CHAPTER

# 6

# Ventilator Initiation

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## OUTLINE



## OBJECTIVES

1. Describe the primary function of a mechanical ventilator.
2. Identify the four major indications for mechanical ventilation.
3. Describe the major goals of mechanical ventilation.
4. Overview the historical development of negative-pressure ventilation.
5. Explain the advantages and disadvantages of negative-pressure ventilation.
6. Define the term trigger variable and compare time-triggered ventilation to patient-triggered ventilation.
7. Explain each of the following terms related to the trigger variable: flow trigger, pressure trigger, and autotrigger.
8. Define each of the following commonly used terms: *assist breath*, *control breath*, *assist-control*, and *controlled ventilation* in terms of the trigger variable associated with each term.
9. Explain how each of the following cycle variables terminates the inspiratory phase: volume cycled, pressure cycled, time cycled, and flow cycled.
10. Compare volume-control (VC) and pressure-control ventilation (PC).
11. Compare pressure-support ventilation (PSV) and pressure-control ventilation (PCV).
12. Define each of the following: continuous mandatory ventilation (CMV), intermittent mandatory ventilation (IMV), and continuous spontaneous ventilation (CSV).
13. Explain the indications, contraindications, advantages, and disadvantages of noninvasive ventilation (NIV).
14. Describe initial ventilator settings for NIV.
15. Describe methods and steps to establish the airway for invasive mechanical ventilation.
16. Contrast endotracheal intubation and tracheostomy when used to provide invasive mechanical ventilation.
17. Summarize the factors that should be considered when choosing a mechanical ventilator.
18. Explain each of the following terms used to define the mode of ventilation employed: control variable, breath sequence, and targeting scheme.
19. Explain methods for providing full and partial ventilatory support and contrast advantages and disadvantages of each.
20. Define each of the five major modes of ventilation and explain the advantages and disadvantages of each.
21. Explain the use of other modes of ventilation to include adaptive pressure control (APC), mandatory minute ventilation (MMV), adaptive support ventilation (ASV), airway pressure-release ventilation (APRV), proportional assist ventilation (PAV), automode, neutrally adjusted ventilatory assist (NAVA), and high-frequency ventilation (HFV).

22. Describe initial ventilator setup for adult patients to include mode, tidal volume, rate, inspiratory pressure, breath trigger, pressure rise time or slope, inspiratory time, expiratory time and I:E ratio, oxygen concentration, PEEP/ CPAP, alarms and limits, and humidification.

## KEY TERMS

**adaptive pressure control (APC)**
**adaptive support ventilation (ASV)**
**adaptive targeting (a)**
**airway pressure-release ventilation (APRV)**
**assist-control volume ventilation**
**autotriggering**
**automode**
**biovariable targeting (b)**
**continuous positive airway pressure (CPAP)**
**controlled ventilation**
**dual targeting (d)**
**flow cycled**
**full ventilatory support**
**high-frequency jet ventilation (HFJV)**
**high-frequency oscillatory ventilation (HFOV)**
**high-frequency percussive ventilation (HFPV)**
**high-frequency positive-pressure ventilation (HFPPV)**
**high-frequency ventilation (HFV)**
**imposed work of breathing ($WOB_I$)**
**intelligent targeting (i)**
**intermittent mandatory ventilation (IMV)**
**invasive ventilation**
**lung-protective ventilatory strategy**
**mandatory breaths**
**mandatory minute ventilation (MMV)**
**negative-pressure ventilation**
**neurally adjusted ventilatory assist (NAVA)**
**noninvasive ventilation (NIV)**
**optimal targeting (o)**
**partial ventilatory support**
**patient-triggered breaths**
**positive end-expiratory pressure (PEEP)**
**positive-pressure ventilation**
**pressure control-continuous mandatory ventilation (PC-CMV)**
**pressure control-continuous spontaneous ventilation (PC-CSV)**
**pressure control intermittent mandatory ventilation (PC-IMV)**
**pressure-control ventilation (PCV)**
**pressure cycled**
**pressure-regulated volume control (PRVC)**
**pressure-support ventilation (PSV)**
**primary breaths**
**proportional assist ventilation (PAV)**
**rapid sequence intubation (RSI)**
**secondary breaths**
**servo targeting (r)**
**set-point targeting (s)**
**spontaneous breaths**
**synchronized intermittent mandatory ventilation (SIMV)**
**targeting scheme**
**time cycled**
**time-triggered breaths**
**volume control-continuous mandatory ventilation (VC-CMV)**
**volume control intermittent mandatory ventilation (VC-IMV)**
**volume control (VC)**
**volume cycled**
**volume support (VS)**
**work of breathing (WOB)**

# Introduction

The primary function of a mechanical ventilator is to augment or replace normal ventilation. Thus, mechanical ventilation may be required when spontaneous breathing is insufficient or absent. The decision to initiate mechanical ventilatory support should be based on a thorough patient assessment, sound clinical judgment, and an understanding of the indications, contraindications, complications, and hazards of mechanical ventilation. The most common reason for initiation of mechanical ventilatory support is acute respiratory failure. Other common diagnoses associated with the need for mechanical ventilatory support include acute exacerbation of chronic obstructive pulmonary disease (COPD), coma, multiple trauma, and neuromuscular disease. The respiratory care clinician should be aware of predisposing factors for the development of acute respiratory failure, the clinical manifestations of acute respiratory failure, and the indications for mechanical ventilation. These indications include:

- Apnea
- Acute ventilatory failure
- Impending ventilatory failure
- Severe oxygenation problems (refractory hypoxemia)

Other possible indications include the administration of general anesthesia, protection of the airway in the absence of a gag reflex, and the need for deep sedation and/or neuromuscular blockade.

The decision to initiate mechanical ventilatory support must also consider contraindications to mechanical ventilation, and possible complications and hazards. Hazards of mechanical ventilation include ventilator-associated lung injury (VALI), ventilator-associated pneumonia (VAP), and increased work of breathing (WOB) and ventilatory muscle dysfunction due to inappropriate ventilator settings. **Positive-pressure ventilation** may result in reduced venous return to the right heart, decreased cardiac output, and hypotension. Other possible adverse effects of mechanical ventilation include the development of barotrauma (e.g., pneumothorax, pneumomediastinum), airway problems (e.g., accidental bronchial intubation, airway occlusion), and ventilator system failure. Chapter 2 reviews respiratory failure, while Chapter 5 provides a discussion of the indications for mechanical ventilation.

Once the decision has been made to institute mechanical ventilatory support, a number of choices must be made. Most patients will receive some form of positive-pressure ventilation, although **negative-pressure ventilation** may be appropriate in a few select cases. Certain patients may do well with noninvasive positive-pressure ventilation (NPPV), while others may require endotracheal (ET) intubation and invasive mechanical ventilation. Many modern ventilators allow the clinician to choose between providing partial and full ventilatory support, and a large number of different ventilator modes are currently available. Following selection of the appropriate mechanical ventilator

and initial mode of ventilation, the respiratory care clinician must choose the initial ventilator settings. Each of these choices will be discussed in this chapter.

**RC Insight**

Major indications for ventilator initiation include apnea, acute ventilatory failure, impending ventilatory failure, and severe oxygenation problems.

## Goals of Mechanical Ventilation

Mechanical ventilation can normalize alveolar ventilation and $PaCO_2$, reverse hypoxemia, relieve respiratory distress, and allow for recovery from ventilatory muscle fatigue. Properly applied, mechanical ventilation may decrease ventilatory muscle and myocardial oxygen consumption and improve oxygen delivery to the tissues. Mechanical ventilation may also allow for deep sedation and neuromuscular blockade for certain procedures to be performed or in cases of severe distress and agitation, delirium, or severe, refractory hypoxemia. However, for most patients, sedation should only be applied as necessary for patient comfort and effective ventilation. In the presence of a closed head injury (e.g., severe traumatic brain injury) or cerebral edema, mechanical ventilation may be used for a short period of time to reduce the $PaCO_2$, cause cerebral vasoconstriction, and reduce intracranial pressure (ICP). Initial hyperventilation should be avoided in such patients except as a life-saving measure when cerebral herniation has occurred or is imminent.

The primary goals of mechanical ventilation are to provide adequate alveolar ventilation, ensure adequate tissue oxygenation, restore and maintain acid-base homeostasis, and reduce the WOB. Mechanical ventilatory support should be adjusted to ensure patient comfort and safety and minimize harmful side effects and complications. Mechanical ventilatory support should also be applied in such a fashion as to promote prompt liberation of the patient from the ventilator. It should also be noted that mechanical ventilation may reduce cardiac work by supporting oxygenation and relieving stress on the heart. Mechanical ventilation may also incorporate **positive end-expiratory pressure (PEEP)** or **continuous positive airway pressure (CPAP)** to help restore or maintain lung volumes, improve compliance, and prevent or treat atelectasis. In cases of severe thoracic trauma with a flail chest requiring ventilatory support, mechanical ventilation may be helpful for internal stabilization of the thorax.

Initiation of mechanical ventilation is not without risk. Hazards include ventilator-associated lung injury (VALI), increased WOB (which may be caused by patient–ventilator asynchrony), ventilatory muscle dysfunction, and decreased venous return and cardiac output. Other hazards include barotrauma, ventilator-associated pneumonia (VAP), oxygen toxicity, and ventilator system failure.

VALI may be caused by elevated transpulmonary pressures during positive-pressure breathing. During mechanical ventilation, plateau pressure ($P_{plateau}$) reflects alveolar pressure and, in turn, transpulmonary pressure. A **lung-protective ventilatory strategy** should be employed, which includes limiting plateau pressure to less than 30 cm $H_2O$ for most patients.[1,2] It should be noted, however, that patients with decreased thoracic compliance may have decreased transpulmonary pressures; in such cases, higher $P_{plateau}$ may be applied (if needed) without causing overdistention. Smaller tidal volumes (e.g., 6 to 8 mL/kg) and appropriate levels of PEEP are used in patients with acute respiratory distress syndrome (ARDS) to avoid ventilator-induced lung injury (VILI). An extensive review suggested that with ARDS, if $P_{plateau}$ remained $< 30$ cm $H_2O$, a slightly larger tidal volume ($V_T$) (8 to 10 mL/kg ideal body weight [IBW]) did not affect outcomes.[3] Properly applied, PEEP can stabilize unstable lung units and avoid repetitive inflation and deflation of alveoli, thus reducing the likelihood of additional injury. As a point of interest, the term ventilator-induced lung injury (VILI) is used when the ventilator can be clearly identified as the source of the injury. Because it can be difficult to be sure that the ventilator caused any lung injury observed (e.g., VILI), the term ventilator-associated lung injury (VALI) is commonly used.

## Methods of Ventilation

Methods of providing mechanical ventilatory support include negative-pressure ventilation, positive-pressure ventilation, **partial ventilatory support**, **full ventilatory support**, volume-control ventilation, pressure-control ventilation, and various ventilatory modes that employ automated targeting schemes (e.g., **proportional assist ventilation [PAV]**, **pressure-regulated volume control [PRVC]**, or **adaptive support ventilation [ASV]**).

### Negative-Pressure Ventilation

The tank ventilator or "iron lung" was developed by Drinker, McKhann, and Shaw at Harvard University in 1928; an improved commercial version was introduced by John H. Emerson in 1932. The Emerson iron lung was in widespread use during the polio epidemics in the United States in the 1940s and 1950s and continued to be manufactured until 1970. Other forms of negative-pressure ventilation include the Port-a-Lung, chest cuirass, and bodysuit. These devices have been used to provide intermittent or continuous negative-pressure ventilatory support to patients with chronic conditions (e.g., polio, other neuromuscular disease, or chronic restrictive disorders). Negative-pressure devices

do not require the placement of an artificial airway and are relatively easy to use to support patients with chronic ventilatory failure. Negative-pressure ventilators enclose the thorax within a chamber, shell, or body suit and apply a negative pressure to effect inspiration. This negative pressure is then released to allow for expiration. Initial settings for adults were at a rate of 12 to 24 breaths/min with a negative inspiratory pressure of −10 to −35 cm $H_2O$. The level of negative pressure applied determines the degree of inspiratory support and resultant tidal volume.

Advantages of negative-pressure ventilators included the maintenance of the natural airway, which allowed patients to talk or eat, and the relative simplicity of the ventilator controls. Problems associated with negative-pressure ventilation include difficulties in accessing the patient for procedures, bathing, or turning. Most devices were large and bulky and difficult to move. Maintaining ventilation could be difficult because of leaks. In the case of full-body tanks, abdominal venous blood pooling could occur, resulting in reduced venous return and acute hypotension or "tank shock." In the absence of an artificial airway, negative-pressure ventilation could result in upper airway soft tissue obstruction, and negative pressure ventilation is contraindicated in patients with obstructive sleep apnea. Because of these problems, negative-pressure ventilators are inappropriate in most modern acute care and ICU settings. Although negative-pressure ventilation may be useful in a handful of long-term care patients based on patient preference, its use has been largely replaced by noninvasive positive-pressure ventilation (NPPV). As late as 2014, a few negative-pressure ventilators remained in use in the United States. Other devices that have been used in the past to noninvasively support ventilation include the rocking bed and pneumobelt. Diaphragmatic pacing (aka phrenic nerve pacing) provides another example of ventilatory support that does not require insertion of an endotracheal or tracheostomy tube for patients with apnea or severe hypoventilation due to bilateral diaphragmatic paralysis.

