Advanced Modes of Mechanical Ventilation
Implications for Practice

Louise Rose, MN, Adult Ed Cert, BN, ICU Cert, Dip Nurs

ABSTRACT

Mechanical ventilation is one of the most commonly applied interventions in intensive care units. Despite its life-saving role, mechanical ventilation is associated with additional risks to the patient and additional healthcare costs if not applied appropriately. To decrease risk, new ventilator modes continue to be developed with the goal of improving patient outcomes. Advances in ventilator modes include dual control modes that enable guaranteed tidal volume and inspiratory pressure, pressure-style modes that permit spontaneous breathing at high- and low-pressure levels, and closed-loop systems that facilitate ventilator manipulation of variables based on measured respiratory parameters. Clinicians need to develop a thorough understanding of these modes including their effects on underlying respiratory physiology to be able to deliver safe and appropriate patient care.

Keywords: closed-loop ventilation, mechanical ventilation, weaning

Although life-saving technology, mechanical ventilation can exacerbate acute lung injury and worsen patient outcomes if not applied appropriately. The primary goal of all ventilator modes is to maintain adequate oxygenation and ventilation, reduce the work of breathing, and improve patient comfort throughout the duration of respiratory failure. This has led to the development of a variety of ventilation modes and applications that potentially reduce complications and shorten the duration of mechanical ventilation, resulting in improved patient outcomes.

Recent advances in ventilator modes have focused on 3 key areas. First, modes have been developed that incorporate guaranteed control of both pressure and volume settings so as to obtain the benefits of both styles of ventilation. An example of this type of dual control mode is pressure regulated volume control (PRVC). Second, pressure style modes have been developed that allow spontaneous breathing to occur during both high- and low-pressure settings. This facilitates spontaneous breathing in the early phase of acute lung injury, as well as during the weaning period. Examples of these modes include biphasic positive airway pressure (BIPAP) and airway pressure release ventilation (APRV).

Third, advances in microcomputer technology have enabled the development of advanced closed-loop systems that allow ventilator, as opposed to clinician, manipulation of ventilator variables based on feedback from patient characteristics.

This article will discuss advances in ventilator modes in these 3 key areas with particular emphasis on appropriate ventilator settings, advantages and disadvantages, their particular

From RMIT University, Bundoora, VIC, Australia.
Reprint requests to Louise Rose, Critical Care Course Coordinator, RMIT University; PhD candidate, The University of Melbourne, The Royal Melbourne Hospital, PO Box 71, Bundoora, VIC, Australia, 3083 (louise.rose@rmit.edu.au).
effects on oxygenation and ventilation, and the monitoring priorities for clinicians.

Guaranteed Control of Pressure and Volume

Traditionally, volume control modes have been favored for management of acute respiratory failure because of the ability to guarantee a preset tidal volume (VT) and minute ventilation (VE) enabling straightforward manipulation of ventilation in response to changes in PaCO₂. However, volume control modes do not provide any limit of peak airway pressures. This may result in high peak airway pressures associated with changes in the patient's compliance and resistance, causing alveolar overdistension and barotrauma. In contrast, pressure control ventilation (PCV) allows control, or limitation of, the peak inspiratory pressure and inspiratory time with no guarantee of VT.

Increasingly, PCV is utilized as a protective lung strategy, particularly in patients with acute lung injury (ALI) and acute respiratory distress syndrome (ARDS). Patients with ALI or ARDS have a higher proportion of diseased, collapsed, or consolidated lung regions that take a longer time to open and thus may require a longer inspiratory time. During PCV, the inspiratory pressure and time are set by the clinician and the ventilator adjusts the inspiratory flow to achieve and maintain the set inspiratory pressure based on the compliance and resistance of the patient. Setting adequate inspiratory time is essential in all of the pressure control-style modes to enable the preset pressure to reach both healthy and diseased lung units.

The primary advantage of PCV is the ability to accurately determine and maintain peak airway pressure and inspiratory time, thus reducing the risk of lung injury. The variable and decelerating inspiratory flow pattern of PCV enables a more rapid alveolar filling and more even gas distribution, resulting in improved gas exchange, decreased work of breathing, and prevention of overdistension in healthy alveoli. The primary disadvantage of PCV is the inability to maintain a fixed VT and VE due to changes in respiratory compliance and resistance and activation of respiratory muscles. This requires the clinician to set appropriate high and low VE and VT alarms, in addition to close monitoring of gas exchange via arterial blood gas (ABG) analysis and end tidal CO₂ (etCO₂) monitoring, to identify the presence of hypercapnia.

Due to the identified disadvantages of volume and pressure controlled modes, dual control modes have been developed to provide the benefits of both volume and pressure control while avoiding the shortcomings of single control modes. Dual control modes include complex closed-loop systems that switch between pressure control and volume control either within a single breath or between individual breaths based on measured patient characteristics (Table 1).

In dual control within-a-breath modes, such as volume assured pressure support (VAPS) (BIRD 8400 STi, Viasys, Palm Springs, California, USA) and pressure augmentation (PA) (Bear 100, Viasys, Palm Springs, California, USA), the ventilator switches from pressure control to volume control or pressure support to volume control during the inspiratory phase of individual breaths based on the patient's inspiratory effort and ability to achieve the clinician-set minimum VT. This enables maintenance of a minimum VT and is meant to reduce work of breathing. VAPS may also be referred to as volume-assisted pressure support.

