Clinical Design Features of Modern Mechanical Ventilators

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Objectives

• Understand the three phases of breath delivery: trigger, target, and cycle
• Understand how the various breath designs constitute the common modes of mechanical ventilation
• Understand newer features of partial closed-loop control

Introduction

Positive-pressure mechanical ventilators have evolved during the past several decades from simple high-pressure gas regulators to sophisticated microprocessor systems controlling many aspects of breath delivery, inspiratory/expiratory timing, and expiratory pressure. Terminology describing these operations has also evolved and is often confusing. Some of this confusion is a consequence of manufacturers’ trade names describing a common design feature in multiple proprietary terms. Another problem has been that simple older terminology is unable to fully describe many of the advances that have occurred. Two examples are the mandatory versus spontaneous breath classifications and the concepts underlying controlled versus assisted ventilation. The terms mandatory versus spontaneous originally meant machine alone versus patient alone. Today things are blurred as patients can trigger breaths (spontaneous feature) with substantial ventilator support supplied (mandatory feature). The term control originally meant parameters that the ventilator manipulated (volume- or pressure-controlled). Now the term is often used to distinguish a patient-triggered breath from a machine-triggered breath (assist-control). In this chapter I will generally avoid the terms mandatory and spontaneous and instead use the terms assist and control to mean patient- and machine-triggered breaths, respectively.

Basic Concepts

Breath Delivery Algorithms

While the engineering principles underlying positive-pressure breath delivery can be quite complex, from a clinical perspective, a mechanical breath can be described in terms of what initiates the breath (trigger variable), what controls gas delivery during the breath (target or limit variable), and what terminates inspiration (cycle variable).

In general, breaths can be initiated (triggered) by patient effort (assisted breaths) or by the machine’s timer (controlled breaths). Effort sensors generally are either pressure or flow sensors and are characterized by their sensitivity/responsiveness. Target or limit variables generally are either a
set flow or a set inspiratory pressure. With flow targeting, the ventilator adjusts pressure to maintain a clinician-determined flow magnitude and pattern (sine, square, accelerating, decelerating); with pressure targeting, the ventilator adjusts flow to achieve and maintain a clinician-determined inspiratory pressure. Modern systems also usually allow adjustment of the rate of pressure rise to the pressure target. Cycle variables are generally a set volume, a set inspiratory time, or a set reduction in inspiratory flow rate as the lung fills during pressure-targeted ventilation. This flow-cycling criterion is either manufacturer specific (eg, 25–35% of peak flow), or clinician-adjusted on many newer machines. A secondary cycling mechanism may be present on some devices if inspiratory time exceeds a certain percentage (eg, 80%) of a set total cycle time without reaching the flow-cycling criterion. Breaths can also be cycled off if pressure limits are exceeded.

With this approach to classifying the inspiratory cycle characteristics, basic breath delivery algorithms from modern mechanical ventilators can be broken into five basic categories of breath: volume control (VC), volume assist (VA), pressure control (PC), pressureassist (PA), and pressure support (PS) (Figure 1).3

Figure 1. The five basic breaths defined by trigger, target, and cycle variables

Depicted are airway pressure, flow, and volume tracings over time. Solid lines reflect set changes; dotted lines reflect variable changes from effort or mechanics changes. The five basic breaths: 1) volume control is machine triggered, flow targeted, volume cycled; 2) volume assist is patient triggered, flow targeted, volume cycled; 3) pressure control is machine triggered, pressure targeted, time cycled; 4) pressure assist is patient triggered, pressure targeted, time cycled; 5) pressure support is patient triggered, pressure targeted, flow cycled.

**Basic Modes of Ventilatory Support**

The availability and delivery logic of different breath types define the mode of mechanical ventilatory support. The mode controller is an electronic, pneumatic, or microprocessor-based system designed to provide the proper combination of breaths according to set algorithms and feedback data (conditional variables). The five most common modes are volume assist-control ventilation (VACV), pressure assist-control ventilation (PACV), volume-synchronized intermittent mandatory ventilation (V-SIMV), pressure-synchronized intermittent mandatory ventilation (P-SIMV), and stand-alone pressure support ventilation (PSV) (Figure 2). Examples of proprietary names for these basic modes are given in Table 1.