## Positive-Pressure Ventilation

During positive-pressure ventilation, the ventilator applies a positive pressure via mask, endotracheal tube, tracheostomy tube, or other interface during inspiration. This positive proximal airway pressure ($P_{AW}$) creates a pressure gradient between the mouth or airway and the alveoli ($P_A$), and inspiration occurs. The peak inspiratory pressure (PIP) is the highest pressure reached during the inspiratory phase. In general, PIP occurs at the end of inspiration during volume-control ventilation. PIP occurs early in the inspiratory phase during pressure-control ventilation and continues until the cycle variable criterion is reached (e.g., time or flow cycle). Occasionally an inspiratory pause or hold of 0.5 to 1.5 seconds may be mechanically applied at the end of inspiration, and airway pressure will fall to a plateau during this inspiratory pause. This plateau pressure ($P_{plateau}$) represents the point at which $P_{AW}$ and $P_A$ have equilibrated (assuming no spontaneous breathing efforts are made during the inspiratory pause). Monitoring PIP and $P_{plateau}$ during mechanical ventilation in the volume-control mode provides valuable information used to detect important clinical changes as well as allowing for the calculation of the patient's static total compliance ($C_{ST}$) and airway resistance ($R_{AW}$).

Following the inspiratory phase, the ventilator allows airway pressure to fall to a baseline value, and expiration occurs due to the natural elastic recoil of the lungs. Baseline pressure may be ambient barometric pressure (conventionally referred to as zero) or elevated with the application of PEEP or CPAP. When properly applied, positive-pressure breathing can be accomplished with little or no work on the part of the patient.

### Terminology

Terminology used to describe positive-pressure ventilation can be confusing, due to the wide variety of terms in common in use. To further complicate the taxonomy for mechanical ventilation, different ventilator manufacturers use different terms to refer to the same modes.[4,5]

The *trigger variable* refers to the method that begins inspiration (i.e., the changeover from expiration to inspiration). The two most common trigger variables are time and patient effort (i.e., patient triggered), which may be further described as a (negative) pressure trigger or flow trigger. **Patient-triggered breaths** are initiated by the patient independent of the ventilator rate settings. Patient-triggered breaths are commonly referred to as *assisted breaths*, although using this terminology for patient-triggered breaths has been discouraged by some authors.[4,5] *Autotriggering* refers to unintentional initiation of breath delivery by the ventilator, most often due to inappropriate trigger sensitivity settings and/or movement of the ventilator circuit.

As noted, in common clinical parlance, the term *assisted breath* is often used to refer to breaths that are patient triggered. In a similar fashion, *control breaths* commonly refer to breaths that are time triggered, and the term *assist-control* is commonly used to refer to a mode of ventilation that may be patient or time triggered, depending on which occurs first. *Controlled ventilation*, in this context, is used to refer to a mode of ventilation in which every breath is time triggered. These latter terms should probably be avoided in favor of simply describing the trigger method that starts a breath (e.g., patient or time triggered).[5] It should be noted that other trigger variables may be employed with certain modes of ventilation. Examples of other trigger variables include preset apnea interval set as a backup safety feature in the event of apnea, and electrical signals from the diaphragm (see neurally adjusted ventilatory assist [NAVA]). Mandatory minute

volume (MMV) ventilation may automatically increase the respiratory rate (or pressure-support level, depending on the ventilator employed) to meet a minimum minute ventilation goal.

The *cycle variable* refers to the method by which inspiration is cycled off or stops (i.e., the changeover from inspiration to expiration). Common cycle variables include inspiratory time, inspiratory pressure (i.e., peak airway pressure), volume, and flow (e.g., percentage of peak inspiratory flow). Thus, a breath may be **volume cycled**, **pressure cycled**, **time cycled**, or **flow cycled**. It should also be noted that a breath may be pressure limited and pressure cycled, pressure limited and time cycled (e.g., pressure-control ventilation), or pressure limited and flow cycled (e.g., pressure-support ventilation), as described below.

**Volume control (VC)** occurs when volume delivery is fixed, and airway pressure varies with changes in resistance and compliance. Put another way, with VC the preset tidal volume is delivered regardless of patient effort, resistance, or compliance and peak airway pressure varies (assuming the ventilator's set pressure limit is not reached). Other terms often used to refer to VC include *volume ventilation*, *volume-targeted ventilation*, and *volume-limited ventilation.* Both volume and flow are preset prior to inspiration during VC. It should be noted that the **targeting scheme** employed refers to the characteristics that distinguish the ventilatory pattern in use.[4,5] For example, a volume-control mode in which the operator sets all parameters for volume and flow waveforms, is known as **set-point targeting**. A targeting scheme that allows the ventilator to automatically adjust pressure between breaths to achieve an average tidal volume over several breaths would be referred to as **adaptive targeting** (e.g., adaptive pressure ventilation [APV] or pressure-regulated volume control [PRVC]). With **dual targeting**, the ventilator can automatically switch between volume control and pressure control during a single breath. Other targeting schemes include **servo**, **optimal**, **biovariable**, and **intelligent targeting** discussed below under modes of ventilation.[4,5]

Pressure control (PC) occurs when inspiratory airway pressure remains constant despite changes in patient effort, resistance and compliance. With PC, tidal volume varies and is dependent on the driving pressure, inspiratory time, patient effort, compliance, resistance, and presence (or absence) of PEEP. Inspiratory pressure is predetermined with PC. It should be noted that a PC breath may be triggered by time or patient effort and cycled to expiration by time (i.e., *time-cycled ventilation*) or flow (i.e., *flow-cycled ventilation*). It should be noted that older ventilators (e.g., Bird Mark series) allowing for *pressure-cycled ventilation* are no longer in common use, although pressure-cycled breath termination may occur if the ventilator's set pressure limit is reached. Other terms sometimes used to refer to PC include *pressure ventilation*, *pressure-targeted ventilation*, and *pressure-limited ventilation*.

**Pressure-support ventilation (PSV)** is a form of spontaneous ventilation (see definition below) in which the beginning of inspiration is patient triggered and the inspiratory pressure rapidly rises to a preset value. With PSV, the change over from inspiration to expiration is flow cycledd. **Pressure-control ventilation (PCV)** is the term employed for PC ventilation in which the beginning of inspiration is time or patient triggered (aka assist-control) and the change over from inspiration to expiration is time cycled.

Although the term *pressure-support ventilation* is commonly used, it should be noted that the recommended taxonomy for PSV is **pressure control-continuous spontaneous ventilation (PC-CSV)**.[4,5] In a similar fashion, while the term *pressure-control ventilation* is in common use, the preferred taxonomy for PCV is pressure control-continuous mandatory ventilation (PC-CMV).[4,5] This taxonomy is described further below.

**Mandatory breaths** occur when the ventilator delivers the same breath type with every cycle, regardless of whether the breath is patient or time triggered to inspiration.[5] Mandatory breaths may be VC or PC breaths. Terms sometimes used to refer to mandatory breaths include machine breaths, or mechanical breaths, although these terms are not recommended.

**Spontaneous breaths** occur when the start and end of inspiration are determined by the patient, independent of other ventilator settings.[5] Put another way, during spontaneous breathing, the patient triggers the breath to inspiration and cycles the breath to expiration. Spontaneous breaths may or may not be pressure supported (i.e., pressure-support ventilation) and may or may not occur with an elevated baseline pressure (i.e., continuous positive airway pressure or CPAP). Some authors have suggested that if the ventilator does some or all the WOB, the breath is *assisted*.[5] Normal spontaneous breathing is *unassisted*, while spontaneous breathing with pressure support is assisted.[5] The use of the term *assisted breathing* in this context should not be confused with the term *assist-control*, which indicates the trigger method.

*Continuous spontaneous ventilation* (CSV) occurs when all breaths are initiated and ended by the patient.[5] Common examples of CSV modes include normal spontaneous breathing, PSV, and CPAP. Other forms of CSV include automatic tube compensation (ATC), proportional assist ventilation (PAV), and **neurally adjusted ventilatory assist (NAVA)**.[4,5]

The term *continuous mandatory ventilation* (CMV) is used when every breath is a mandatory breath, regardless of whether the breath is patient or time triggered (aka assist-control).[4] CMV breaths may be **pressure control-continuous mandatory ventilation (PC-CMV)** breaths or **volume control-**

**continuous mandatory ventilation (VC-CMV)** breaths. VC-CMV is commonly referred to as *assist-control (A/C) volume ventilation.* To add to the confusion, the terms *controlled-volume ventilation* or *volume ventilation in the control mode* are commonly used to refer to time-triggered VC-CMV. These latter terms should be avoided in favor of *time-triggered VC-CMV*.

**Intermittent mandatory ventilation (IMV)** occurs when patients can breathe spontaneously between mandatory breaths. **Synchronized intermittent mandatory ventilation (SIMV)** is a form of IMV in which the mandatory breaths may be time or patient triggered. With SIMV, spontaneous breaths may be pressure supported (i.e., SIMV with pressure support). SIMV may also be provided with (or without) an elevated baseline pressure (i.e., PEEP/CPAP). Note the term IMV has been suggested for mode classification purposes regardless whether intermittent mandatory breaths are time or patient triggered.[4,5] That said, the term SIMV remains in common use by both clinicians and manufacturers. **Table 6-1** summarizes terminology in use to describe common modes of ventilation. **Box 6-1** lists additional modes available on certain ventilators.

## Noninvasive Ventilation

**Noninvasive ventilation (NIV)** refers to techniques that do not require insertion of an invasive artificial airway (e.g., endotracheal intubation or tracheostomy). NPPV is the most common form of NIV in use today. CPAP and bilevel positive airway pressure (BiPAP) have been used in the home for management of obstructive sleep apnea (OSA) for many years. BiPAP combines inspiratory positive airway pressure (IPAP) and expiratory positive airway pressure (EPAP). The routine use of NIV for patients with acute respiratory failure has been a relatively recent development.

NIV requires the use of a nasal mask, oronasal mask, nasal pillows, mouthpiece, or helmet interface. Properly applying the interface to avoid excessive leaks without causing patient discomfort or skin breakdown is one of the more important and challenging aspects of NIV. The oronasal or full-face mask is the most common interface for use in patients with acute respiratory failure. NIV may be delivered by volume-limited or pressure-limited ventilators. Most BiPAP devices are flow triggered to inspiration, flow cycled to expiration, and pressure limited. Newer critical care ventilators may also have an NIV mode built in.

Indications for NIV include acute exacerbation of COPD with hypercapnic acidosis, cardiogenic pulmonary edema, and acute hypoxemic respiratory failure.[6] NIV may also be useful to prevent postextubation respiratory failure. Nocturnal NIV may be useful for stable COPD patients with chronic respiratory failure and daytime hypercapnia. NIV may also be useful for acute or impending respiratory failure in pediatric patients who do not require emergency endotracheal intubation.[7]

### RC Insight

Indications for NIV in the acute care setting include acute exacerbation of COPD with hypercapnic acidosis, cardiogenic pulmonary edema, and acute hypoxemic respiratory failure. NIV may also be used to prevent extubation failure.

NIV is also commonly used to support ventilation in patients with chronic hypoventilation due to neuromuscular or chest wall disease (e.g., muscular dystrophy, post-polio syndrome, other slowly progressing neuromuscular diseases, or chest wall deformity).[8] Such patients may be candidates for nocturnal or sustained NIV, especially if they have either daytime hypercapnia or nocturnal hypoventilation with sustained oxygen desaturation.[8]

Contraindications for NIV include cardiac or respiratory arrest; hemodynamic or cardiac instability (e.g., unstable cardiac arrhythmias), or severely impaired consciousness (Glasgow coma score [GCS] $< 10$).[6] NIV may also be contraindicated in the presence of facial trauma, facial surgery, or facial deformity. Upper airway obstruction, inability to protect the airway or clear secretions, and high risk for aspiration are relative contraindications for the use of NIV. For example, patients with upper gastrointestinal bleeds are not good candidates for NIV. Patients with acute respiratory failure who are likely to require prolonged mechanical ventilatory support may be best treated with invasive mechanical ventilation. Patients with encephalopathy (i.e., brain dysfunction) caused by hypercapnia may respond to NIV, but these patients must be carefully monitored; if there is no prompt response, intubation and invasive mechanical ventilation should occur.[6] NIV can result in gastric inflation at pressures above 20 to 25 cm $H_2O$; NIV is also contraindicated in patients who have recently received esophageal surgery or in the presence of a tracheal-esophageal fistula.[6] NIV may be provided using BiPAP, PSV, assist-control (A/C) volume ventilation (aka VC-CMV), PAV, and NAVA. Initial NIV ventilator settings using BiPAP, PSV, or volume ventilation typically include:[6,8]

- Lower initial pressures for BiPAP and PSV to allow for patient adaptation to the device and interface.
  - IPAP 8 to 20 cm $H_2O$ (begin at 8 to 12 cm $H_2O$ for most patients).
  - EPAP 3 to 5 cm $H_2O$.
  - Delta P ($\Delta P$ = IPAP – EPAP) should be adjusted to about 5 to 15 cm $H_2O$ to ensure adequate tidal volume.
  - IPAP should be maintained $<$ 25 to 30 cm $H_2O$ in order to avoid gastric insufflation and ventilator-induced lung injury.