In these modes, the clinician is required to set the respiratory frequency, peak flow, pressure support, and the minimum desired VT to achieve adequate gas exchange. The clinician adjusts the peak flow to achieve an appropriate inspiratory time and I:E ratio that facilitates gas exchange and does not induce gas trapping. Setting of the initial level of pressure support may be guided by the plateau pressure obtained in a volume control breath at the minimum desired VT. In addition, positive end expiratory pressure (PEEP), fraction of inspired oxygen (FiO₂), and trigger sensitivity are set by the clinician.

The within-a-breath modes may be used during mandatory or pressure-supported breaths. They are designed to combine the benefits of the flow characteristics of PCV with a guaranteed VT. When used with pressure supported breaths, VAPS and PA prevent the occurrence of ineffective ventilation as the minimum desired VT works as a safety net. Small clinical studies of the within-a-breath modes have found a reduction in work of breathing. This finding was attributed to the higher and more rapid delivery of inspiratory flow as opposed to the guaranteed VT.

Appropriate setting of pressure support is an important aspect of this mode to be considered by clinicians. Appropriate pressure support will ensure the patient's inspiratory effort is augmented to achieve the set minimum VT. If
If the pressure support is set too low, the breath will change to a volume control breath, resulting in an increased proportion of mandatory breath that increases the potential for impaired V/Q match and patient-ventilator dysynchrony. Ongoing monitoring of the style of breath delivery is required by clinicians to ensure optimum ventilation is delivered.

Dual control between-breath modes are pressure limited and either flow-cycled or time-cycled. Cycling refers to the criterion used to terminate inspiration. Flow cycled, dual control between-breath modes combine the fast initial flow of pressure support with the constant VE and VT of volume control. An example of this style of mode is Volume Support Ventilation (VSV; Servo 300, Siemens Medical Systems, Solna, Sweden). This mode is similar to pressure support ventilation (PSV) in that the patient determines the respiratory frequency, inspiratory time, and flow. The peak pressure is adjusted to ensure the delivery of the target VT based on the patient’s compliance measured during the previous breath. Therefore, VT is used as the feedback control to adjust pressure support. This is equivalent to PSV with VT again functioning as a safety net.

On commencement of VSV, the ventilator delivers 4 test breaths of incremental pressure while measuring VT and calculating compliance. The peak pressure is adjusted by the ventilator to ensure the delivery of the target VT using the lowest possible inspiratory pressure. Pressure adjustments are made based on the patient’s compliance measured during the previous breath. This occurs because the pressure support is adjusted based on the patient’s respiratory compliance during the previous breath. If the patient’s compliance is improving, the VT target will be met with lower levels of pressure support. Theoretically, VSV can also be used as a weaning mode by clinician-reduction of the target VT.

Reports of clinical experience of VSV have describe VT instability, patient-ventilator dysynchrony, and failure to wean. In patients
with rapid shallow breathing, a well-recognized sign of respiratory failure,\textsuperscript{12} V SV tends to reduce the pressure support setting as opposed to increasing it, thus worsening the patient's respiratory distress. Clinicians need to closely monitor the patient's respiratory rate, ABGs, and work of breathing including use of accessory muscles to identify respiratory distress and revert to either conventional PSV or a mandatory mode, such as synchronized intermittent mandatory ventilation (SIMV) or assist control (AC).

Time cycled, pressure limited, dual control between-breath modes, such as PRVC, may be patient or time triggered. These modes enable the ventilator to adjust inspiratory flow according to patient flow demand combined with maintenance of a constant \( V_T \), ensuring adequate ventilation. The pressure limit is adjusted using the clinician-set desired \( V_T \) as the negative feedback control. PRVC (Servo 300, Siemens Medical Systems, Solna, Sweden), Autoflow (Dräger Evita 4, Dräger Medical, Lübeck, Germany), Variable Pressure Control (Venturi, Cardiopulmonary Corporation, New Haven, Connecticut, USA) are all examples of time cycled, pressure limited between-breath dual control.\textsuperscript{13} Dual control between-breath modes are described as equivalent to a bedside clinician adjusting the pressure limit of each breath according to the previous \( V_T \).\textsuperscript{14} The primary advantage of these modes is the reduction in peak inspiratory pressures associated with a decelerating flow pattern, as opposed to the constant flow pattern commonly associated with volume control ventilation, combined with the guaranteed delivery of \( V_E \) regardless of changes in patient compliance, ensuring adequate oxygenation and ventilation.\textsuperscript{15} In addition, automatic weaning of the inspiratory pressure will occur if the patient's compliance improves.