Depending upon the set (backup) control breath rate, VACV and PACV can range from totally machine controlled to totally patient assisted. V-SIMV and P-SIMV can provide VA and VC or PA and PC breaths.

### Table 1. Examples of Proprietary Names for the Five Basic Modes and Two Feedback Features

<table>
<thead>
<tr>
<th>Mode</th>
<th>VAC</th>
<th>VA</th>
<th>PC</th>
<th>PA</th>
<th>PS</th>
<th>Sp</th>
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<tbody>
<tr>
<td>Volume assist—control</td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td>Pressure assist—control</td>
<td></td>
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<td>X</td>
<td>X</td>
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<tr>
<td>Volume SIMV</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Pressure SIMV</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Pressure support</td>
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<td>X</td>
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</table>

The breaths are the five breaths depicted in Figure 1 plus an unassisted spontaneous breath (Sp). Note that the clinician-set breath rate can result in VACV and PACV being totally controlled ventilation (high set rate), virtually totally assisted ventilation (very low or absent set rate), or assist-control ventilation (intermediate set rate).

Abbreviations: PA, pressure assist; PACV, pressure assist-control ventilation; PC, pressure control; PS, pressure support; SIMV, synchronized intermittent mandatory ventilation; Sp, spontaneous breath; VA, volume assist; VACV, volume assist-control ventilation; VC, volume control.

interspersed among either unsupported or PS breaths. Data from international surveys\(^4\) indicate that the most commonly used mode worldwide is VACV, with PACV a distant second. Intermittent mandatory ventilation modes have been steadily decreasing in use while stand-alone PSV modes have been increasing in use.

Choice of mode depends on the clinical goals coupled with an understanding of ventilator breath design features. Mandatory (backup) breath rates are set based on the patient’s basic ventilation need per minute and the reliability of the patient’s effort to achieve it. The choice of pressure versus flow/volume targeting involves balancing the synchrony enhancement of pressure targeting against the volume guarantee of flow/volume targeting.\(^5\) When using patient-triggered, pressure-targeted breaths, cycling on time (PA breaths) versus flow (PS breaths) depends on patient comfort/synchrony.

Airway pressure release ventilation (APRV) is often touted as a new mode but can be viewed as a variant of P-SIMV in which the inspiratory time is set longer than the expiratory time and the patient is allowed to effectively draw breaths during the high-pressure phase. Patient efforts thus usually occur during the inflation phase and can produce additional unassisted or PS breaths. A point of confusion exists in setting up APRV—dedicated APRV modes on most devices have the set inspiratory pressure referenced to atmospheric pressure rather than the set expiratory pressure as is customary with more conventional modes. Proponents of APRV argue that the long inspiratory-expiratory (I:E) ratio raises mean airway pressure without additional set positive end-expiratory pressure (PEEP) or tidal volume (Vt) and that the spontaneous efforts during the inflation phase enhance gas mixing and cardiac filling.\(^6\) Examples of proprietary names are given in Table 1.

### Positive End-Expiratory Pressure

PEEP can be generated in two basic ways: applied or intrinsic. Applied PEEP is set by the clinician and is usually provided by valving systems in the expiratory limb. Modern ventilators also can adjust circuit flow during exhalation to assure PEEP maintenance in the setting of circuit leaks. Intrinsic PEEP develops in the setting of high minute ventilation, short expiratory times, and high airway resistance/high compliance lung units. Total PEEP is the sum of intrinsic PEEP and any PEEP externally set by the clinician. Confusion sometimes develops when intrinsic PEEP is taken to mean total PEEP. Because of this, some use the term auto-PEEP instead of intrinsic PEEP in settings in which applied PEEP is present. Importantly, applied PEEP distributes evenly throughout the lung, while intrinsic PEEP is highest in high resistance/high compliance lung units and lowest in low compliance/low resistance units.\(^7\) Conventional approaches to PEEP generally rely on set PEEP and avoidance of intrinsic PEEP. However, proponents of APRV argue for the use of intrinsic PEEP to maximize expiratory flow and minimize expiratory time.