**TABLE 6-1**
**Terminology Used to Describe Modes of Ventilation**

| Preferred Taxonomy | Common Terminology[1–6] | Alternative Terminology | Description |
|---|---|---|---|
| **Volume Control-Continuous Mandatory Ventilation (VC-CMV):** *patient or time triggered.*<br>Note: all breaths are mandatory and may be patient triggered or time triggered. | • Volume A/C or **VAC**<br>• Assist-control (A/C) volume ventilation<br>• Volume-control ventilation assist-control mode (VC AC)<br>• Volume-targeted A/C ventilation | • Volume assist-control (VA/C)<br>• Volume-limited ventilation A/C<br>• Volume-cycled ventilation (A/C)<br>• Assist-control volume control (A/C VC)<br>• Synchronized controlled mandatory ventilation (S)CMV<br>• CMV | **All breaths are mandatory:**<br>• Changeover from expiration to inspiration is patient or time triggered (i.e., assist-control mode).<br>• Inspiratory flow waveform may be adjustable (e.g., square wave or down ramp); waveform does not vary during inspiration.<br>• Changeover from inspiration to expiration is volume cycled (or time cycled but volume is constant based on flow and time).<br>• Expiratory phase allows for the application of PEEP. |
| **Volume Control-Continuous Mandatory Ventilation (VC-CMV):** *time triggered*<br>Note: all breaths are mandatory and time triggered. | • Volume control or **VC**<br>• Control mode volume ventilation<br>• Volume-targeted ventilation: control mode | • Controlled mechanical ventilation<br>• Volume-limited ventilation: control mode | **All breaths are mandatory:**<br>• Changeover from expiration to inspiration is time triggered (i.e., control mode).<br>• Inspiratory flow waveform may be adjustable (e.g., square wave or down ramp); waveform does not vary during inspiration.<br>• Changeover from inspiration to expiration is volume cycled (or time cycled but volume constant based on flow and time).<br>• Expiratory phase allows for the application of PEEP. |
| **Pressure Control-Continuous Mandatory Ventilation (PC-CMV)**<br>Note: all breaths are mandatory and may be patient triggered or time triggered. | • Pressure assist-control or **PAC**<br>• Pressure-control ventilation (PCV)<br>• Pressure-targeted ventilation<br>• A/C pressure control<br>• Pressure-control CMV | • Pressure control (PC): sometimes used to refer to time-triggered, time cycled pressure-control ventilation<br>• Pressure assist (PA): sometimes used to refer to patient-triggered pressure-control ventilation<br>• Pressure limited: time-cycled A/C<br>• Pressure-control mandatory ventilation (P-CMV) | **All breaths are mandatory:**<br>• Changeover from expiration to inspiration is patient or time triggered (i.e., assist-control mode or PAC). If the trigger variable is time, this is commonly referred to as control mode.<br>• Inspiration is pressure limited.<br>• Inspiratory flow waveform is decreasing or decelerating.<br>• Changeover from inspiration to expiration is time cycled.<br>• Expiratory phase allows for the application of PEEP. |
| **Volume Control Intermittent Mandatory Ventilation (VC-IMV)**<br>Note: mandatory breaths are interspersed with spontaneous breaths. Mandatory breaths may be patient or time triggered (i.e., SIMV). Spontaneous breaths may be pressure augmented (e.g., pressure support or automatic tube compensation [ATC]) | • Volume SIMV or **V-SIMV**<br>• Synchronized intermittent mandatory ventilation (SIMV)<br>• SIMV (VC) | • SIMV (volume control)<br>• SIMV volume control with pressure support<br>• Volume-targeted SIMV<br>• Volume-limited SIMV<br>• SIMV | **Mandatory breaths:**<br>• Changeover from expiration to inspiration is patient or time triggered.<br>• Inspiratory flow waveform for VC mandatory breaths may be adjustable (e.g., square wave or down ramp) and waveform does not vary during mandatory breaths.<br>• Changeover from inspiration to expiration is volume cycled (or time cycled but volume constant based on flow and time).<br>• Expiratory phase allows for the application of PEEP.<br>**Spontaneous breaths:**<br>• Baseline pressure may be ambient or elevated (CPAP).<br>• Pressure support (PSV) may be added for spontaneous breaths.<br>• Inspiratory pressure support is patient triggered, pressure limited, and flow cycled. |

(*Continues*)

**TABLE 6-1**
**Terminology Used to Describe Modes of Ventilation (*Continued*)**

| Preferred Taxonomy | Common Terminology[1–6] | Alternative Terminology | Description |
|---|---|---|---|
| **Pressure Control Intermittent Mandatory Ventilation (PC-IMV)**<br>Note: mandatory breaths are interspersed with spontaneous breaths. Mandatory breaths may be patient triggered or time triggered. Spontaneous breaths may be pressure augmented (e.g., pressure support or automatic tube compensation [ATC]) | • Pressure-control SIMV or **P-SIMV**<br>• SIMV pressure control<br>• SIMV (PC) | • SIMV pressure control<br>• Pressure-SIMV (P-SIMV)<br>• Pressure synchronized intermittent mandatory ventilation (P-SIMV)<br>• Pressure-limited SIMV<br>• Pressure-targeted SIMV<br>• SIMV pressure control with pressure support | **Mandatory IMV breaths**:<br>• Changeover from expiration to inspiration is patient or time triggered.<br>• Inspiration is pressure limited.<br>• Inspiratory flow waveform is decreasing or decelerating.<br>• Changeover from inspiration to expiration is time cycled.<br>• Expiratory phase allows for the application of PEEP.<br>**Spontaneous breaths**:<br>• Baseline pressure may be ambient or elevated (CPAP).<br>• Pressure support (PSV) may be provided during inspiration for spontaneous breaths.<br>• Inspiratory pressure support is patient triggered, pressure limited, and flow cycled. |
| **Pressure Control-Continuous Spontaneous Ventilation (PC-CSV)** | Pressure-support ventilation or **PSV** | • Pressure support (PS)<br>• Spontaneous pressure support<br>• Standalone pressure support | **Spontaneous breaths:**<br>• Patient-triggered, pressure-limited, flow-cycled ventilation.<br>• Baseline pressure may be ambient or elevated (CPAP).<br>• Pressure support provided during inspiration for spontaneous breaths.<br>• Inspiratory pressure support is patient triggered.<br>• Changeover from inspiration to expiration is flow cycled. |

*Mandatory breaths* occur when the ventilator delivers the same breath type with every breath. Mandatory breaths may be time or patient triggered and pressure or volume controlled (PC or VC). The term *assisted breath* is commonly used to refer to PC or VC breaths that are patient triggered. In a similar fashion, the term *control breaths* is commonly used to refer to PC or VC breaths that are time triggered. When every breath is a mandatory breath, the mode is referred to as continuous mandatory ventilation (CMV). CMV may be volume or pressure controlled (VC-CMV or PC-CMV). *Spontaneous breaths* are initiated by the patient and the patient determines when the end of inspiration occurs (i.e., patient cycled). Pressure support (PS) or automatic tube compensation (ATC) may be applied during spontaneous breaths and support some of the work of inspiration. When used alone, PSV is a form of pressure control-continuous spontaneous ventilation (PC-CSV).

PEEP, positive end-expiratory pressure; CPAP, continuous positive airway pressure.

1. AC (or A/C) indicates assist-control, which may be time or patient triggered.
2. VC indicates volume control.
3. PC indicates pressure control.
4. PA indicates pressure assist.
5. PS indicates pressure support.
6. Modes available using this simplified nomenclature are volume assist-control (VAC); pressure assist-control (PAC); volume-synchronized intermittent mandatory ventilation (V-SIMV); pressure-synchronized intermittent mandatory ventilation (P-SIMV); and pressure-support ventilation (PSV).

## BOX 6-1 Other Available Modes of Ventilation

- *Noninvasive ventilation* (NIV) is sometimes referred to as noninvasive positive-pressure ventilation (NPPV).
  - The ventilator is connected to the patient using a nasal mask or pillows, full face mask, mouthpiece, or helmet interface.
  - The ventilator is typically patient triggered, pressure limited, and flow cycled.
  - NIV is currently available on most critical care ventilators.
- *Bi-level positive airway pressure* (BiPAP).
  - Often used to deliver noninvasive ventilation, BiPAP delivers a preset inspiratory pressure (IPAP) that is patient triggered to inspiration and flow cycled to expiration similar to pressure support (PSV).
  - Inspiratory positive airway pressure (IPAP) refers to the pressure delivered during inspiration.
  - Expiratory positive airway pressure (EPAP) refers to the baseline pressure maintained during expiration.
  - Along with compliance, resistance, and patient effort, the difference between IPAP and EPAP determines the tidal volume delivered.
- *Pressure-control inverse-ratio ventilation* (PC-IRV).
  - Typically, the ventilator is time triggered, pressure limited, and time cycled in a manner such that inspiration is longer than expiration (I:E ratio > 1:1; e.g., 1.5:1, 2:1).
  - Inverse-ratio ventilation (IRV) increases mean airway pressure and may improve oxygenation in certain patients (e.g., severe ARDS).
- *Pressure-regulated volume control* (PRVC).
  - PRVC is a form of adaptive pressure control (see below).
  - Provides a volume-targeted, pressure-control breath.
  - Inspiration is patient or time triggered, pressure limited, and time cycled. Pressure is automatically adjusted breath to breath to achieve a volume target.
  - Delivered tidal volume is measured and compared to the set (targeted) tidal volume; pressure control is gradually increased or decreased until the target tidal volume is reached.
  - PRVC is available under that name on the Maquet Servo-i and Servo-u; Yvaire AVEA and VELA; and eVent Inspiration 7i (eVent Medical, Lake Forest, CA).
  - Other proprietary names for PRVC include *Autoflow* (Dräger Evita E-4, Infinity V500 Elite), *VC+* (Covidien PB 840, PB 980) and *adaptive pressure ventilation* (HAMILTON G5 and G3).
- **Volume support (VS).**
  - Like pressure support, breaths are patient triggered and flow cycled. The pressure-support level is adjusted automatically breath to breath to achieve a volume target.
  - Inspiration is patient triggered; spontaneous breathing is required.
  - VS is a form of adaptive pressure control (see below).
- *Adaptive pressure control* (APC) automatically adjusts pressure control or pressure support to achieve the target tidal volume.
  - Inspiratory pressure varies automatically between breaths to achieve the target tidal volume.
  - Maintains tidal volume with changes in ventilatory mechanics.
  - May improve patient–ventilator synchrony due to variable inspiratory flow provided.
  - APC is also known as PRVC (Servo-i, Servo-u), adaptive pressure ventilation (HAMILTON Galileo), AutoFlow (Dräger), volume control plus (Puritan Bennett), and volume-targeted pressure control (General Electric).
  - Support is reduced if the patient's tidal volume consistently exceeds the target.
- *Adaptive support ventilation* (ASV) makes automatic adjustments in respiratory rate and inspiratory pressure based on measurements of respiratory mechanics to deliver the desired minute ventilation and minimize the WOB.
  - Desired minute ventilation is calculated based on the patient's ideal body weight and estimated dead space where target $\dot{V}_E$ = 0.1 L/min/kg or 100 mL/min/kg.
  - The level of ventilatory support to be provided is set by the clinician as a percentage of the target $\dot{V}_E$.
  - The ventilator uses an algorithm to determine optimal breathing frequency (f) and a target tidal volume is calculated based on $\dot{V}_E$ and f ($V_T = \dot{V}_E/f$)
  - Pressure control is then adjusted automatically to achieve the targeted tidal volume.

(*Continues*)

## BOX 6-1 Other Available Modes of Ventilation (*Continued*)

- **Airway pressure-release ventilation (APRV).**
  - APRV provides two levels of CPAP, which are time triggered and time cycled. APRV allows for spontaneous breathing at both levels.
  - APRV is typically used as a form of pressure-control inverse-ratio ventilation (PCIRV) in which the high-pressure time exceeds the low-pressure time.
  - APRV may reduce shunt and improve oxygenation and gas exchange as compared to conventional ventilation in ARDS patients; improved patient outcomes have not been clearly demonstrated.
- *Automatic tube compensation* (ATC).
  - Imposed airway resistance due to the endotracheal tube or tracheostomy tube is estimated.
  - Pressure-support level is automatically adjusted to compensate for the $WOB_I$.
  - The clinician may choose 100% tube compensation or a lower value.
- *Proportional assist ventilation* (PAV).
  - PAV incorporates an algorithm to calculate the pressure required to ventilate based on the patient's tidal volume, elastance, resistance, and gas flow.
    - The ventilator estimates WOB based on inspiratory flow, volume, pressure, compliance, resistance, and pressure.
  - Breaths are patient triggered, pressure limited, and flow cycled.
  - Pressure, flow, and volume are proportional to the patient's spontaneous effort and clinician-set parameters.
    - Pressure varies depending on the amount of inspiratory flow and volume demanded by the patient and the amplification level selected by the clinician.
    - Flow increases proportionally as patient's inspiratory effort increases.
  - The clinician adjusts the percentage of support (from 5% to 95%) to achieve WOB in the range of 0.5 to 1.0 joules per liter.
  - Applied pressure and inspiratory time vary breath by breath and within each breath depending on changes in compliance, resistance, and flow demand. Inspiratory time is determined by the flow cycle setting.
  - PAV may be more comfortable for some patients and improves patient–ventilator synchrony by matching the patient's inspiratory demand.
  - PAV has not been shown to improve patient outcomes.
- *Neurally adjusted ventilatory assist* (NAVA) uses the electrical discharge from the diaphragm (i.e., electromyography [EMG]) to trigger and cycle mechanical breaths.
  - NAVA requires an esophageal catheter that incorporates a multiple array esophageal electrode.
  - NAVA increases ventilator pressure as patient effort increases.
  - NAVA may improve patient–ventilator synchrony.
- *Mandatory minute volume ventilation* (MMV) is aka **mandatory minute ventilation**, minimum minute ventilation, or augmented minute ventilation).
  - Designed to promote ventilator weaning.
  - A minimum minute ventilation ($\dot{V}_E$) is set for spontaneously breathing patients.
  - The ventilator monitors the patient's spontaneous minute volume and provides additional ventilatory support as needed to achieve the set minimal minute volume.
  - With increased spontaneous $\dot{V}_E$, the ventilator reduces the level of support provided.
  - Additional ventilatory support may be in the form of increased pressure support or increased IMV rate, depending on the ventilator employed.
  - MMV using automatic adjustments in SIMV rate can vary the number of mandatory breaths from 0 to the set SIMV rate, depending on the patient's spontaneous $\dot{V}_E$.
- **High-frequency ventilation (HFV)** delivers small tidal volumes at a very high respiratory frequency. Possible indications for HFV include ARDS, bronchopleural fistula, and air leaks. HFV is not recommended as a first choice for mode of ventilation and should be avoided in patients with obstructive lung disease.
  - **High-frequency oscillatory ventilation (HFOV)** is delivered using an oscillator to provide a respiratory frequency in the range of 3 to 15 Hz (180 to 900 breaths/min).
    - HFOV may minimize alveolar over distention and derecruitment.
    - HFOV seems to be effective in neonatal respiratory failure.

