e.g., 5% of the peak rate) will prolong the duration of the breath, which may be desirable in situations of a low compliance such as ARDS.

*SmartCare*® (Draeger) is a closed-loop application (using ventilator output as a feedback signal to adjust the system toward the desired output) of PSV designed for ventilator weaning (51). It adapts the level of PSV to the patient's ventilatory needs, with the goal to keep the patient within a comfort zone. Comfort is defined primarily as a respiratory

![Flow, pressure, and volume waveforms during pressure support ventilation delivered by a lung model. All breaths are triggered. (Adapted from Gibbons FK, Hess DR: Mechanical ventilation. In: Bigatello LM, ed. Critical Care Handbook of the Massachusetts General Hospital. 4th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2006.)](image-url)
rate that can vary in the range of 15 to 30 breaths/min, a VT above a minimum threshold (>300 mL), and an end-tidal CO2 (PetCO2) below a maximum threshold (usually <55 mmHg). The level of support is periodically adapted by the system in increments or decrements of 2 to 4 cm H2O. The system automatically tries to reduce the pressure level to a minimum value. At this value, a spontaneous breathing trial is performed. If successful, a message on the screen recommends removal from the ventilator (i.e., extubation). This mode was shown to reduce the duration of MV as compared with physician-controlled weaning (52), but these data were not confirmed by subsequent studies (53,54). A recent Cochrane review (55) suggested that, SmartCare may result in reduced duration of weaning time, days on MV, and length of stay in ICU with no increase in adverse events, but due to a substantial heterogeneity in trials reporting weaning duration, further randomized controlled trials need to better evaluate its clinical role on patients' outcome (56).

Volume support uses PSV in a manner analogous to the use by PRVC of PCV (21–27). In other words, the ventilator adjusts the inspiratory pressure according to a set minimal VT. If the patient's effort increases (higher VT for the set level of PSV), the ventilator decreases the support of the next breath. If the compliance or patient effort decreases, the ventilator increases the support to maintain the set VT. This combines the attributes of PSV with the guaranteed minimum VT. A concern with this mode is that the ventilator takes away support if the patient's respiratory demand increases and VT exceeds what was set. This results in increased WOB (28).

AutoMode is a dual-controlled mode available on the Maquet ventilators (21,22). It provides automated weaning from PCV to PSV, and automated escalation of support if patient effort diminishes. The ventilator provides PRVC if the patient is making no breathing efforts. If the patient triggers two consecutive breaths, the ventilator switches to PSV. If the patient becomes apneic, the ventilator switches back to PRVC. AutoMode can also switch between PCV and PSV or VCV and VS.

Adaptive Support Ventilation

ASV is based on the minimal work-of-breathing concept. The patient will breathe at a VT and respiratory frequency that minimizes the elastic and resistive loads while maintaining oxygenation and acid-base balance (57). The ventilator attempts to deliver 100 mL/kg V̇E (expired minute volume) for an adult and 200 mL/kg for a child. This can be adjusted by setting the % V̇E control from 20% to 350%, which allows the clinician to provide full ventilatory support or encourage spontaneous breathing and facilitate weaning. When first connected to the patient, the ventilator delivers a series of test breaths and measures C, Ṙaw, and auto-PEEP. The input of body weight allows the ventilator’s algorithm to choose a required V̇E. Lung mechanics are measured on a breath-to-breath basis, and ventilator settings are altered to meet the desired targets. If the patient breathes spontaneously, the ventilator will support breaths. Spontaneous and mandatory breaths can be combined to meet the minute ventilation target. The pressure limit of both the mandatory and spontaneous breaths is adjusted continuously. This means that ASV is continuously using adaptive pressure control for mandatory and spontaneous breaths.