### FEEDBACK CONTROL FEATURES

As mechanical ventilators have evolved, the capability has grown for microprocessor-
Based systems to monitor conditional variables and use this information to automatically adjust timing, flow, pressure, and even fraction of inspired oxygen (FiO₂) (feedback control). An early example was the use of a patient effort sensor (conditional variable) to adjust the number of mechanical breaths provided during either assist control modes or SIMV. A variation on this breath rate feedback mechanism was mandatory (or minimum) minute ventilation, which used minute ventilation to adjust the number of positive-pressure breaths delivered. Currently available systems that partially close the loop are described below.

**Inspiratory Pressure and Flow Adjustments Based on Artificial Airway Geometry**

The endotracheal tube (ETT) imposes a significant inspiratory (as well as expiratory) resistance on a spontaneously breathing patient. This imposed inspiratory load can have an impact on flow synchrony during interactive assisted/supported breaths and can make it difficult to assess potential for ventilator withdrawal during periods of unassisted/unsupported breathing.

Low level (eg, 5–8 cm H₂O) PS has been proposed as a way of eliminating the ETT resistive load. However, the PS algorithm supplies a constant inspiratory pressure, which, because of the high fixed resistance of the ETT, tends to undercompensate the load at the beginning of the breath. Moreover, the need varies with minute ventilation. Patient muscle unloading thus is uneven and may be suboptimal.

To better address this loading pattern, many ventilators have the capability to calculate the ETT resistance properties based on clinician input of ETT length and diameter. The ventilator incorporates this calculation with measurements of instantaneous flow to apply pressure proportional to resistance throughout the total respiratory cycle. It must be recognized that the ETT compensation strategy is based on the input geometry of the artificial airway and cannot account for changes in tube characteristics induced by kinks or partial occlusions or the relationship of the tube opening against the tracheal wall.

**Feedback Control of Combination Pressure- and Flow-Targeted Breaths**

During the past two decades, a number of engineering innovations have attempted to combine the flow synchrony advantages of pressure-targeted breaths with the volume guarantee features of flow-/volume-targeted breaths. The most common approach uses standard pressure-targeted breaths with the ventilator adjusting the pressure target according to a clinician-set Vt. When these breaths are exclusively supplied with time cycling, the mode is commonly referred to as pressure-regulated volume control (PRVC) but has a number of proprietary names (Table 1). When these pressure-targeted breaths are supplied exclusively with flow cycling, the mode is commonly referred to as volume support (VS). Some ventilators switch between these two breath types, depending on the number of patient efforts. The maximum pressure change from breath to breath on most systems generally is limited to a few centimeters of water to prevent sudden large swings in pressure and volume.
These modes have been assessed clinically in two settings. First, in severe parenchymal lung injury (eg, acute respiratory distress syndrome [ARDS]), PRVC has been used as a way to provide more synchronous pressure-targeted breaths while assuring that safe Vt delivery is maintained. One study demonstrated that this was generally possible, although a minority of patients had significant periods of time with Vt that exceeded the targeted value.\textsuperscript{10} Second, VS has been touted as a means to automatically wean patients, the theory being that, as patients recover, they will make stronger inspiratory efforts and VS will automatically reduce inspiratory pressure. Conversely, inspiratory pressure would increase if patient effort diminished or respiratory system mechanics worsened. It should be noted that the majority of patients do not benefit from graded withdrawal of machine support. Therefore, whether this approach is superior to routine spontaneous breathing trials is unclear.

Clinicians must also be cautious in using VS in this weaning setting because if the clinician-set volume is excessive for patient demand, a patient may not attempt to take over the work of breathing for that volume and thus support reduction, and weaning may not progress. In addition, if the pressure level increases in an attempt to maintain an inappropriately high set Vt in the patient with airflow obstruction, an increase of intrinsic PEEP may result. VS may also inappropriately lower inspiratory pressure in a patient with excessive flow demands induced by pain, anxiety, or acidosis.\textsuperscript{11}