- HFOV may be considered for refractory hypoxemic respiratory failure in adults, although better patient outcomes have not been demonstrated.
- **High-frequency jet ventilation (HFJV)** is delivered using a jet gas flow delivered to the endotracheal tube via a small cannula.
- **High-frequency percussive ventilation (HFPV)** combines time-cycled pressure-control ventilation with a phasitron to provide oscillatory or percussive ventilation throughout inspiration and expiration. HFPV may improve secretion clearance, improve oxygenation and ventilation, and lower airway pressures.
- **High-frequency positive-pressure ventilation (HFPPV)** uses a conventional ventilator with a low tidal volume setting and a very rapid respiratory rate.

- *Continuous positive airway pressure (CPAP).*
  - CPAP allows for spontaneous breathing at elevated baseline pressure.
  - CPAP increases functional residual capacity (FRC) and may improve compliance, oxygenation, and ventilation in patients with acute restrictive lung disease.

$WOB_I$ - imposed work of breathing

- For volume ventilation, larger initial tidal volumes of 6 to 10 mL/kg have been suggested to compensate for air leaks during NIV.
- Trigger effort should be set for minimal patient work without autocycling.
- A backup respiratory rate may be set 2 to 4 breaths/min below the patient's spontaneous rate. Patients often initially hyperventilate, and the backup rate may be adjusted accordingly. Patients' rates may slow within 6 to 12 hours as they become accustomed to NIV, and the backup rate may need to be decreased at that time.
- Initial $F_{IO_2}$ should be selected to avoid hypoxemia without administration of excessive oxygen concentrations.

Following initial ventilator setup, the ventilator is adjusted to ensure adequate oxygenation, ventilation, and patient comfort while avoiding patient–ventilator asynchrony. Chapter 10 provides additional information regarding NIV.

### Invasive Ventilation

Invasive mechanical ventilation is provided via an artificial airway whose tip is located in the trachea (e.g., endotracheal tube or tracheostomy tube). **Invasive ventilation** has the advantage of securing and protecting the airway and providing a more dependable form of ventilatory support for unstable, critically ill patients. For example, in patients requiring mechanical ventilatory support, the loss of protective airway reflexes are an important indication for endotracheal intubation. On the other hand, patients who can swallow and speak may not require endotracheal intubation to protect the lower airway; these patients may be candidates for NIV. Patients with depressed mental status (e.g., unconsciousness, coma), hemodynamic instability, severe oxygenation disorders, and those requiring (or likely to require) sophisticated mechanical ventilatory support probably are best served by invasive mechanical ventilation. The placement of an endotracheal tube or tracheostomy tube may also facilitate suctioning of airway secretions.

**RC Insight**

Invasive ventilation has the advantage of securing and protecting the airway and providing a more dependable form of ventilatory support for unstable, critically ill patients.

## Establishment of the Airway

Nasopharyngeal or oral pharyngeal airways may be helpful in certain patients with soft tissue obstruction; however, they do little to protect the lower airway and do not allow for invasive mechanical ventilatory support. Extraglottic airways (aka supraglottic airways) have been sometimes used during general anesthesia or as an adjunct to manage difficult and emergency airways.[9] An example of an extraglottic airway is the laryngeal mask airway (LMA).

Most patients requiring invasive mechanical ventilation, however, are endotracheally intubated, and the clear majority (95%) of these intubations are done orally; the remaining endotracheal tubes are placed nasally. A subset of patients requiring extended invasive mechanical ventilation will receive a tracheostomy at some point (most often > 10 to 14 days, but earlier in some patients).

### Endotracheal Intubation

Indications for endotracheal intubation include the inability to maintain a patent airway, inability to protect the airway against aspiration, failure to ventilate, failure to oxygenate, and anticipation of deterioration in the patient's condition that will lead to respiratory failure.[10]

## BOX 6-2 Indications, Contraindications, and Complications of Endotracheal Intubation

**Indications**

- Cardiac arrest
- Apnea (e.g., respiratory arrest)
- Upper airway obstruction
- Need to provide a patent airway (e.g., coma, depressed mental status)
- Need to protect the airway (e.g., high risk of aspiration, lack of gag reflex)
- Respiratory failure (failure to oxygenate and/or ventilate)
- Need to provide mechanical ventilatory support to critically ill patients (i.e., invasive mechanical ventilation; NIV contraindicated or impractical)
- Anticipated deterioration in the patient's condition that will lead to respiratory failure

**Contraindications**

- Supraglottic or subglottic pathology (e.g., blunt trauma with laryngeal fracture)
- Penetrating trauma of the upper airway (e.g., hematoma, airway transection)
- Severe laryngeal edema or supralaryngeal edema (e.g., anaphylaxis, bacterial infection, or burns)
- Difficult airway due to anatomic features or injuries

**Complications During the Procedure**

- Difficult intubation may result in complications
- Prolonged intubation attempts
- Hypoxemia, hypercarbia, and acidosis
- Trauma to the upper airway
- Glottis, vocal cord, or laryngeal trauma
- Aspiration of stomach contents (patient may gag and vomit)
- Inadvertent mainstem bronchial intubation
- Inadvertent esophageal intubation
- Airway obstruction

**Complications Following the Procedure**

- Accidental extubation
- Airway malfunction
  - Obstruction
  - Secretions
  - Kinks
  - Cuff leaks
  - Pilot balloon failure
  - Aspiration of secretions due to cuff failure or improper inflation
- *Complications associated with suctioning*
  - Hypoxemia
  - Arrhythmias
  - Vagal stimulation
  - Bradycardia
  - Hypotension
  - Cardiac arrest
- Ventilator-associated pneumonia (VAP)
- Tracheobronchitis
- Nasal complications (due to nasal endotracheal intubation)
  - Sinusitis due to impaired sinus drainage
  - Nasal necrosis (following nasal intubation)
- Laryngeal injury due to ETT
  - Vocal cord ulceration
  - Glottic edema
  - Subglottic edema
  - Vocal cord ulceration
  - Vocal cord paralysis
  - Laryngeal inflammation
  - Granuloma formation
  - Laryngotracheal stenosis
- Tracheomalacia
- Tracheal arterial fistula
- Tracheoesophageal fistula
- *Complications discovered following extubation*
  - Swallowing disorders
  - Hoarseness
  - Sore throat
  - Speech impairment
  - Tracheal stenosis
  - Extubation failure requiring re-intubation or NIV

Contraindications to endotracheal intubation generally are those in which the procedure for tube insertion is likely to cause additional airway trauma or is likely to be unsuccessful. NIV may be helpful in such situations, although an emergency tracheostomy (or in rare cases cricothyrotomy) may be necessary if ventilation is compromised. **Box 6-2** summarizes indications, contraindications, and hazards associated with endotracheal intubation.

**Rapid-sequence intubation (RSI)** is performed for emergency airway management. Completion of RSI includes the administration of an induction agent (e.g., ketamine [Ketalar], etomidate [Amidate], midazolam

[Versed], and propofol [Diprivan]) resulting in unconsciousness immediately followed by a paralytic agent (e.g., rocuronium [Zemuron], succinylcholine [Anectine]) for neuromuscular blockade.[10] Initial medication dosage is based on the patient's weight and designed to achieve unconsciousness and paralysis within 1 minute.[10] Induction and paralysis may not be necessary in already unconscious and apneic patients (e.g., a crash airway). Specific indications for emergency endotracheal intubation include cardiac arrest, respiratory arrest, and upper airway obstruction not relieved by other methods.

Direct laryngoscopy is often employed to achieve endotracheal intubation. Prior to intubation, the patient is assessed and the appropriate equipment, supplies, and medications are gathered.[9,11] The patient is prepared, positioned, and preoxygenated with 100% oxygen using a bag-valve mask system with a PEEP valve.[9,11] For oral intubation, the patient's mouth is opened and the laryngoscope is introduced and advanced until the epiglottis and glottis can be visualized. The endotracheal tube is then guided to the glottis and inserted between and past the vocal cords into the trachea. Recent advances in intubation include the common use of a video laryngoscope (e.g., the Glide Scope), where the entire glottis can be visualized from the level of the pharynx and a specialized stylet allows the ET tube to be placed past the level of the vocal cords. Following insertion to an appropriate depth (e.g., 21 cm for most adult females or 23 cm for most adult males) the tube is secured, and the patient is mechanically supported using the manual resuscitator bag and 100% oxygen.[9,11] Equal and bilateral breath sounds should be confirmed by auscultating the patient's chest and assessment for the presence of exhaled $CO_2$ using capnography should be promptly performed to confirm proper tube placement.[9,11] Once proper placement of the endotracheal tube has been assured and the tube secured, mechanical ventilation can begin. **Figure 6-1** describes assessment of the difficult airway. The modified Mallampati Classification system for airway assessment is described below.

**Class I**: Visible structures include the tongue, hard palate, soft palate, uvula, and posterior pharynx.
**Class II**: Visible structures include the tongue, hard palate, soft palate, and part of the uvula, and posterior pharynx.
**Class III**: Visible structures include the tongue, hard palate, soft palate; posterior pharynx NOT visible.
**Class IV**: Visible structures include only the anterior tongue and hard palate.

Portable chest x-rays taken shortly after intubation are often useful in confirming proper tube placement. The tip of the endotracheal tube generally should lie in the middle one-third of the trachea and be at least 2 cm above the carina. Following tube placement, bedside ultrasound may be useful to confirm bilateral lung ventilation by observing the lung sliding sign on each side (i.e., movement of the parietal and visceral pleura as the lung expands and contracts).[11] If the lung sliding sign is present on only one side, bronchial intubation may have occurred. Absence of sliding is also seen with a pneumothorax or scarring between the visceral and parietal pleura. **Box 6-3** summarizes key points regarding endotracheal intubation. Chapter 9 provides additional information regarding patient assessment and the procedure for endotracheal intubation.

## RC Insight

Endotracheal intubation can maintain a patent airway, protect the airway against aspiration, and allow for ventilation and oxygenation.

## Tracheostomy

Indications for tracheostomy include long-term mechanical ventilation, weaning failure, upper airway obstruction, and for the management of copious secretions.[12] A surgical tracheostomy is performed in the region of the second to fourth tracheal cartilages, while percutaneous tracheostomy is done between the first and second or the second and third tracheal cartilages.[13] Percutaneous tracheostomy is simpler, quicker, and has a lower rate of

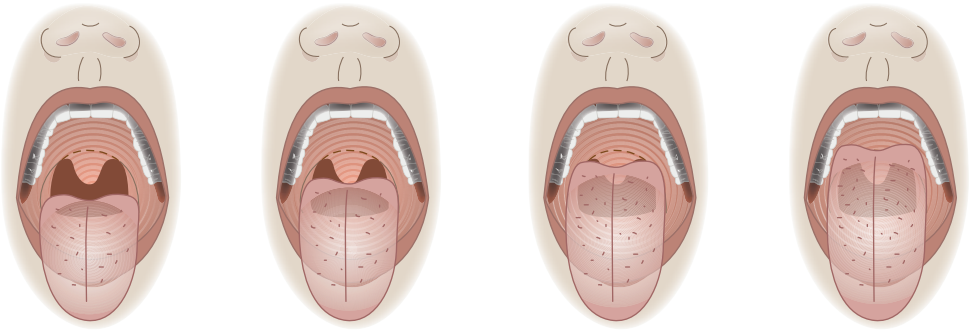


**FIGURE 6-1** Modified Mallampati Classification. The modified Mallampati difficulty classification is based on structures visible during oropharyngeal examination via direct laryngoscopy. Class I is least difficult intubation, while Class IV is most difficult intubation.

## BOX 6-3 Endotracheal Intubation

The following steps are recommended in order to perform successful and safe endotracheal intubations.

1. Assess the airway – **HAND**
   - **H**istory of difficult intubation?
   - **A**natomic considerations present?
     - 3-3-2 rule assessment. A difficult to intubate airway may be present if one of or more of the following are present:
       - Patient's mouth *cannot* be opened to permit placement of three fingers between the upper and lower teeth.
       - Three fingers *do not fit* under the chin between the tip of the jaw and the beginning of the neck.
       - There is *not enough space* for two fingers between the thyroid notch and the floor of the mandible.
     - Modified Mallampati classification is employed to assess probable difficulty of intubation.
       - Oropharyngeal examination of the tongue, hard palate, soft palate, uvula, and posterior pharynx during laryngoscopy.
       - Classification (I through IV) is based on structures visible during the oral pharyngeal exam.
       - Class I indicates least difficult airway to intubate.
       - Class IV indicates most difficult airway to intubate.
     - Other risk factors present for airway distortion, any obstruction?
   - **N**eck mobility.
   - **D**ifficult airway should be considered if concerns with any of the factors above.
2. Preoxygenate using 100% oxygen, bag-valve mask with PEEP valve.
3. Prepare.
   - Patient: Sniffing position, headboard off and patient head just below intubator's xyphoid process
   - Medications: Free-flowing IV, premedication, induction, paralytic and vasopressor agents
   - Right side: Suction, endotracheal tube with stylet and syringe attached
   - Left side: Laryngoscope handle, blades, oral and nasal airways end-tidal $CO_2$ detector
4. Review team member roles, primary and backup intubation plans.
5. Oxygen cut offs: Identify signals to abort; reinitiate bag-valve mask ventilation.
6. Administer medication, if indicated.
7. Confirm endotracheal tube placement using two indicators (including end-tidal $CO_2$).
8. Hold endotracheal tube until secured.