In the few reported clinical studies, the only significant benefit of PRVC compared to volume control ventilation (VCV) was the reduction of peak inspiratory pressure, suggesting potential benefits in terms of prevention of alveolar distention and barotrauma.\textsuperscript{16-18} However, a reduction in peak inspiratory pressure is a predictable finding when comparing the constant flow pattern of VCV with the decelerating flow pattern of PRVC. When comparing PRVC to conventional PCV, no differences in peak inspiratory pressures were found.\textsuperscript{19}

Automode (Servo 300A, Siemens Medical Systems, Solna, Sweden) combines PRVC and VSV in the one mode to enable seamless weaning from pressure control to pressure support or volume control to volume support while maintaining a guaranteed \( V_T \).\textsuperscript{19} In the apneic patient, pressure limited, time cycled breaths, are delivered. Once the patient triggers 2 consecutive breaths, the ventilator switches to VSV to support the patient's spontaneous efforts. In the one identified clinical study,\textsuperscript{20} Automode was compared to SIMV in postoperative patients without respiratory failure. Notably the duration of ventilation was shorter and the number of ventilator manipulations by staff were fewer in the Automode group, suggesting a potential reduction in clinician workload. However, further clinical studies need to be conducted to evaluate this mode further.

Modes that ensure a guaranteed \( V_T \) and limit peak airway pressure potentially provide additional patient protection from alveolar distension and barotrauma caused by high peak airway pressures. However, clinicians need to closely monitor and respond to triggering of the peak airway pressure alarm. The maximum pressure used by the ventilator to achieve the desired \( V_T \) is 5 cmH\textsubscript{2}O below the high pressure alarm. Activation of this alarm may indicate the presence of secretions or worsening compliance and resistance and thus requires the clinician to perform a respiratory assessment and review the desired \( V_T \) setting. Moreover, these modes may prevent periods of hypoventilation and worsening respiratory distress due to inadequate ventilatory support arising from changing respiratory parameters. This may be particularly pertinent in units with insufficient nursing resources or levels of expertise to provide timely recognition and intervention for changing respiratory parameters.

**Partial Ventilatory Support**

Scientific studies have shown spontaneous breathing during mechanical ventilation prevents atelectasis and promotes alveolar recruitment.\textsuperscript{21-23} This results in an improved ventilation/perfusion (V/Q) match and hence promotes effective gas exchange.\textsuperscript{8} Furthermore, spontaneous ventilation reduces the need for sedation and muscle relaxants, resulting in reduced durations of ventilation and intensive care (ICU) stay and ventilator-associated complications.\textsuperscript{23-25}

Radiologic studies indicate gas is directed to dependent well-perfused regions of the lungs during spontaneous breathing due to the movement of the posterior muscular sections of the
Conversely, full ventilatory support causes dependent atelectasis and reduced functional residual capacity. This is due to the upward displacement of the diaphragm by intra-abdominal pressure, with resultant preferential ventilation of the anterior lung regions. Therefore, full ventilatory support results in ventilation of nondependent lung areas and perfusion of dependent areas, creating a worsening V/Q match and impaired ventilation of dependent lung areas and perfusion of dependent areas, creating a worsening V/Q match and impaired oxygenation. In addition, positive pressure ventilation produces hemodynamic effects, such as reduced venous return, cardiac output, and thus decreased organ perfusion, which have long been recognized.

The gas distribution pattern of spontaneous breathing has also been shown to occur in partial ventilatory support, resulting in improved V/Q matching. Modes, such as BIPAP and APRV, may be considered as partial ventilatory support modes when applied in a spontaneously breathing patient. These modes do not support the patient's own inspiratory efforts; rather, application of continuous positive airway pressure (CPAP) facilitates recruitment of atelectic alveoli and decreases the elastic work of breathing. Increasingly, partial ventilatory support is being used during the acute phase of respiratory failure as well as during weaning.

**Biphasic Intermittent Positive Airway Pressure**

Biphasic Positive Airway Pressure, also known as Bilevel, Bivent, and DuoPAP, was first described by Benzer and Baum and has been available for over twenty years. BIPAP was originally described as a combination of pressure control-style ventilation with unrestricted spontaneous breathing during both high- and low-pressure settings (Figure 1). This is in contrast to traditional PCV, which does not allow spontaneous breathing at the upper pressure level. BIPAP is also described within the literature as a CPAP system with time cycling between 2 clinician-set pressure levels. BIPAP can therefore be viewed as a progression of monophasic CPAP and was initially regarded as a weaning mode. In addition, BIPAP differs from PSV given that spontaneous breaths are allowed by the ventilator without synchronized support, as opposed to support of each spontaneous breath, available in PSV. However, while BIPAP may be categorized

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**Figure 1:** Airway pressure graphs during 3 different modes of mechanical ventilation: continuous positive airway pressure (CPAP), pressure controlled ventilation, and biphasic positive airway pressure (BIPAP). Reprinted with permission of Dräger Medical, Lübeck, Germany.
as a partial ventilatory mode suitable for weaning, if a patient is not breathing spontaneously, BIPAP is equivalent to time-cycled PCV.

In recent studies, by combining spontaneous breathing with pressure control-style ventilation, BIPAP has been shown to be beneficial in patients during the acute phase of ALI and ARDS by improving dependent gas distribution. Therefore, BIPAP can be used for different phases of the patient’s course of mechanical ventilation and can be considered as a flexible, universal mode that covers the spectrum of respiratory failure.

During BIPAP, unrestricted spontaneous breathing throughout the ventilator cycle is achieved via an active expiratory valve that opens during inspiration, as well as the traditional expiratory opening. The active expiratory valve enables continuous control of airway pressure and compensates for pressure variations normally found in the ventilator circuit. If the airway pressure drops below the set level due to spontaneous inspiration, gas is rapidly supplied to ensure return to the preset pressure level.