**Enhanced Feedback Control of Combination Pressure- and Flow-Targeted Breaths**

Monitoring of airway occlusion pressure, oxygen saturation, and end-tidal CO\textsubscript{2} concentrations have been incorporated in various fashions into the pressure-flow/volume hybrid breaths described above.\textsuperscript{12} One commercial system uses end-tidal CO\textsubscript{2} and respiratory rate along with the Vt to adjust the applied inspiratory pressure (SmartCare). This system attempts to find an inspiratory pressure that maintains the respiratory rate and Vt in a clinician-set “comfort zone,” adjusting it as necessary. The end-tidal CO\textsubscript{2} serves as a backup signal to ensure adequate ventilation. Inspiratory pressure is reduced to as low a level as possible within these boundaries. The system will alert the clinician to perform a spontaneous breathing trial when this pressure reaches 9 cm H\textsubscript{2}O. Although clinical trials have failed to consistently show an advantage to this approach,\textsuperscript{13} an automated system that is just as good as clinicians could have applications in settings of rapidly recovering patients or low availability of clinicians to make frequent assessments.

**Feedback Control of Ventilator Breath Delivery Based on Respiratory System Mechanics**

A novel approach to automated feedback control of ventilator support controls a pressure-targeted breath using a Vt, frequency, and I:E ratio algorithm based on respiratory system mechanics. The objective is to help the patient maintain an efficient and effective breathing pattern. Known as
adaptive lung ventilation or adaptive support ventilation (ASV), the system calculates respiratory system mechanics using several controlled test breaths. It then uses a “minimal work” calculation to set the frequency-Vt pattern that minimizes the combined resistance and compliance components of work. The ASV algorithm then attempts to minimize intrinsic PEEP by measuring the expiratory time constants (RCe) and providing an expiratory time of at least three RCes.

With ASV, clinicians must set the desired minute ventilation and the proportion of that minute ventilation that the machine is to supply. Ideal body weight also can be used to calculate the desired minute ventilation based on metabolic demands and predicted dead space. Clinicians practicing in the United States also must set the PEEP and FiO2. When spontaneous efforts occur with ASV, the algorithm responds with fewer mandatory breaths and adjusts inspiratory pressure according to the minimal work Vt considerations above. ASV has been shown to perform as designed. In healthier lungs, Vts may exceed lung-protective guidelines. There are no meaningful outcome studies showing clear benefit.

**Feedback Systems Controlling PEEP and FiO2**

On a mechanical ventilator, an FiO2 controller conceptually could be coupled to a feedback controller of PEEP to meet oxygenation and mechanical goals (ie, partial arterial oxygen pressure [Pao2] or oxygen saturation targets balanced against lung compliance or plateau pressure). One system approved outside the United States incorporates the PEEP-FiO2 table used by the National Institutes of Health ARDS Network study. With this algorithm, PEEP and FiO2 combinations are guided by a partial arterial oxygen pressure target range of 55–80 mm Hg and a plateau pressure limit of 30–35 cm H2O. While this table proved safe and effective in ARDS Network trials, it has yet to be demonstrated whether an automated system using it will improve outcomes.

**MODES DrIVEN BY NOVEL SENSORS OF PATIENT EFFORT**

Two new modes have recently been introduced that use unique feedback control based on patient effort to control positive-pressure breath delivery. The first is proportional assist ventilation (PAV), an approach that applies a clinician-set pressure and flow “gain” on patient-generated flow and volume. PAV uses intermittent controlled “test breaths” to calculate resistive and elastic work. The clinician is required to set a desired proportion of the total work that should be performed by the ventilator. The ventilator continuously measures the patient flow and volume during each breath, adding sufficient flow and airway pressure to achieve the selected proportion of the breathing work. The combined application of pressure and flow distinguishes it from PSV, which applies variable flow and a clinician-set fixed airway pressure. PAV has been compared to
power steering on an automobile, an apt analogy. Like PAV, power steering reduces the work to turn the wheels but does not automatically steer the car; the driver must control the car’s ultimate direction just as the patient ultimately must control the magnitude of the breath and the timing of the breathing pattern. Newer PAV modifications (PAV+) automatically revise machine output by recalculating tidal mechanics periodically during a brief occlusion applied at the start of exhalation. In this way, the clinician simply has to select the percentage of the breathing workload that the machine should supply.