Data from the American College of Chest Physicians Airway Management Program Curriculum, 2013.

early complications. Because of this, well over half (66% to 86%) of tracheostomies performed are now percutaneous tracheostomies.[12,13] Advantages of tracheostomy (as compared to endotracheal intubation) include improved patient comfort, less sedation/analgesia required, reduced oral/laryngeal injury, and improved oral care.[14] Tracheostomy can also improve patient communication by enabling lip-reading or the use of speaking valves. Tracheostomy better preserves the swallow, allowing for earlier feeding and helps maintain glottic competence, which may have some benefit in avoiding aspiration and the development of ventilator-associated pneumonia.[14]

Tracheostomy may also slightly reduce anatomic dead space (due to bypass of the upper airway), decrease airway resistance and WOB, improve secretion clearance, reduce the need for sedation, and decrease the risk of aspiration.[15,16] Because of these advantages, some have speculated that tracheostomy may facilitate ventilator weaning in certain patients.[15,17,18] Tracheostomy should be considered after an initial period of stabilization on the ventilator when it becomes apparent that the patient will require prolonged ventilatory assistance. Early tracheostomy may be beneficial in patients who require high levels of sedation to tolerate the endotracheal tube. As noted, tracheostomy placement may slightly reduce airway resistance and anatomic dead space and reduce WOB. Patients may derive benefit from the ability to eat orally, communicate by articulated speech, and enhanced mobility.

Tracheostomy is not without complications, which may include infection of the wound site, pneumothorax, subcutaneous emphysema, tube obstruction, and accidental decannulation.[16–18] Later complications include aspiration (30% to 50% of patients), pneumonia, tracheal stenosis, tracheoarterial fistula (most commonly tracheoinnominate artery fistula), tracheoesophageal fistula, and tracheomalacia.[12,14,16,19,20] Tracheostomy bypasses the natural warming, filtration, and humidification provided by the upper airway. Inadequate humidification can lead to chronic inflammatory changes,

squamous metaplasia, desiccation of the tracheal mucosa, and reduced ciliary function. Tracheostomy also diminishes cough effectiveness and may hamper an effective swallow.

Although rare (especially with the higher position of tracheostomy tubes done percutaneously), innominate artery erosion (i.e., tracheoarterial fistula) can lead to massive hemorrhage and death. Immediate recognition and maneuvers to sustain the patient until surgical repair can be done should be applied.[16] For example, the tube cuff may be overinflated to compress the innominate artery, or an endotracheal tube inserted allowing for removal of the tracheostomy tube. The ETT tip is then advanced distal to the tracheostomy stoma and the cuff inflated.[16] As a last resort, the artery may be digitally compressed using a finger placed through the stoma.[16]

In summary, the effect of early tracheostomy on hospital mortality, duration of mechanical ventilation, and development of ventilator-associated pneumonia remains unclear.[21,22] Tracheostomy appears to have benefits in terms of reduced sedation requirements, patient comfort, resumption of oral feeding, decreased oral and laryngeal injury, and reduced WOB. Early tracheostomy should be considered in patients likely to require prolonged mechanical ventilation. **Box 6-4** lists the indications, contraindications, and hazards of tracheostomy.

## BOX 6-4 Indications, Contraindications, and Complications of Tracheostomy

### Indications

- Provide secure airway for mechanical ventilation (especially prolonged mechanical ventilation).
- Failure to wean from the ventilator in 1 to 3 weeks following endotracheal intubation.

### Advantages

- Improve weaning parameters (e.g., rapid shallow breathing index [RSBI]).
- Reduce WOB.
- Improve patient comfort.
- Reduce need for sedation and analgesia.
- Improved patient mobility.
- Improved patient communication (speaking tubes, lip-reading).
- Allow patient to eat orally.
- Improved secretion clearance and ease of suctioning.
- Easier nursing care.
- Percutaneous tracheostomy is faster, less expensive, and may be performed at the bedside.

### Contraindications

- Age < 15 years (percutaneous tracheostomy)
- Bleeding diathesis (tendency to bleed, e.g., clotting disorder)
- Neck tumor
- Thyromegaly (enlarged thyroid)
- Tracheomalacia (weak, soft, floppy tracheal cartilages)
- Soft-tissue infection
- Obesity
- Cervical spine instability
- Short neck

### Complications During the Procedure

- Bleeding
- Airway obstruction/malfunction
- Hypoxemia/hypoventilation

### Complications Following the Procedure

- Airway malfunction
  - Obstruction
  - Secretions
  - Cuff leaks
  - Pilot balloon failure
  - Aspiration of secretions due to cuff failure or improper inflation
  - Accidental decannulation
  - Migration of the tube
- Pneumothorax; subcutaneous emphysema
- Postoperative hemorrhage
- Infection
- Nosocomial pneumonia
- Reduced or lost phonation (vocal fold sound production, speech)
- Tracheoarterial fistula (e.g., tracheal innominate artery erosion)
- Wound infection
- Oral secretion aspiration (cuff failure or poor cuff maintenance)
- Complications at the cuff site
  - Tracheomalacia
  - Tracheoesophageal fistula (more common with endotracheal intubation)
  - Tracheal stenosis
- Complications associated with suctioning (e.g., hypoxemia, arrhythmias, vagal stimulation, bradycardia, hypotension, and cardiac arrest)

## Choice of a Ventilator

Prior to initiation of mechanical ventilation, the respiratory care clinician must choose an appropriate ventilator. Ventilator choice should be driven by consideration of the patient's needs, the goals to be achieved, patient safety, and the clinician's familiarity with the ventilator to be employed. For example, an unstable, critically ill patient in acute ventilatory failure with severe, refractory hypoxemia may require a ventilator with in-depth monitoring and graphics capabilities able to apply sophisticated modes of ventilation. On the other hand, a long-term high cervical spinal cord injury patient with little or no lung injury may require a dependable and reliable ventilator able to safely support the patient; sophisticated graphics packages and modes of ventilation may not be needed. Patients expected to continue to make spontaneous ventilatory efforts during ventilatory support may do well with a ventilator able to provide a mode of ventilation that better promotes patient–ventilator synchrony. An apneic patient generally will require time-triggered volume ventilation (aka control mode), while a COPD patient with acute respiratory failure may do well with NIV.

When choosing a specific ventilator, features, modes available, pressure and flow capabilities, and integrated alarms and monitoring systems should be considered. Reliability, cost, and familiarity with the ventilator are also important factors in ventilator choice. Most modern ventilators have sufficient pressure and flow capabilities to ventilate patients with low compliance, high resistance, or markedly increased inspiratory flow demands. The ventilator chosen should adequately and safely ventilate patients under changing conditions and provide the features and modes required. Most ventilator manufacturers offer several ventilators with different capabilities and features. Typically, manufacturers will offer a sophisticated, high-end ventilator for critical care use that incorporates a number of modes and special features. The same manufacturer may also offer an intermediate critical care ventilator that does not include some modes of ventilation and/or some specific features. These intermediate ventilators are often less expensive and may be easier to operate by personnel unfamiliar with newer and more sophisticated modes of ventilation. Manufacturers also often offer specific ventilators for patient transport or very short-term use. While most of the newer critical care ventilators have NIV capability, some manufacturers offer ventilators that are designed primarily for NIV. In a similar fashion, some ventilators are designed primarily for use in the neonatal intensive care unit, while other ventilators are able to support infants, children, and adults. Several manufacturers offer ventilators particularly suited for long-term or home-care use. As manufacturers develop and market newer ventilators, older models are often gradually phased out, and may be acquired at a reduced cost.

Current adult critical care ventilators in common use include the Covidien Puritan Bennett series (PB 840, PB 980), Dräger Evita series (Evita XL, Evita Infinity V500), GE Healthcare CARESCAPE R860, Getinge Group Maquet Servo ventilators (Servo-s, Servo-i,, Servo-u), HAMILTON Medical Ventilators (HAMILTON G-5, HAMILTON C-3), and Vyaire ventilators (AVEA, VELA). Other ventilators for use in acute and postacute care include the Covidien Newport e360 ventilator and the Vyaire LTV 1200 and LTV 1150. Ventilators especially well-suited to provide NIV include the Philips Respironics ventilators (e.g., V60, V200, BiPAP, and Trilogy series) and Devilbiss ventilators (e.g., Intelli PAP AutoBilevel and Bilevel S). High-frequency ventilators include the Vyaire 3100B Oscillator, Percussionaire VDR-4, and Bunnell Life Pulse high-frequency ventilator. There are also transport and home care ventilators available, although these ventilators in general are not appropriate for continuing support of patients in the ICU. To summarize, factors that should be considered when choosing a ventilator include:

- Clinical goals and patient's needs
- Availability
- Reliability
- Ventilator features
- Alarms and monitoring capabilities
- Modes available
- Cost
- Clinician's familiarity with the ventilator

Chapter 4 provides additional information regarding specific critical care ventilators currently available.

### RC Insight

The most important factor in choice of ventilator is the clinician's familiarity with the device.

## Choice of Mode

The mode of ventilation is determined by the control variable (e.g., volume control [VC] or pressure control [PC]), breath sequence (e.g., continuous mandatory ventilation [CMV] or intermittent mandatory ventilation [IMV]), and targeting scheme employed.[4,5] Mandatory breaths occur when the start and/or end of inspiration is determined by the ventilator, independent of the patient. A mandatory breath may be patient or time triggered to inspiration but is cycled to expiration by ventilator-determined parameters, which may be set by the clinician or automatically determined by the ventilator. For example, continuous mandatory ventilation (CMV) may incorporate mandatory breaths that are time or patient triggered to inspiration (assist-control) and volume or time cycled to expiration. IMV intersperses mandatory breaths with spontaneous breaths. By definition, spontaneous breaths are initiated

by the patient and the patient determines when the end of inspiration occurs. In order to allow for spontaneous breathing through the ventilator circuit, modern ventilators incorporate a patient trigger to provide inspiratory gas flow and a cycle mechanism to allow flow to be patient cycled to expiration. Spontaneous breaths provided by the ventilator may include pressure support or automatic tube compensation during inspiration and may include CPAP during inspiration and expiration. The only requirement for a breath to be classified as spontaneous is that the breath is patient triggered to inspiration and patient cycled to expiration. Recall that PSV is patient triggered to inspiration and cycled to expiration when the patient's inspiratory flow rate declines to a preset value; thus, PSV can be considered a form of spontaneous ventilation.[4,5]

To review, the common control variables are PC or VC for the primary breath. The **primary breath** is defined as either the spontaneous breath in continuous spontaneous ventilation (CSV), the mandatory breath in continuous mandatory ventilation (CMV), or the mandatory breath in intermittent mandatory ventilation. With CSV, all breaths are spontaneous. With CMV, all breaths are mandatory. With IMV, spontaneous breaths are interspersed with mandatory breaths. Using the breath sequence of either CSV, CMV, or IMV coupled with the control variable of either pressure or volume, the clinician can describe the basic mode of ventilation being employed. Using this system, the five basic modes of ventilation available are: VC-CMV, VC-IMV, PC-CMV, PC-IMV, and PC-CSV.[5]

Within these broad modes, there are several variations that can be distinguished by their targeting schemes. There are seven targeting schemes in current use: set-point (s), dual (d), servo (r), adaptive (a), biovariable (b), optimal (o), and intelligent (i).[5] The mode of ventilation can be further described by placing the targeting scheme subscripts after the basic mode description. For example, **assist-control volume ventilation** (aka volume control-continuous mandatory ventilation) with set-point breath targeting can be further described as VC-$CMV_s$. Volume control-SIMV with set-point breath targeting for both mandatory and spontaneous breaths would be described as VC-$IMV_{s,s}$. These targeting schemes are further described in **Table 6-2**.

Currently, there are very large number of modes of ventilation available. While many of these modes have distinct advantages from a theoretical point of view, research demonstrating that a specific mode is more effective in improving patient outcomes is often lacking. Consequently, we will focus on common modes used to provide adult ventilatory support. Other, newer modes will be discussed later in this section.

## More on Nomenclature

Nomenclature for different modes of ventilation can be confusing and specific manufacturers often use different terms to refer to the same mode. As noted, what distinguishes different modes of ventilation are the control variables (pressure or volume), breath sequence (CMV, IMV, or CSV), and the targeting scheme or schemes used for the primary and secondary breaths.[4,5] The primary breath generally refers to mandatory breaths (CMV or IMV) although with continuous spontaneous breathing (absent mandatory breaths) spontaneous breaths would be considered primary. The **secondary breaths** are those that occur in addition to the primary breaths. For example, IMV combines mandatory breaths with spontaneous breaths. To further complicate the nomenclature, there are seven basic targeting schemes (set point [s], dual [d], biovariable [b], servo [r], adaptive [a], optimal [o], and intelligent [i]).[4,5] For example, for the Covidien PB 840 and PB 980, in the assist-control (A/C) volume-control mode the clinician sets the tidal volume, peak flow, and trigger sensitivity. The tidal volume and flow waveform are set by the clinician and not adjusted automatically by the ventilator. This is referred to as set-point targeting; the recommended nomenclature for this mode would be VC-$CMV_s$ where the s indicates the set-point targeting scheme.[4,5] Other names used for VC-CMVs include *CMV* and *VC-CMV* (Dräger Evita XL and Evita Infinity V500 respectively [VC-CMV provided by the V500 is time triggered only]), and s*ynchronized controlled mandatory ventilation* (HAMILTON G5, HAMILTON C-3). The Maquet Servo-i and Servo-u have a similar mode called *volume control*; this mode allows patient or time triggering (i.e., assist-control).