Careful setting of pressure levels is required in BIPAP to avoid shear stress due to repetitive alveolar opening and closing and lung distension due to inappropriate low-pressure (P_low) and high-pressure (P_high) settings respectively. The difference in the 2 pressure settings, which can be viewed as 2 levels of functional residual capacity (FRC), determines the VT. The pressure difference creates a driving pressure to permit gas to enter the lung units and represents the difference between airway pressure (Paw) and alveolar pressure (Palv). The VT decreases with poor respiratory compliance and equally increases with improved respiratory compliance. Therefore, VT is derived from the product of the driving pressure and the patient’s compliance. VT targets should aim towards 6 mL per kg of ideal body weight in patients with ALI/ARDS based on improved outcomes shown in the ARDSnet study.

Recommended Settings

BIPAP requires the setting of upper and lower pressures (P_high and P_low) and their respective time durations (T_high and T_low). Hörmann and associates recommend initially setting the P_low equivalent to PEEP. The P_high should be set at a level equivalent to the inspiratory plateau pressure obtained if the patient is already ventilated in another mode. If the patient’s ventilation is to be initiated on BIPAP, the P_high setting may be set 12 to 16 cm H2O above the P_low setting, adjusted according to the patient’s compliance and resultant VT.

BIPAP routinely implies time cycling phases that approximately maintain a 1:1 inspiratory:expiratory (I:E) ratio. Careful consideration of the patient’s underlying pathophysiology is required when adjusting settings. The duration of both of the predefined time cycling phases (T_high and T_low) may be adjusted independently of the 2 pressure levels. Longer T_high and shorter T_low times may be beneficial to patients with ALI/ARDS to encourage alveolar recruitment, improve oxygenation, and facilitate spontaneous breathing. In contrast, patients with chronic obstructive pulmonary disease (COPD), experience hyperexpansion and do not require an increased FRC. Extending the T_high will result in further gas trapping, increased work of breathing, and worsening compliance in these patients. Rather, this patient group requires a long T_low to enable full expiration and prevent gas trapping and auto-PEEP. Extending the T_high and T_low times may be beneficial to patients with chronic obstructive pulmonary disease (COPD), experience hyperexpansion and do not require an increased FRC. Extending the T_high will result in further gas trapping, increased work of breathing, and worsening compliance in these patients. Rather, this patient group requires a long T_low to enable full expiration and prevent gas trapping and auto-PEEP. Figure 2 shows how the gas flow waveforms may be utilized by the clinician to check the appropriateness of the T_high and T_low in order to prevent gas trapping. In addition, as with other pressure control-style modes of ventilation, careful and continuous monitoring is required to identify potential changes in patient compliance with the resultant effect on gas flow and VT.

Weaning of Biphasic Positive Airway Pressure

Weaning BIPAP is achieved by reducing the pressure difference between the 2 pressure settings, followed be a reduction in rate. The mode can then be changed to CPAP with a CPAP level equivalent to the mean airway pressure when on the reduced BIPAP settings. However, some patients may be switched directly to CPAP and not require weaning of the pressure difference or respiratory rate. The CPAP level may then be weaned to a minimum of 5 to 7 cm H2O based on the patient’s oxygenation status. BIPAP can also be combined with pressure support in the weaning phase to further augment the patient’s spontaneous inspiratory effort.

Mode Terminology

The use of the term BIPAP in European literature originally created misunderstanding in North America. The term BiPAP® is reserved
for noninvasive, positive pressure ventilation available on Respironics ventilators (Respironics, Murraysville, Pa). Ventilator companies are prevented from using the term BIPAP by law in North America and this has led to the use of terms such as Bilevel on the Puritan Bennett 840 ventilators (Puritan Bennett, Pleasanton, Calif) and Bivent on the Servo 300 range. In addition, Airway Pressure Release Ventilation (APRV) was also introduced as a new mode around the same time as BIPAP, producing further misunderstanding.30

Definitional differences of BIPAP and APRV are confusing within the literature. Hedenstierna and Lattuada8 state that APRV is frequently called BIPAP in Europe. However, while being a continuum of the same concept (ie, allowing spontaneous breathing during time-cycled changes in airway pressure), there are some distinct differences (Table 2). BIPAP conventionally maintains the high-pressure setting for more traditionally acceptable inspiratory times, whereas APRV always implies an inverse ratio.32,33 Therefore, APRV can be regarded as a special setting or extension of BIPAP.21 APRV can be used to maintain a high mean airway pressure for the majority of the respiratory cycle with only brief pressure releases. APRV is usually reserved for patients in the more acute phase of ALI/ARDS, whereas BIPAP can be viewed as a mode applicable for patients with acute and resolving ALI who are moving into the weaning phase.21 Nonetheless, BIPAP can be applied with varying time and pressure durations that enable it to mimic other modes of ventilation.