The ventilator adjusts the I:E ratio and inspiratory time of mandatory breaths by calculation of the expiratory time constant (compliance × resistance) and maintains sufficient expiratory time to prevent auto-PEEP. If the patient is triggering, the number of mandatory breaths decreases and the ventilator chooses a pressure support that maintains a tidal volume sufficient to ensure alveolar ventilation based on a dead space calculation of 2.2 mL/kg. ASV can provide pressure-limited, time-cycled ventilation, add adaptive pressure control, allow for mandatory breaths and spontaneous breaths (SIMV + PSV), and eventually switch to pressure support (adaptive pressure control with PSV).
Tube Compensation
Tube compensation (TC) is designed to overcome the flow-resistive work of breathing imposed by the endotracheal or tracheostomy tube (58,59). It uses the known resistive coefficients of the artificial airway (tracheostomy or endotracheal tube) and measurement of instantaneous flow to apply a pressure proportional to resistance throughout the total respiratory cycle. With TC, the ventilator targets the tracheal pressure, rather than proximal airway pressure, increasing the proximal airway pressure necessary to overcome the flow-resistive properties of the artificial airway (Fig. 104.16). The clinician can set the fraction of tube resistance for which compensation is desired (e.g., 50% compensation rather than full compensation). On some ventilators, TC can be used with any mode, whereas on others, it can be used only with CPAP. Because in vivo tracheal tube resistance tends to be greater than in vitro resistance, incomplete compensation for endotracheal tube resistance may occur. Additionally, kinks or bends in the tube as it traverses the upper airway and accumulation of secretions in the inner lumen will change the tube’s resistive coefficient and result in incomplete compensation. Available evidence suggests that TC can effectively compensate for resistance through the artificial airway but has not shown improved outcomes with this mode (60,61). At present there is no convincing evidence that TC is a superior mode for SBT except for patients with a resistive work of breathing imposed by the tracheal tube (62).

Proportional Assist Ventilation
With PAV (63–65), the ventilator applies inspiratory pressure as a positive feedback controller, where respiratory E and R are the feedback signal gains, defined as $K_1$ (cm H2O/L) and $K_2$ (cm H2O/L/sec), respectively, following the equation of motion of the respiratory system Eq. (6).

$$P_{\text{appl}} = K_1 \times V + K_2 \times \dot{V} \quad (9)$$

where $K_1$ and $K_2$ substitute $E$ and $R_{\text{ins}}$, respectively. $K_1$ and $K_2$ are the preset values of volume and flow gains of the proportional assist ventilator. The ventilator measures the patient’s instantaneous inspiratory flow rate and provides the set support through a rapid positive feedback loop (Fig. 104.17). PAV should provide optimal patient–ventilator synchrony by following and amplifying the patient’s inspiratory flow on a breath-by-breath basis. This differs from PSV, in which the level of support is constant regardless of demand, and VCV, in which the level of support decreases when demand increases. It is important to note that, like other continuous spontaneous breathing modes, PAV requires the presence of an intact ventilatory drive. A dangerous runaway,
that is, a continuous increase in respiratory support, may occur in situations like a large air leak, where the ventilator does not record an end to the inspiratory flow and continues to amplify the support. This is a similar situation to the prolonged inspiratory time that can occur with an air leak during PSV.

A concern with PAV is its dependence on measures of \( R_{AW} \) and \( E \). These can be difficult to measure during spontaneous breathing, and they change frequently over the course of MV. In its initial application, the clinician measured (or estimated) compliance and resistance and set the proportion of inspiratory support that the ventilator would provide, generally as a percentage of elastic and resistive work, respectively. In a newer algorithm of PAV (PAV\(^+\), Puritan-Bennett 840/980), the ventilator applies a 300-msec end-inspiratory and end-expiratory pause every 8 to 15 breaths to measure \( R_{AW} \), \( E \), and auto-PEEP. The clinician sets the trigger, the cycle (3 L/min default), and the % support. For example, for 50% support, half of the work of breathing is performed by the patient and half by the ventilator.

As with PSV, PAV is able to unload the respiratory muscles (66,67) to optimize patient–ventilator synchrony, and to diminish sleep disruptions (68–71). Just like PSV, PAV can also be delivered through noninvasive ventilation.