For the Covidien PB 840 and PB 980 in the *SIMV volume control with pressure support* mode, the clinician sets the tidal volume, peak flow, and trigger sensitivity for the mandatory breaths and the pressure-support level for spontaneous breaths. The recommended nomenclature for this mode of ventilation would be VC-$IMV_{s,s}$, indicating a set-point targeting scheme for both primary and secondary breaths. VC-$IMV_{s,s}$ is simply called *SIMV* by Dräger and HAMILTON (Dräger Evita XL, Dräger Evita Infinity V500, and HAMILTON Medical G5 and C-3). Dual targeting allows the ventilator to automatically switch between volume control and pressure control during a single breath.[4,5] The Maquet Servo-i and Servo-u incorporate dual targeting when using AutoMode for PC, VC, and PRVC. In this case, dual targeting allows the ventilator to automatically switch between volume or pressure control and pressure support during a single breath.

## Full and Partial Ventilatory Support

Mechanical ventilation may be employed to provide 100% of the WOB required to meet the patient's ventilatory needs. In such cases, the patient is receiving full ventilatory support. Other modes of ventilation may be selected that do not provide 100% of the patient's ventilatory needs and require the patient to provide some

**TABLE 6-2**
**Ventilator Modes and Targeting Schemes**

| The five basic ventilator modes are: | | |
|---|---|---|
| **Mode** | **Abbreviation** | **Common Terminology** |
| Volume control-continuous mandatory ventilation | VC-CMV | Assist-control volume ventilation |
| Volume control-intermittent mandatory ventilation | VC-IMV | IMV or SIMV volume ventilation |
| Pressure control-continuous mandatory ventilation | PC-CMV | Pressure-control ventilation (PCV) |
| Pressure control-intermittent mandatory ventilation | PC-IMV | IMV pressure-control ventilation |
| Pressure control-continuous spontaneous ventilation | PC-CSV | The most common form is PSV |

| The seven available targeting schemes* are: | | | |
|---|---|---|---|
| **Name** | **Abbr.** | **Description** | **Example** |
| Set-point | s | The clinician sets the volume and flow waveforms for VC and the pressure and pressure waveform for PC. Set-point breath targeting is easy to understand and apply. | Covidien PB 840 and PB 980: *A/C volume control (VC-CMVs).* |
| Dual | d | The ventilator can automatically switch between VC and PC *during a single inspiration.* Originally introduced as volume-assured pressure support (VAPS) in which a breath began as a pressure-support breath and then could switch to a volume-control breath if tidal volume target was not being achieved.<br>Dual targeting may also be used to switch between volume-control and pressure-support breaths. With *flow adaptive volume control*, if the patient makes minimal or no effort, breath delivery is like assist-control VC-CMV. If the patient makes sufficient inspiratory effort, the breath changes to pressure support.<br>Dual targeting can allow for consistent tidal volume delivery but can be complicated and difficult to set. | Evita XL, Evita Infinity V500: *CMV with pressure-limited ventilation (VC-CMVd).* |
| Servo | r | Proportional assist ventilation (PAV), automatic tube compensation (ATC), and neurally adjusted ventilatory assist (NAVA) are modes that incorporate servo targeting.<br>With servo targeting, ventilator output automatically adjusts based on varying input measures. For example, inspiratory pressure may be adjusted proportional to inspiratory effort; as effort increases support increases (and vice versa). | Proportional assist ventilation is available on the Covidien PB 840 and PB 980 as *proportional assist ventilation plus (PAV+).* PAV+ would be classified as PC-CSVr. ATC is available on the HAMILTON G5, Covidien PB 840 and PB 980, Dräger Evita XL and Infinity 500, Yvaire AVEA, HAMILTON G5, and Maquet Servo-i and Servo-u. NAVA is available with the Maquet Servo-i and Servo-u. |
| Adaptive | a | The ventilator automatically adjusts targets *between breaths* in response to varying patient input. Adaptive targeting is used in combination with pressure control to allow the ventilator to automatically change the pressure-control level as needed to maintain a clinician-set target tidal volume. Adaptive targeting can maintain a stable tidal volume in the face of changing pulmonary mechanics or patient inspiratory effort. | Servo-i and Servo-u: *Pressure-regulated volume control (PRVC or PC-CMVa).* |
| Biovariable | b | The ventilator randomly adjusts inspiratory pressure or tidal volume to simulate the variability associated with normal spontaneous breathing. | Evita Infinity V 500: *Variable pressure support (PC-CSVb).* |
| Optimal | o | Ventilatory pattern is automatically adjusted to optimize WOB in the face of changing lung mechanics or patient effort. | HAMILTON G5: Adaptive support ventilation (ASV or PC-IMVoi,oi). |

| The seven available targeting schemes* are: | | | |
|---|---|---|---|
| **Name** | **Abbr.** | **Description** | **Example** |
| Intelligent | i | Artificial intelligence is used to adjust the ventilator in the face of changing lung mechanics or patient inspiratory effort. Intelligent breath targeting can adapt the ventilator in the face of patient changes similar to human decision making. Intelligent targeting may make inappropriate ventilator changes if algorithm assumptions are violated or do not match the patient's actual physiology. | Evita XL and Evita Infinity V 500: *Smart Care/PS (PC-CSVi)* |

The mode of ventilation is determined by the control variable (e.g., VC or PC), breath sequence (e.g., CMV or IMV), and targeting scheme employed.
* Note: the targeting scheme is indicated by the abbreviation following the major mode description. For example, *volume-controlled continuous mechanical ventilation with set-point targeting* would be described as **VC-CMV**$_{s}$. Targeting schemes for mandatory and spontaneous breaths are listed for IMV modes. For example, *SIMV volume control with pressure support* (PB840 and 980) using set-point targeting for spontaneous and mandatory breaths would be described as **VC-IMV**$_{s,s}$, indicating set-point targeting for both spontaneous and mandatory breaths. Targeting schemes can be mixed in the IMV mode. For example, *adaptive pressure ventilation SIMV* (HAMILTON G5) would be described as **PC-IMV**$_{a,s}$, indicating adaptive targeting for pressure-control breaths and set-point targeting for spontaneous breaths.

portion of the WOB in order to achieve effective ventilation. When less than 100% of the WOB is performed by the ventilator, this is known as partial ventilatory support. Advantages and disadvantages of these two approaches are discussed below.

## Full Ventilatory Support

When mechanical ventilation is initiated to provide full ventilatory support, adequate alveolar ventilation is maintained even if the patient makes no spontaneous breathing efforts. Full ventilatory support can be provided using volume- or pressure-controlled ventilation. The key to providing full ventilatory support is ventilator settings that deliver a tidal volume, respiratory rate, and resultant minute ventilation sufficient to provide 100% of the patient's needs with little or no work on the part of the patient. In the case of spontaneously breathing patients in the CMV mode, the patient can trigger the ventilator (aka assist breaths); care must be taken to minimize trigger work and maximize patient–ventilator synchrony. In the event of apnea, the set ventilator rate, tidal volume, and minute ventilation are sufficient, and the patient's WOB is zero. The term **controlled ventilation** is sometimes used to refer to time-triggered continuous mandatory ventilation and should not be confused with volume control or pressure control.

Full ventilatory support is required in the presence of apnea. Causes of apnea include anesthesia, sedative or narcotic drugs, cardiac arrest, heart failure, shock, trauma, head injury, cerebral hypoxia, neurologic/neuromuscular disease (e.g., major stroke, spinal cord injury, and brain death), poisoning (e.g., carbon monoxide, cyanide) and administration of neuromuscular-blocking agents (e.g., succinylcholine, rocuronium). Full ventilatory support is also generally indicated as an initial approach for patients with severe respiratory failure and increased WOB. Properly applied, full ventilatory support may allow for ventilatory muscle rest and recovery in cases of diaphragmatic fatigue.

Controlled ventilation is a time-triggered form of full ventilatory support that requires apnea. Controlled ventilation eliminates the WOB and allows for complete control over the patient's ventilatory pressures, volumes, and flows. Controlled ventilation will reduce oxygen consumption of the ventilatory muscles and provide ventilatory muscle rest. Administration of sedatives and (in some cases) neuromuscular-blocking agents (aka paralytic drugs) may be needed to achieve controlled ventilation. Neuromuscular-blocking agents paralyze the voluntary muscles, including the diaphragm. In the event of a ventilator malfunction or disconnect, the patient will be unable to breathe spontaneously, and a catastrophic outcome may follow. It should also be noted that paralytic agents do not alter cognitive function, perception, or the experience of pain.[23] Because of this, neuromuscular-blocking agents should be given in conjunction with sedatives and appropriate analgesics for pain and anxiety. Neuromuscular-blocking agents can also cause anaphylaxis, hypotension, cardiac arrhythmias, electrolyte disturbances, and prolonged paralysis and muscle weakness.[23] Neuromuscular-blocking agents used in the ICU include vercuronium (Norcuron), pancuronium (Pavulon), and cisatracurium (Nimbex). Neuromuscular-blocking agents should be used cautiously, and other options should be considered for managing patient agitation, excessive movement, or ventilator asynchrony.[23] Prolonged controlled ventilation may also result in ventilatory muscle atrophy and reductions in diaphragmatic muscle strength and endurance.[24]

To summarize, full ventilatory support provides 100% of the patient's ventilatory needs. Full ventilatory support can be provided using assist-control volume-control ventilation (aka VC-CMV), assist-control pressure-control ventilation (PC-CMV), and volume- or pressure-control SIMV (e.g., VC-IMV or PC-SIMV).

## Partial Ventilatory Support

When mechanical ventilation is initiated to provide partial ventilatory support, the ventilator settings and mode require that the patient provide a portion of the ventilation and associated work required to maintain an acceptable $Paco_2$. The most common form of partial ventilatory support is IMV with mandatory rates less than 8 to 10 breaths/min. This requires the patient to breathe spontaneously between mandatory breaths at a spontaneous rate and tidal volume sufficient (in combination with the ventilator's support) to maintain effective alveolar ventilation. With partial ventilatory support in the IMV mode, should the patient's spontaneous breathing cease or become inadequate, acute hypercapnia and respiratory acidosis may occur. Full ventilatory support can be provided using IMV if the mandatory rate, tidal volume, and resultant minute ventilation meets all the patient's needs (e.g., $V_T \geq 6$ to 8 mL/kg and $f \geq 10$ to 12 breaths/min).

There are several other modes of ventilation that require the patient to breathe spontaneously. These include PSV, volume support (VS), PAV, and NAVA, all of which can be used to provide partial ventilatory support.

Mandatory minute ventilation (MMV) and adaptive support ventilation (ASV) automatically vary the level of mechanical ventilatory support with changes in the patient's spontaneous minute ventilation. Thus, MMV and ASV adjust automatically to provide partial or full ventilatory support as the patient's spontaneous minute ventilation varies.

In summary, partial ventilatory support requires the patient to continue to breathe spontaneously to maintain adequate alveolar ventilation. Modes sometimes used to provide partial ventilatory support include IMV/SIMV, PSV as a standalone mode, VS, PAV, and NAVA. Partial ventilatory support may help maintain ventilatory muscle function and reduce the loss of ventilatory muscle strength that sometimes occurs with mechanical ventilation.[24,25] Partial ventilatory support may require less sedation and improve patient–ventilator synchrony in some patients. Because spontaneous breathing occurs during partial ventilatory support, there may be some advantages in stabilizing and recruiting alveoli because of the negative intrathoracic pressures that occur during spontaneous breathing. A major disadvantage of partial ventilatory support is that it may not allow for adequate ventilatory muscle rest and recovery in cases where diaphragmatic fatigue has occurred.

## Major Modes of Ventilation

As noted, there are five basic ventilatory modes at the clinician's disposal: volume control-continuous mandatory ventilation (VC-CMV), pressure control-continuous mandatory ventilation (PC-CMV), **volume control-intermittent mandatory ventilation (VC-IMV)**, pressure control-intermittent mandatory ventilation (PC-IMV), and pressure control-continuous spontaneous ventilation (PC-CSV). VC-CMV and VC-IMV are the most frequently used forms of ventilation for adult patients at many institutions and most clinicians are familiar with these two modes.[25,26] While multiple breath-targeting schemes are used in various adaptations of these five basic modes, we will focus our discussion to use of these modes where the clinician determines most ventilator parameters (i.e., set-point breath targeting). Advantages and disadvantages of each of these major modes are discussed below.

### Volume Control-Continuous Mandatory Ventilation (VC-CMV)

VC-CMV with set-point breath targeting is commonly referred to as volume-limited ventilation, volume-targeted ventilation, volume-cycled ventilation, volume assist-control (VA/C), or just plain *volume ventilation*. VC-CMV may be patient or time triggered to inspiration and is volume cycled to expiration. Typically, the clinician sets the desired tidal volume, minimum mandatory (machine) rate, inspiratory peak flow, and trigger sensitivity. Other ventilators instead have the clinician set the desired tidal volume, mandatory (machine) rate and inspiratory time, or inspiratory percentage time. Most ventilators also allow the clinician to select the inspiratory flow waveform, typically as a square wave or down ramp, although some ventilators have a sinewave option (e.g., HAMILTON G5). A square flow waveform (aka constant flow waveform) may reduce mean airway pressure, which may be useful in patients who are hemodynamically compromised.[27] A down-ramp flow waveform (aka decreasing flow waveform) may increase mean airway pressure, reduce peak inspiratory pressure, and improve distribution of inspired gases.[27]

With VC-CMV, every breath is a mandatory breath delivered at the clinician-selected $V_T$. Commonly referred to as *assist-control volume ventilation*, the patient can trigger the primary breath (aka assist breath). If no spontaneous effort is detected during the respiratory cycle time, the ventilator will provide a **time-triggered breath** (aka control breath). **Figure 6-2** illustrates patient- and time-triggered VC-CMV.