Airway Pressure Release Ventilation
Airway pressure release ventilation was originally described as CPAP with an intermittent release phase.34,35 During APRV, mechanical ventilation occurs through a time-cycled switching between 2 pressure levels, with spontaneous breathing occurring during any phase of the ventilatory cycle in a manner equivalent to BIPAP.36 However, when used in apneic patients, APRV is identical to pressure-controlled inverse ratio ventilation. The higher continuous airway pressure level (P_high) is designed to maintain adequate lung volumes and promote alveolar recruitment and oxygenation, whereas the lower pressure level (P_low) enables alveolar ventilation and carbon dioxide (CO₂) removal.37 The estimated upper and lower inflection points of the volume pressure curve are used as a guide to the 2 pressure levels.38 The upper inflection point is the part of the curve where the pressure continues to rise, but the volume no longer increases. The lower inflection point marks the point on the curve where the volume starts to increase as pressure is applied. During spontaneous breathing, the patient can control the rate and duration of both spontaneous inspiration and expiration.37

APRV differs conceptually from conventional modes of ventilation. In order to achieve tidal ventilation, conventional modes elevate airway pressures from a low baseline pressure, whereas APRV uses a short deflation to a lower pressure level then returns to a high baseline pressure.39 The temporary pressure release facilitates removal of intrapulmonary gas, which is then replaced once the higher pressure level is reestablished and augments the patient’s own minute ventilation.32 During

![Figure 2: Checking T_high and T_low using the flow waveform. The arrow indicates failure of the expiratory flow to return to zero prior to inspiration representing gas trapping. Reprinted with permission of Dräger Medical, Lübeck, Germany.](image-url)
APRV, the peak airway pressures never exceed the $P_{\text{high}}$ and airway pressures decrease rather than increase to deliver $V_T$. As with BIPAP, APRV can be regarded as the 2 levels of FRC, with the inspiratory level of FRC maintained for a prolonged duration without risk of overdistension. This differs conceptually from conventional ventilation that superimposes the $V_T$ on the FRC (Figure 3).

### Recommended Settings

In APRV, the $P_{\text{high}}$ is maintained for an extended $T_{\text{high}}$ and the $P_{\text{low}}$ is maintained for a short release duration or $T_{\text{low}}$. In the original description of APRV, the $T_{\text{high}}$ and $T_{\text{low}}$ were 1.8 and 1.3 seconds respectively indicating a moderate inverse ratio. An extension of the original description of APRV is well described by Habashi. This application of APRV utilizes a $T_{\text{high}}$ that is extended by 4 to 6 seconds to improve recruitment of alveoli by increasing the mean airway pressure. The mean airway pressure correlates with mean alveolar volume, which contributes to the increased surface area available for gas exchange. The $T_{\text{low}}$ may be reduced to as little as 0.2 seconds.

![Figure 3](image-url)

**Figure 3:** Volume/time diagrams comparing functional residual capacity in airway pressure release ventilation and intermittent mandatory ventilation. Reprinted with permission of Dräger Medical, Lübeck, Germany.

### Table 2: Classifications and Characteristics of Biphasic Positive Airway Pressure and Airway Pressure Release Ventilation

<table>
<thead>
<tr>
<th>Name of Mode</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMV-BIPAP, equivalent to PCV</td>
<td>Time cycled, pressure controlled; No spontaneous breathing</td>
</tr>
<tr>
<td>BIPAP</td>
<td>Time cycled, pressure controlled; Spontaneous breathing at both pressure levels; $P_{\text{high}}$ long enough to allow spontaneous breathing at upper level; $I:E$ ratio approximately 1:1</td>
</tr>
<tr>
<td>BIPAP + PS</td>
<td>Pressure support provides additional inspiratory assistance of spontaneous efforts at the lower pressure level; Used with longer $T_{\text{low}}$ settings during weaning</td>
</tr>
<tr>
<td>APRV (traditional)</td>
<td>Time cycled, pressure controlled; $P_{\text{high}}$ longer than $P_{\text{low}}$; Spontaneous breathing occurs at upper level; If no spontaneous breathing is equivalent to PCV-inverse ratio</td>
</tr>
<tr>
<td>APRV (extended)</td>
<td>Time cycled, pressure controlled; $T_{\text{high}}$ extended to 4 to 6 seconds; $T_{\text{low}}$ reduced to $\leq0.8$ seconds; Spontaneous breathing at upper level</td>
</tr>
</tbody>
</table>

BIPAP: biphasic positive airway pressure; APRV, airway pressure release ventilation; CMV, controlled mandatory ventilation; PCV, pressure-controlled ventilation; $I:E$, inspiratory/expiratory; $P_{\text{high}}$, pressure high; PS, pressure support; $T_{\text{high}}$, time high; $T_{\text{low}}$, time low.
(default setting of 0.8 sec) in order to terminate the expiratory flow early, causing retention of lung volume referred to as end-release lung volume.\textsuperscript{37} This will prevent de-recruitment associated with the lack of PEEP due to maintenance of an end-expiratory volume.\textsuperscript{38}

This application of APRV requires a $P_{\text{high}}$ setting based on the inspiratory plateau pressure or a setting of 30 to 35 cm H\textsubscript{2}O. The recommended $P_{\text{low}}$ setting is 0 cm H\textsubscript{2}O. Setting the $P_{\text{low}}$ at 0 cm H\textsubscript{2}O facilitates rapid expiratory gas flow driven by lung recoil, which reduces the time required for release and provides more time for $P_{\text{high}}$.\textsuperscript{38} Use of a higher $P_{\text{low}}$ setting will reduce expiratory gas flow and result in gas trapping and CO\textsubscript{2} retention.\textsuperscript{39}