**Neurally Adjusted Ventilatory Assist**

NAVA delivers a variable support in proportion to the patient’s effort by measuring the electrical activity of the diaphragm (EAdi) and applying a gain selected on the ventilator (72,73). The ventilator is triggered and cycled based on the EAdi value, which directly reflects the activity of the neural respiratory output, provided that motor neuron disease is not present. EAdi is measured by an electromyography electrode array located on a special nasogastric tube at the position of the diaphragm (Fig. 104.18). Correct position of the catheter is mandatory to obtain a representative EAdi signal from the diaphragm (74).

The inspiratory pressure applied by the ventilator is determined by the following equation:

\[
P_{AW} = NAVA \text{ level} \times \text{EAdi}
\]

The NAVA level reflects the amount of WOB reduced by the ventilator. The level is usually set between 1 and 4 cm H\(_2\)O/μV and it can be adjusted over time in small increments. Is it possible to set any value between 0 and 15 cm H\(_2\)O/μV (75)? Because NAVA’s trigger is based on diaphragmatic activity rather than pressure or flow measured at the proximal airway, triggering is not adversely affected in patients with flow limitation and auto-PEEP, but at the same time it is not useful in patients with weak respiratory drive or motor neuron disease. NAVA is effective in optimizing patient–ventilator synchrony compared to conventional ventilatory modes (76–79). However, there is still a paucity of data regarding its effect on clinical outcomes (80). Like PAV, NAVA can be used in both invasive and noninvasive ventilation. A representative trace of NAVA is shown in Figure 104.19.

**SUMMARY**

The plethora of settings available for the various modes on modern ventilators can be overwhelming. New modes are often based on technical and engineering capability rather than a clear clinical superiority over previously available modes. There is little evidence that any mode improves patient outcome. Patient outcomes are affected more by how the mode is used than by the mode per se.
Section 11
Respiratory Disorders

Figure 104.20 Ventilator screens showing waveforms for volume-control ventilation (VCV) and pressure-control ventilation (PCV) obtained in the same patient, achieving comparable tidal volume (VT) and minute ventilation (VE). Airway pressure is at the top, flow in the middle, and exhaled CO2 at the bottom. Note the same VT in VCV (set) and PCV (result of the set PIP), and the same end-tidal CO2.

Key Points

- The equation of motion of the respiratory system Eq. (6) provides the structure for understanding MV. The result of any variable set on the ventilator (the control variable) depends on the setting itself, the patient's mechanics and any active inspiratory effort.
- Pressure control (PCV) and volume control (VCV) differ not only in what is set on the ventilator (the control variable) and what is variable, but also in how the breath is delivered in each mode (Fig. 104.20). With VCV, the inspiratory flow is fixed and set by the operator, while with PCV it is variable, and it is the result of the set pressure and the patient's mechanics and effort. Hence, with PCV the inspired gas may distribute more evenly through an inhomogeneous lung, and the spontaneous breathing activity may synchronize more easily with the ventilator.
- When setting a lung-protective strategy of low tidal volume (VT) and low driving pressure, the desired VT can be obtained in either volume- (VCV) or pressure (PCV)-control ventilation. However, VCV assures the size of the VT, whereas PCV may allow it to increase beyond the desired limit due to changes in respiratory mechanics or an increased patient effort.
- BiLevel ventilation in the absence of spontaneous breathing is indistinguishable from PCV. With spontaneous breathing activity, breaths occur at both high and low pressure levels. As such, BiLevel is a form of synchronized intermittent mandatory ventilation (SIMV) and, as with SIMV, the spontaneous breaths can be supported with PSV. However, unlike SIMV, spontaneous breathing can occur also at the high pressure level, which can be applied for longer periods of time to enhance alveolar recruitment.
- Both assist-control ventilation (ACV) and synchronized intermittent mandatory ventilation (SIMV) can be delivered in the volume-control and the pressure-control modes even though not all ventilators provide all four combinations. During both volume- and pressure-control SIMV the spontaneous breaths can be supported by PSV.
- During PSV, a fast time constant (i.e., low compliance and normal resistance) as is seen in acute respiratory distress syndrome (ARDS), may result in a low mean airway pressure and low tidal volume; a slow time constant (i.e., normal or high compliance and high resistance) as is seen in asthma/COPD, may result in a high mean airway pressure, large tidal volumes, and auto-PEEP.

References

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