Volume-control ventilation is available as *A/C volume control* (Covidien PB 840 and PB P980), *CMV* and *VC-CMV* (Dräger Evita XL and Evita Infinity V500) and *synchronized controlled mandatory ventilation* [(S) CMV] (HAMILTON G-5). The Maquet Servo-i and Servo-u also feature a *volume control* mode, which (in the absence of Automode) functions as VC-CMV.

A major advantage of VC-CMV is the fact that it will deliver a constant $V_T$ in the face of changes in compliance and resistance limited only by the clinician-set maximum pressure alarm limit and the machine's

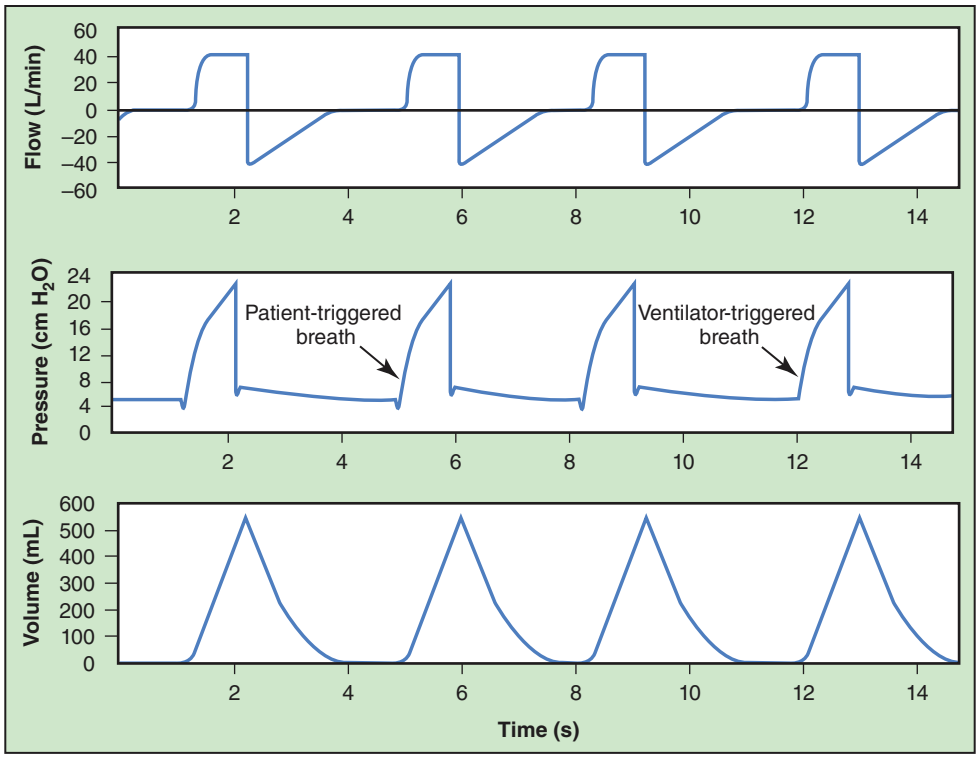


**FIGURE 6-2** Continuous Mandatory Ventilation Illustrating Ventilator-Triggered and Patient-Triggered Breaths.

pressure and flow capabilities. A minimum guaranteed minute ventilation ($\dot{V}E$) will be delivered based on the VT and set backup rate. In the assist-control mode, the patient can trigger the ventilator above the set minimum respiratory rate; a minimum $\dot{V}E$ will be provided in the absence of a patient trigger (e.g., apnea due to sedation or CNS problems). Properly applied assist-control volume ventilation provides full ventilatory support with a lower WOB then partial ventilatory support modes. Ventilatory muscle fatigue occurs due to high ventilatory workloads, such as may occur in patients with acute respiratory failure. Because VC-CMV can reduce or eliminate the WOB, it is especially well-suited to allow for ventilatory muscle rest and recovery from ventilatory muscle dysfunction. It must be noted, however, that prolonged ventilatory muscle inactivity may result in ventilatory muscle weakness and atrophy.[24] VC-CMV is easy to understand and apply and is well-suited for most patients.

Disadvantages of VC-CMV include the possible delivery of unsafe peak and plateau pressures (PIP and $P_{plateau}$) in the presence of decreasing compliance or increasing airway resistance. Use of large tidal volumes may also result in excessive PIP and $P_{plateau}$ and excessive airway pressures may result in barotrauma or VILI. This emphasizes the need for setting the ventilator alarms at appropriate levels to alert the respiratory therapist to make ventilator adjustments, when needed. It is also important to note that with patient-triggered breaths, patients continue to actively inspire even though the machine breath has been triggered. This can result in an increase in WOB, especially if inspiratory time or peak inspiratory flow rates are set improperly.

Problems with patient–ventilator asynchrony may also occur due to inappropriate trigger-sensitivity settings, high patient trigger rates, or inadequate peak inspiratory flow rates. For example, a patient in distress may trigger the ventilator at a rapid assist rate resulting in decreased expiratory time and increased mean airway pressures. Excessive patient effort required to trigger a mandatory breath will increase the patient's WOB. This can be caused by inappropriate trigger sensitivity or autoPEEP, both of which may increase trigger work. Inappropriate peak inspiratory flow rate settings that do not meet or exceed the patient's inspiratory flow demand may increase the patient's WOB and result in patient–ventilator asynchrony. Inadequate expiratory times may cause the development of autoPEEP, especially in patients with obstructive lung disease. High mean airway pressures may impede venous return and reduce cardiac output in hemodynamically compromised patients. Some patients who are awake, alert, and anxious do not tolerate VC-CMV well, and other forms of ventilatory support may be considered.

*Controlled ventilation* (time-triggered VC-CMV) requires patient apnea, which in turn may require the administration of sedative and possibly paralytic agents, which can delay ventilator weaning and discontinuance. Controlled ventilation may be required in patients with an absent ventilatory drive due to CNS problems (e.g.,

coma), spinal cord injury, or neuromuscular paralysis. Provision of a relatively high minute ventilation via time-triggered VC-CMV that meets all the patient's physiologic needs may reduce the drive to breathe and cause an absence of patient-triggered breaths. Time-triggered VC-CMV eliminates diaphragmatic activity and the WOB. Patients may also develop ventilatory muscle weakness, and atrophy and neuromuscular weakness related to critical illness is not uncommon.[24] Diaphragmatic inactivity can cause atrophy in as little as 18 to 69 hours.[28] Careful monitoring of the apneic patient is required as a ventilator malfunction or disconnect can be catastrophic in patients unable to spontaneously breathe. **Box 6-5** summarizes the advantages and disadvantages of patient- and time-triggered VC-CMV (aka assist-control volume ventilation).

## Pressure Control-Continuous Mandatory Ventilation

Pressure control-continuous mandatory ventilation (PC-CMV) with set-point breath targeting is patient- or time triggered to inspiration, pressure limited and time cycled to expiration. Other terms employed for PC-CMV include pressure assist-control, pressure A/C, pressure-control ventilation (PCV), and (when used with an inverse I:E ratio) *pressure-control inverse-ratio ventilation* (PC-IRV). With PC-CMV, the respiratory care clinician sets the respiratory rate, inspiratory time (or inspiratory percent time), and inspiratory pressure limit. The clinician also determines the patient trigger sensitivity and may adjust the inspiratory rise time or ramp. During inspiration, airway pressure rises to a preset value; inspiration is terminated when the inspiratory time limit is reached. Normal adult inspiratory time ($T_I$) is set at 0.6 to 1.0 seconds with a respiratory rate of 12 to 20 breaths/min and I:E ratio of 1:2 or lower. Some patients do well with slightly longer $T_I$ (e.g., 0.8 to 1.2 seconds). Typically, PC-CMV results in a square wave-like inspiratory pressure waveform and a decreasing or decelerating inspiratory flow waveform, which may improve patient comfort and improve the distribution of inspired gases. The square wave pressure pattern will also increase mean airway pressure, which may improve oxygenation. Recall, however, that increased mean airway pressure may impede venous return and reduce cardiac output in patients with hemodynamic instability. Properly applied, PC-CMV provides full ventilatory support and minimizes the WOB, which may be helpful to rest the ventilatory muscles in the presence of ventilatory muscle fatigue.

### RC Insight

With PC-CMV, tidal volume is adjusted by adjusting the pressure gradient (ΔP = PIP–PEEP) to obtain the desired VT.

With PC-CMV, the clinician sets the pressure-control level, which assures (if properly set) that airway pressures remain in a safe range ($P_{plateau} \leq$ 28 to 30 cm $H_2O$). PC-CMV provides a decreasing flow waveform that varies flow with patient demand. For example, gas flow to the patient will increase with increased patient effort. This variable flow may better match patient inspiratory demand, improve patient comfort, provide better patient–ventilator synchrony and allow for earlier liberation from the ventilator. As noted, the square wave inspiratory pressure waveform results in a decreasing flow waveform. The square wave inspiratory pressure waveform also results in more sustained inspiratory pressure, which may improve alveolar recruitment, as well as improve distribution of inspired gases.

Pressure rise time or slope may be adjusted by the clinician to adjust the rate at which inspiratory gas flow increases from baseline to peak flow during the first part of the inspiratory phase. Rise time should be adjusted so that inspiratory gas flow meets or exceeds patient demand. Slow rise times may not provide adequate flow and increase the WOB. Rapid rise times may provide more flow than necessary and result in an inspiratory pressure spike near the beginning of the inspiratory phase.

VT is determined by the pressure gradient (ΔP = PIP – PEEP), inspiratory time, patient effort, and pulmonary mechanics (compliance and resistance). In general, VT increases as the inspiratory pressure increases (assuming ventilatory mechanics, patient effort, inspiratory time, and PEEP are constant); decreases in inspiratory pressure generally reduce VT. Changes in PEEP will affect delivered VT if inspiratory pressure is not simultaneously adjusted, although most ventilators in the pressure-control mode will automatically adjust inspiratory pressure with changes in PEEP to maintain a constant ΔP. For initial ventilator setup, inspiratory pressure generally is adjusted to achieve a VT in the range of 6 to 8 mL/kg of ideal body weight (IBW) while maintaining a safe plateau pressure ($P_{plateau} \leq$ 28 to 30 cm $H_2O$).

With PC-CMV, as inspiratory time ($T_I$) increases, inspiratory flow to the patient decreases because of the decreasing flow waveform provided. If sufficient inspiratory time is provided, flow will decrease to zero and any remaining inspiratory time will provide an inspiratory hold or plateau. Increases in inspiratory time generally will increase VT up until the point at which flow reaches zero.

Initial ventilator set up for PC-CMV includes selecting a $T_I$ that provides enough time for the inspiratory flow to decrease to zero before beginning the expiratory phase. In cases where inspiratory flow does not reach zero at end inspiration, increasing inspiratory time will tend to increase VT. As noted, if inspiratory time continues past the point of zero gas flow, an inspiratory pause or hold will ensue, which may further improve the

## BOX 6-5 Advantages and Disadvantages of Volume Control-Continuous Mandatory Ventilation (VC-CMV)

VC-CMV, commonly known as assist-control volume ventilation, allows the clinician to set the desired tidal volume ($V_T$), minimum mandatory (machine) rate (f), inspiratory peak flow, and trigger sensitivity. Other ventilators have the clinician set tidal volume, mandatory (machine) rate, and inspiratory time or inspiratory percentage time and trigger sensitivity. VC-CMV allows for control of the $F_{IO_2}$ and the addition of PEEP. Assist-control volume ventilation allows for a patient or time trigger, whichever occurs first. Controlled volume ventilation is time triggered and requires apnea.

**Advantages of VC-CMV**

- $V_T$ constant in the face of changes in compliance and resistance (within the clinician-set maximum pressure limit and the machine's pressure and flow capabilities).
- Guaranteed minimum minute ventilation delivered ($\dot{V}_E$) based on set minimum f and $V_T$.
- Provides full ventilatory support.
- Minimizes or eliminates the WOB.
  - Patient-triggered (assist) breaths should have minimal work if proper trigger sensitivity and appropriate peak inspiratory flowrates are set in spontaneously breathing patients.
  - Time-triggered ventilation (control mode) eliminates the WOB but requires apnea.
- Allows for ventilatory muscle rest and recovery from ventilatory muscle dysfunction.
- Flow waveform is adjustable on some ventilators.
  - Square wave flow waveform (aka constant flow waveform) may reduce mean airway pressure and inspiratory time (in ventilators with peak flow control) but increase peak inspiratory pressure (PIP). This flow waveform may be useful in patients who are hemodynamically compromised.
  - Down ramp (aka decreasing flow waveform) may increase mean airway pressure, reduce PIP, and increase inspiratory time in ventilators with the peak flow control. This may improve the distribution of inspired gases and oxygenation.
- Assist-control volume ventilation is easy to understand and apply and is a type of ventilation familiar to most clinicians.
- Mode is well-suited for most patients.