The short release time may result in the development of intrinsic PEEP in patients with delayed alveolar emptying. However, in some patients, intrinsic PEEP may beneficially improve gas exchange due to alveolar recruitment. Nonetheless, excessive intrinsic PEEP will result in alveolar hyperinflation.\textsuperscript{24,38} This mandates careful assessment of the inspiratory portion of the flow waveform (Figure 2) and differentiation between restrictive or obstructive lung disease when selecting the $T_{\text{low}}$. Patients with restrictive lung disease may tolerate $T_{\text{low}}$ settings of 0.2 to 0.8 seconds, whereas patients with obstructive disease may require a longer $T_{\text{low}}$ (0.8 to 1.5 seconds) to prevent deleterious levels of intrinsic PEEP.\textsuperscript{37} In a study by Neumann and associates\textsuperscript{41} comparing different $T_{\text{high}}$ and $T_{\text{low}}$ settings in APRV, an increase in PaCO\textsubscript{2} was only noted in patients with COPD when the $T_{\text{low}}$ was reduced to 0.5 seconds. Notably, the study did not identify significant differences in oxygenation when extending the $T_{\text{high}}$ despite the increase in mean airway pressure. However, patients were only maintained on the settings for 20 minutes, which arguably is not enough time to produce dramatic changes in oxygenation. The study also noted an increase in the proportion of spontaneous breathing with the extended $T_{\text{high}}$ setting. This indicates the $T_{\text{high}}$ setting has to be long enough to facilitate spontaneous breathing at the upper pressure level.

**Advantages and Disadvantages**

APRV has been shown to be an effective mode in the management of recruitable diseases, such as ALI and ARDS, that are characterized by atelectasis and V/Q mismatch.\textsuperscript{38} Spontaneous breathing during APRV produces a better distribution of gas to dependent lung regions, improving alveolar recruitment.\textsuperscript{37} However, a recent evidence-based review of mechanical ventilation in sepsis-induced ALI and ARDS recommends APRV should only be used in controlled clinical trials or as a rescue therapy.\textsuperscript{42}

Increased resources may be required to train staff in the principles of APRV.\textsuperscript{38} In order to gain confidence with APRV, clinicians need good knowledge of flow waveforms in order to be able to assess the appropriateness of $T_{\text{high}}$ and particularly $T_{\text{low}}$ settings. Close monitoring of minute ventilation is required to respond appropriately to changes resulting from alterations in compliance and resistance.\textsuperscript{24} In addition, the management of patients on APRV with higher pressure levels may produce periods of respiratory instability during procedures that warrant the use of transport ventilators without APRV capability and manual resuscitation bags.\textsuperscript{38} Clinicians are required to carefully monitor tidal volumes and gas exchange during these procedures. In addition, transportation of patients out of the ICU should only be considered when the clinical outcomes outweigh the associated risks.

**Clinical Studies of Biphasic Positive Airway Pressure and Airway Pressure Release Ventilation**

Careful interpretation of research findings for BIPAP and APRV is required due to previous misunderstanding with the terminology. Examination of the inspiratory and expiratory times cited in the study will help determine which method of partial ventilatory support (BIPAP, APRV [traditional], APRV [extended technique]) is being referred to.

Clinical studies have compared these 2 modes to a variety of other ventilation modes including SIMV, PSV, and inverse ratio volume control. Significant findings of studies on BIPAP and APRV have shown improvements in V/Q match and oxygenation, a reduction in the work of breathing and peak inspiratory pressures.\textsuperscript{22,26,28,36,41,44} In a recent study, Putensen and associates\textsuperscript{25} compared APRV (traditional) with PCV-CMV in 30 trauma patients at risk of developing ARDS. The APRV group demonstrated consistently better oxygenation and hemodynamic parameters plus reductions in sedation and inotrope use, and the durations of ventilation and ICU stay.
Studies on partial ventilatory support modes have shown a reduced effect on the cardiac output with these modes compared to controlled mechanical ventilation. Furthermore, studies have examined if the hemodynamic benefits identified with spontaneous breathing during APRV using the traditional approach can also be seen in spontaneous breathing with PSV with equivalent minute ventilation and airway pressures. Putenson and associates found improved V/Q match in APRV with spontaneous breathing; however, no improvements were noted in the PSV group. In addition, Hering and associates examined the effects of APRV with and without spontaneous breathing on renal perfusion in patients with ALI. The study identified a statistically significant improvement in renal perfusion and function in the spontaneously breathing patients.

Unlike the dual control modes (PRVC, VSV), BIPAP and APRV do not provide guarantee of a minimum VT. Therefore, clinicians are required to monitor V T, respiratory frequency, and ABGS to identify and respond to changes in these parameters caused by alterations in resistance and compliance. The P high setting and respiratory frequency may be adjusted either up or down to increase or decrease V E. Furthermore, increasing the T high may assist in improving gas exchange in patients exhibiting refractory hypoxemia.