Because PAV requires sensors in the ventilator circuitry to measure patient effort, it is susceptible to the same sensor performance and intrinsic PEEP issues that affect breath triggering in other assisted modes. Also like conventional assisted modes, the clinician must set PEEP and Fio2. Finally, breath termination (cycling) is much like pressure support and is determined by a clinician-adjustable percentage of maximal inspiratory flow.

In multiple studies, PAV has been shown to perform as designed.12,16 However, whether PAV improves meaningful clinical outcomes (eg, sedation needs, shorter duration of mechanical ventilation) remains to be determined.

A second novel mode is neurally adjusted ventilatory assist (NAVA), which uses a diaphragmatic electromyography (EMG) signal to trigger, govern flow, and cycle ventilatory assistance.12,17 The EMG sensor is an array of electrodes mounted on a catheter that is positioned in the esophagus at the level of the diaphragm. Ventilator breath triggering is thus virtually simultaneous with the onset of phrenic nerve excitation of the inspiratory muscles, and breath cycling is tightly linked to the cessation of inspiratory muscle contraction. Flow delivery is driven by the intensity of the EMG signal (electrical activity of the diaphragm) and the clinician sets an mL/mV gain factor. Output from the catheter provides a unique means of tracking inspiratory and expiratory neural timing and has been used effectively in recent research for this purpose.

Like PAV, NAVA depends exclusively on patient effort for timing, intensity, and duration of the breath. Thus, like PAV, clinicians must set appropriate alarms and backup positive-pressure ventilation, especially for patients with unreliable respiratory drives. Also like PAV, clinicians must set PEEP and Fio2.

NAVA has been shown to perform as designed12,17 and, conceptually, it should provide excellent patient-ventilator synchrony. However, data are lacking that demonstrate improved outcomes (eg, duration of mechanical ventilation, sedation needs). Another concern with NAVA is the expense associated with the EMG sensor.

**DESIGN CONSIDERATIONS FOR PEDIATRIC/NEONATAL APPLICATIONS**

Design features for pediatric and neonatal applications are similar to those already described for adult applications. However, mechanical ventilation of pediatric patients
(especially neonates) does require a number of adjustments to device performance specifications and sometimes availability of specific modes.

Specific differences among adult, pediatric, and neonatal operations usually involve the available ranges for breath rates, Vts, flows, breath timing, and alarm configurations. In general, pediatric (especially neonatal) applications require faster breath rates, smaller Vts, lower maximal flows, and shorter inspiratory times. These capabilities require flow sensor technology that is able to accurately measure flow to less than 30 mL/min and volumes to less than 2 mL. Displays must be modified accordingly. To ensure accurate monitoring, it is also advisable to use proximal flow sensors, especially in neonates, whose respiratory system compliances are often lower than the breathing circuit.

Pediatric and neonatal mechanical ventilator strategies generally do not include modes such as PRVC or APRV. Instead, a popular mode, especially for neonates, is time-cycled, pressure-limited ventilation—a pressure-targeted mode that requires clinician input for inspiratory flow and duration.

In the past, these features often required a dedicated pediatric or neonatal ventilator. Modern devices, however, are usually capable of providing the necessary range of performance capabilities and can be configured by the operator to support patients across the age spectrum.¹⁸

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**KEY POINTS**

- The goal of mechanical ventilation is to provide positive-pressure breaths to the lungs that are adequate for gas exchange and appropriate muscle unloading while minimizing any risk for injury or discomfort.
- In general, breaths can be initiated (triggered) by patient effort (assisted breaths) or by the machine’s timer (controlled breaths).
- The latest generation of ventilators uses sophisticated feedback systems to “sculpt” positive-pressure breaths according to patient effort and respiratory system mechanics to accomplish these goals.
- At present, new control strategies are not totally closed-loop systems because the automatic input variables are still limited, some clinician settings are still required, and the specific features of the perfect breath design still are not entirely clear.
- Despite these limitations, there is at least some rationale for many of the newer feedback features, even though virtually all of them await outcome studies to further justify their widespread use.

**REFERENCES**