Another clinically significant aspect of these modes is the ability to maintain unrestricted spontaneous breathing during both the inspiratory and expiratory phase of ventilation. This results in improved patient-ventilator synchrony and thus reduced sedation requirements. Patients are able to participate in activities, such as physiotherapy and respiratory muscle training, that potentially reduce the duration of ventilation and incidence of ventilator-associated pneumonia. Clinicians need to balance the need to reduce sedation to facilitate spontaneous breathing while preventing increased anxiety and agitation associated with increased awareness of the ICU environment and critical illness.

**Optimal and Knowledge-based Control**

**Adaptive Support Ventilation**

Adaptive support ventilation (ASV) is a new mode available on the Galileo ventilator (Hamilton Medical, Rüzins, Switzerland). This mode provides full or partial ventilatory support during the initiation, maintenance, or weaning phases of mechanical ventilation. Clinicians are required to set the ideal body weight, desired percentage of V E (20% to 200%), FIO2, PEEP, and maximal inspiratory pressure alarm. A desired VE setting of 200% is equivalent to a VE of 200 mL/min/kg and represents full ventilatory support. Reduction of the desired VE percentage setting by the clinician facilitates weaning of the patients. Thus, the desired VE percentage enables the clinician to titrate ventilation to provide full mechanical support or encourage spontaneous breathing with the aim of weaning and extubation. The ventilator delivers 5 test breaths that determine the initial respiratory frequency, V T, pressure limit of mandatory and spontaneous breaths, inspiratory time of mandatory breaths, and I:E ratio when spontaneous breathing is absent. The ventilator determined settings maintain the predetermined desired VE percentage set by the clinician. Titration of the desired VE percentage requires clinician decision input to enable progression to readiness for extubation.

ASV has been described as a mode incorporating PCV and PSV, with automatic adaptation of respiratory rate and pressure levels. In the absence of spontaneous ventilation, ASV delivers SIMV style PCV, using lung mechanics measured during each breath to guide adjustment of ventilator settings. During spontaneous respiratory effort, the ventilator switches from PCV to PSV and reverts to PCV if the patient’s VE drops below the guaranteed minimum. The level of pressure support is also adapted to provide adequate tidal volumes according to the desired VE percentage set. If the patient develops rapid shallow breathing indicative of inadequate ventilatory support, the pressure support is automatically increased, thus providing real-time adaptation of ventilator support according to the patient’s respiratory demands and preventing the development of respiratory distress.

The majority of clinical studies of ASV have been conducted in cardiothoracic patients. This is remarkable considering the complexity of the mode and the perceived straightforwardness of ventilatory management in this patient group. These studies found ASV was safe and resulted in durations of ventilation comparable to those published in other studies of early extubation postcardiac surgery. A notable finding in one study was
the reduction in apnea and high-pressure alarms in the ASV group that the authors suggested could potentially improve the working environment of nurses.

**Proportional Assist Ventilation**

Proportional assist ventilation (PAV) is a spontaneous mode designed to deliver support based on continuous measurement of the patient's ventilatory parameters. There are no set targets of pressure, volume, or flow; rather, the airway pressure is increased or decreased in proportion to the patient effort via positive feedback control using respiratory elastance and resistance as the feedback signals. The patient's respiratory drive determines the respiratory rate and inspiratory time while FIO₂ and PEEP are set by the clinician. The other settings required are the percentage of volume assist and the percentage of flow assist. The percentage of volume assist overcomes elastance and the percentage of flow assist overcomes resistance. These assist settings are routinely set at 80%.

Proportional assist ventilation has been described as the only mode to be primarily designed on a physiological basis rather than the technical abilities of ventilators. Proportional assist ventilation is available as Proportional Pressure Support (PPS) on Dräger Evita 4 and XL ventilators (Dräger Medical, Lübeck, Germany). One proposed advantage of PAV is the ability to respond to rapid changes in ventilatory effort associated with increased elastance and resistance that occurs in patients with respiratory failure. This enables respiratory muscle unloading during increases in inspiratory effort and improves patient comfort due to a reduction in the work of breathing.

Negative aspects associated with PAV include difficulties with accurate measurement of elastance and resistance in spontaneously breathing patients or those receiving partial support, and the confounding effects imposed by endotracheal tube resistance and the presence of auto-PEEP. Difficulty in determining appropriate settings for percentage of volume and flow assist has discouraged the adoption of this mode into mainstream clinical practice.

**Knowledge-based System (Smartcare)**

Various other systems for titration of mechanical ventilation and weaning have been developed and investigated as a potential solution to inefficient weaning and alternative to traditional methods. One system that has been made available for commercial application is the knowledge-based system (Smartcare), available on the Dräger XL ventilator.

The knowledge-based ventilation system differs from the other modes described above. The Smartcare™ application uses several inputs to enable titration of pressure support in response to changes in patient respiratory rate, V₁, and etCO₂ in order to maintain the patient in a “respiratory zone of comfort.” The patient's respiratory rate is the most influential parameter, as it reflects the respiratory muscles' ability to adapt to changes in workload. V₁ and etCO₂ are incorporated into the system to ensure safety.

The application was designed for weaning in the presence of spontaneous ventilation using the pressure support mode. To commence Smartcare™ weaning simply requires activation of the Smartcare™ option on the ventilator; no other setting changes are required. The Smartcare™ system acquires data on the patient’s current respiratory status and its time course, establishes a respiratory status diagnosis, determines the intervention, and acts on the ventilator to adjust pressure support. The Smartcare™ system samples patient parameters over periods of 2 minutes and adjusts the pressure support level accordingly. Acceptable parameter ranges are noted in Table 3.

The modification of pressure support also takes into account the patient's breathing

<table>
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<tr>
<th>Table 3: Acceptable Ranges for Ventilator Parameters with Smartcare, Respiratory Zone of Comfort</th>
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<tr>
<td><strong>Parameter</strong></td>
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<tr>
<td>Respiratory rate</td>
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<td>Tidal volume</td>
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<td>End tidal carbon dioxide (EtCO₂)</td>
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pattern history. If the pressure support is below 15 cm H₂O, it will be decreased by 2 cm H₂O once the patient’s ventilation has been stable within the “respiratory zone of comfort” for 30 minutes; if the pressure support level is higher than 15 cm H₂O, it will be decreased by 4 cm H₂O if the ventilation has been acceptable for the last 60 minutes. When the respiratory rate exceeds 30 breaths/min, the pressure support is increased by 2 cm H₂O and increased by 4 cm H₂O when the respiratory rate exceeds 36 breaths/min. The system also tolerates transient instabilities for 2 or 4 minutes depending on the level of pressure support. When the patient has tolerated the lowest level of pressure support for 1 to 2 hours depending on the initial pressure support setting, the Smartcare™ system suggests the potential for disconnecting from the ventilator, termed “readiness for separation.” It is then up to the clinician to determine whether the patient is ready for extubation or if there are additional factors that mandate the ongoing requirement for intubation.

The key aspect of this technology is the ability to monitor the patient’s respiratory status in real time, which potentially encourages a rapid, safe, and efficient weaning process and minimizes possible complications, such as respiratory distress, increased work of breathing, and impaired ventilation and oxygenation. Furthermore, the Smartcare™ system has the potential to reduce the duration of ventilation and weaning. A recent study of patients receiving mechanical ventilation for greater than 24 hours found a halving of the weaning duration and significant reductions in the duration of total ventilation, ICU stay, and use of non-invasive ventilation post extubation.

The benefits of this application may be most evident in units with barriers to ventilation decision-making processes, such as poor staffing ratios and levels of experience. The Smartcare™ program potentially reduces the number of clinician decisions required to wean the patient to the point of extubation. However, the decision to activate the Smartcare™ program to commence the weaning process remains that of the clinician. Assessment of respiratory parameters that indicate weaning readiness is performed by the clinician prior to initiation of the program. This requires knowledge and recognition of both objective and subjective indices of weaning readiness and their thresholds.

Implications of Advanced Modes for Clinicians

Advanced modes of ventilation have a number of direct implications for clinical practice. Incorporation of new modes into practice requires intense education programs and experienced members of staff to facilitate appropriate and safe mechanical ventilation for all patients. Education programs need to focus on the clinical applications of modes including appropriate settings, weaning techniques, and assessment of patient-ventilator interaction. Advanced modes require high levels of expertise in arterial blood gas and waveform analysis, combined with knowledge of current scientific recommendations for management of the various patient groups that require mechanical ventilation. Clinicians require excellent assessment skills and knowledge of respiratory parameters and weaning indices in order to assess the appropriateness of a ventilator mode’s ability to meet the ongoing needs of the patient.

Dual control modes that guarantee V̇̇ while maintaining set peak inspiratory pressures provide an additional safety feature for patients and busy clinicians who possibly may be unable to respond to changes in a patient’s ventilation status in a timely manner. Modes that offer real-time monitoring and adjustment of ventilator parameters may prevent inappropriate ventilation, that leads to increased rates of ventilator-associated complications to which clinicians are required to respond and manage. Ventilator-initiated as opposed to clinician-initiated titration of ventilator parameters arguably may overcome barriers to timely ventilation decision making, such as unavailability of experienced staff and overstretched resources.

Another potential advantage of some advanced modes is a reduction in ventilation and ICU stay durations. These outcomes produce significant patient benefits relating to reduced complications associated with mechanical ventilation and ICU admission. However, it must be noted that the favorable reductions in ventilation and ICU durations also alter the staff workload profile. Nonventilated patients frequently entail a lower staff/patient ratio despite potentially requiring a higher number of interventions. For example, the confused, combative patient requiring non-invasive ventilation often requires more clinical interventions than the stable mechanically ventilated
patient. Reduced durations of stay result in increased levels of patient throughput, which may place additional stressors on the clinical workforce. These issues require consideration from an organizational perspective to inform current workforce discussions.

Summary

Advances in computer technology and scientific knowledge of lung pathophysiology continue to produce new and sophisticated ventilator modes designed to facilitate the most appropriate and safe method of delivering mechanical ventilation. Advanced modes combine pressure control-style ventilation with guaranteed volume or spontaneous breathing at upper and lower pressure levels and facilitate ventilator recognition and adaptation to patient parameters. Increasingly, ICU clinicians need to develop a sophisticated level of understanding of mechanical ventilation and accompanying respiratory physiology to ensure safe and effective management of patients ventilated by these modes. Although physiological benefits have been identified, there are few reported large clinical studies that evaluate the efficacy of these modes; hence, further research is required.

REFERENCES