**Disadvantages of VC-CMV**

- Unsafe peak inspiratory pressures (PIP > 35 to 40 cm $H_2O$) may occur with reduced compliance or increased airway resistance as the ventilator attempts to maintain delivered $V_T$.
- Unsafe plateau pressures ($P_{plateau}$ > 28 to 30 cm $H_2O$) may occur with inappropriate tidal volume settings and/or reduced lung compliance, which may result in alveolar overdistention.
- Improper trigger sensitivity may increase the WOB.
- Inspiratory flow rate is typically fixed and does not vary with patient effort. This may cause patient–ventilator asynchrony.
- Inadequate ventilator flow rates may increase the WOB in spontaneously breathing patients and result in patient–ventilator asynchrony.
  - Low inspiratory flow rates also increase inspiratory time and (assuming a constant respiratory rate) decrease expiratory time.
- Inadequate expiratory times may result in auto PEEP, particularly in patients with obstructive lung disease.
- With patient-triggered breaths, patients continue to actively inspire even though the ventilator has begun to provide support; this may increase the WOB especially in cases of inappropriate ventilator peak flow settings.
- High mean airway pressures may reduce venous return and impede cardiac output in hemodynamically unstable patients.
- High pressures may result in *barotrauma* (e.g., pneumothorax, pneumomediastinum, pneumoperitoneum, and subcutaneous emphysema) or *ventilator-induced lung injury* (VILI). VILI is caused by alveolar overdistention (aka volume trauma), cyclic alveolar expansion and collapse (aka atlectrauma), or inflammation associated with mechanical ventilation (aka biotrauma).
- Patients may trigger the ventilator at a rapid rate resulting in respiratory alkalosis, patient–ventilator asynchrony, and increased peak and mean airway pressures.
- Inappropriate inspiratory flow rates that do not meet the patient's inspiratory flow demand in spontaneously breathing patients may increase the WOB.

(*Continues*)

**BOX 6-5 Advantages and Disadvantages of Volume Control-Continuous Mandatory Ventilation (VC-CMV) (*Continued*)**

- Assist-control volume ventilation may be poorly tolerated in patients who are awake, anxious, or in pain; this may result in the patient fighting the ventilator.
- Controlled ventilation (time-triggered VC-CMV) requires apnea.
  - Sedative and (possibly) paralytic drugs may be required.
  - Paralytic drugs should not be administered alone and require the addition of sedatives for pain and anxiety. Prolonged use of paralytic agents is uncommon in the modern ICU.
  - Ventilator malfunction or disconnect can be catastrophic in the presence of apnea.
- Development of ventilatory muscle weakness and atrophy is associated with controlled ventilation, prolonged use of sedatives, and use of neuromuscular-blocking agents.

distribution of inspired gases. That said, with patients making spontaneous respiratory efforts, excessive inspiratory times may cause patient–ventilator asynchrony. Care should also be taken to ensure adequate expiratory time to avoid autoPEEP and gas trapping, especially in patients with obstructive lung disease.

Disadvantages of PC-CMV include variable tidal volume delivery in the face of changes in the level of patient effort, system compliance, or airway resistance and this may result in inadvertent hypo- or hyperventilation. This requires the clinician to pay careful attention to delivered $V_T$ and $\dot{V}_E$ and set the ventilator's alarms appropriately. Changes in inspiratory time may also affect delivered $V_T$. PC-CMV may also result in a higher mean airway pressures, which may decrease venous return and impair cardiac output in hemodynamically unstable patients. As with other modes, improper trigger sensitivity may increase WOB. Inadequate inspiratory flow rates, which may occur with inappropriate rise time settings, may also increase WOB and cause patient–ventilator asynchrony. As with other modes of ventilation, excessive airway pressures may cause barotrauma or VILI and inadequate expiratory times may result in the development of auto PEEP and air trapping. Some awake and alert patients will not tolerate PC-CMV. For example, pain and anxiety may result in rapid patient-triggering rates, increased airway pressures, respiratory alkalosis, and patient–ventilator asynchrony. Controlled ventilation (time-triggered PC-CMV) requires apnea, which in turn may require the use of sedatives and possibly paralytic agents.

*Pressure-control inverse-ratio ventilation* (PC-IRV) is a form of PC-CMV in which the ventilator is adjusted so that inspiratory time is longer than expiratory time. PC-IRV increases mean airway pressure and may improve oxygenation in certain patients with severe hypoxemic respiratory failure despite optimal PEEP and appropriate $F_{IO_2}$. While PC-IRV can improve oxygenation, evidence of improvement in other important outcomes (e.g., time on the ventilator, time in the ICU, and mortality) is lacking.[26] PC-IRV often requires the use of sedatives and (sometimes) paralytic agents, as spontaneously breathing patients generally do not tolerate the use of inverse-ratio ventilatory patterns well and may fight the ventilator. The clinician should also be aware that increased mean airway pressures may reduce venous return and cardiac output in hemodynamically compromised patients.

PC-CMV is available as *A/C pressure control* (Covidien PB 840 and PB 980); *pressure-control ventilation plus assisted, CMV with Autoflow*, and *CMV with Autoflow and tube compensation,*(Dräger Evita XL); *pressure control assist-control*, and *volume control assist-control with Autoflow* (Evita Infinity V500); *pressure control CMV, pressure-control CMV with tube-resistance compensation, adaptive pressure ventilation CMV*, and *adaptive pressure ventilation and CMV with tube-resistance compensation* (HAMILTON G-5). The Maquet Servo-i and Servo-u also feature *pressure control and pressure-regulated volume control* modes. **Box 6-6** summarizes the advantages and disadvantages of PC-CMV.

## Volume-Controlled Intermittent Mandatory Ventilation

Volume-controlled intermittent mandatory ventilation (VC-IMV) intersperses volume-targeted mandatory breaths with spontaneous breathing. VC-IMV is commonly referred to as volume-targeted SIMV or V-SIMV. With SIMV mandatory breaths may be time or patient triggered. Older forms of IMV did not allow for patient-triggered mandatory breaths. With SIMV, if the patient does not trigger a breath during the time window provided, the ventilator will provide a time-triggered mandatory breath. SIMV was introduced to help avoid breath stacking and reduce patient–ventilator asynchrony, which can occur with time-triggered IMV.

Most modern ventilators today provide SIMV. For VC-SIMV, the clinician sets $V_T$ and mandatory rate, inspiratory peak flow or inspiratory time, trigger sensitivity, and $F_{IO_2}$. Spontaneous breaths may include pressure

## BOX 6-6 Advantages and Disadvantages of Pressure Control-Continuous Mandatory Ventilation (PC-CMV)

PC-CMV, commonly known as assist-control pressure-control ventilation (PCV), allows the clinician to set the desired inspiratory pressure, minimum mandatory (machine) rate (f), inspiratory time (or inspiratory percentage time), and trigger sensitivity. PC-CMV allows for control of the $F_{IO_2}$ and the addition of PEEP. Assist-control PCV allows for a patient or time trigger, whichever occurs first. Time–triggered control mode PCV requires patient apnea.

**Advantages of PC-CMV**

- Inspiratory pressure is constant in the face of changes in compliance and resistance.
  - Plateau pressure can be maintained at safe levels ($P_{plateau} \leq$ 28 to 30 cm $H_2O$).
  - Resultant PIP may be lower than can be achieved with VC-CMV (square wave).
  - Risk of alveolar overdistention is reduced with changes in compliance.
  - Square wave-like inspiratory pressure waveform results in more sustained inspiratory pressure, which may improve alveolar recruitment.
- Desired $V_T$ may be achieved by adjusting pressure control level (PIP) or inspiratory time.
  - $V_T$ is determined by the pressure gradient ($\Delta P$ = PIP – PEEP), patient effort, inspiratory time ($T_I$), and pulmonary mechanics (compliance and resistance).
  - Increasing $\Delta P$ by increasing PIP generally increases $V_T$ and vice versa.
  - In cases where inspiratory flow does not reach zero at end inspiration, increasing inspiratory time will tend to increase $V_T$.
  - PEEP changes may affect $\Delta P$ and delivered $V_T$. PEEP alterations will require attention to alterations in PIP to maintain the same $\Delta P$ and tidal volume delivery.
  - Increased patient inspiratory effort will generally increase $V_T$; decreased effort tends to decrease $V_T$.
- Properly applied, PC-CMV can provide full ventilatory support.
- PC-CMV may minimize or eliminate the WOB.
  - Patient-triggered (assist) breaths should have minimal work if proper trigger sensitivity is set and adequate inspiratory gas flow is provided to meet or exceed the patient's inspiratory demand (i.e., appropriate rise time settings).
  - Time-triggered ventilation (control mode) eliminates the WOB but requires apnea.
- Allows for ventilatory muscle rest and recovery from ventilatory muscle dysfunction if properly applied.
- Decreasing flow waveform varies flow based on patients' inspiratory effort.
  - Patient comfort and patient–ventilator synchrony may improve with PC-CMV because inspiratory flow varies with patient effort.
  - Decreasing flow waveform (aka down ramp) increases mean airway pressure and may improve inspired gas distribution and oxygenation.
  - Decreasing flow waveform results in a square wave pressure pattern, which may open alveoli earlier in the inspiratory phase, improve inspired gas distribution, and improve oxygenation.
  - Improved gas distribution may allow for use of a lower $V_T$.
  - Pressure rise time or slope can be adjusted. Rise time allows the clinician to adjust the rate at which inspiratory gas flow increases from baseline to peak flow. Rise time should be adjusted to ensure that machine gas flow meets or exceeds patient demand.
  - Rise time adjustment of the pressure waveform can be made to avoid a pressure spike at the beginning of inspiration due to rapid rise times in which the flow to the patient exceeds patient demand.
  - Rise time should also be adjusted to ensure that inspiratory gas flow is not too slow and meets or exceeds patient demand. Slow rise times may increase WOB.
- Pressure-control inverse-ratio-ventilation (PC-IRV) has been suggested for severe hypoxemic respiratory failure (e.g., severe ARDS) where optimal PEEP and $F_{IO_2}$ have been ineffective in providing adequate oxygenation. While PC-IRV may improve oxygenation, cardiac output may be compromised due to increased mean airway pressures and decreased venous return.

(*Continues*)

## BOX 6-6 Advantages and Disadvantages of Pressure Control-Continuous Mandatory Ventilation (PC-CMV) (*Continued*)

- Assist-control PCV is relatively easy to understand and apply.
- Mode is well-suited for most patients, assuming skilled clinicians and careful monitoring of delivered volumes.

**Disadvantages of PC-CMV**

- $V_T$ will vary with changes in compliance, resistance, or patient effort.
  - Decreased compliance, increased resistance, or decreased patient effort will reduce delivered $V_T$.
  - Increased compliance, decreased resistance, or increased patient effort will increase delivered $V_T$.
  - Careful monitoring of exhaled $V_T$ is required to avoid inadvertent hyperventilation or hypoventilation associated with changes in pulmonary mechanics or patient effort.
- Because $V_T$ is determined by the pressure gradient ($\Delta P = PIP - PEEP$), increases in PEEP without increases in PIP will decrease $\Delta P$ and decrease delivered $V_T$. Most ventilators make this adjustment automatically (i.e., PC is maintained at the set value above PEEP).
- No guaranteed minimum minute ventilation ($\dot{V}_E$) because $V_T$ may change due to changes in compliance, resistance, or patient effort.
- Improper trigger sensitivity may increase the WOB.
- Inadequate inspiratory flow rates may increase the WOB in spontaneously breathing patients and result in patient–ventilator asynchrony.
- High mean airway pressures may reduce venous return and impede cardiac output in hemodynamically unstable patients.
- Pressure-control inverse-ratio ventilation (PC-IRV) will further increase mean airway pressure and may reduce venous return and cardiac output. PC-IRV may also cause autoPEEP due to short expiratory times resulting in further decreases in venous return and impairment of cardiac output.
- PIP and $P_{plateau} > 28$ to 30 cm $H_2O$ may result in barotrauma (e.g., pneumothorax, pneumomediastinum, pneumoperitoneum, and subcutaneous emphysema) or VILI. VILI is caused by alveolar overdistention (aka volume trauma), cyclic alveolar expansion and collapse (aka atelectrauma), or inflammation associated with mechanical ventilation (biotrauma).
- Patients may trigger the ventilator at a rapid rate resulting in respiratory alkalosis and patient–ventilator asynchrony.
- Inappropriate inspiratory flow rates that do not meet the patient's inspiratory flow demand in spontaneously breathing patients may increase the WOB.
- Pressure rise time or slope may be improperly set. Rise time allows the clinician to adjust the rate at which inspiratory gas flow increases from baseline to peak flow at the beginning of the inspiratory phase.
  - If inspiratory flow exceeds patient demand, a pressure spike may occur early in the inspiratory phase. Adjustment of the rise time can eliminate a pressure spike at the beginning of inspiration due to inappropriately high initial machine flow rates.
  - If inspiratory flow is reduced to the point at which patient demand exceeds machine flow, the pressure waveform will be deformed. Adjustment of rise time can increase inspiratory flow to meet or exceed patient demand.
- Assist-control PC ventilation may be poorly tolerated in patients who are awake, anxious, or in pain; this may result in the patient fighting the ventilator.
- Inadequate expiratory times may result in auto PEEP, particularly in patients with obstructive lung disease.
- Controlled ventilation (time-triggered PC-CMV) requires apnea.
  - Sedative and paralytic drugs may be required.
  - Paralytic drugs should not be administered alone and require the addition of sedatives for pain and anxiety.
- Development of ventilatory muscle weakness and atrophy is associated with controlled ventilation, prolonged use of sedatives, and use of neuromuscular-blocking agents.
- Pressure control is a less familiar type of ventilation for some clinicians (as compared volume control).

augmentation (e.g., pressure support or automatic tube compensation). PEEP/CPAP may be added to provide an elevated baseline pressure. VC-IMV probably was the most popular and widely used mode of ventilation in United States from the late 1970s through the 1990s, and most clinicians from that era have had a great deal of experience in the use of IMV and/or SIMV.

SIMV is currently available as *SIMV volume control with pressure support or tube compensation* (Covidien PB 840 and PB 980), *SIMV* and *SIMV with automatic tube compensation* (Dräger Evita XL), *volume-control SIMV* (Evita Infinity V500), and *SIMV* and *SIMV with tube resistance compensation* (HAMILTON G-5). The Maquet Servo-i and Servo-u also feature SIMV (volume control).

IMV was originally advanced as a preferred mode of ventilation because IMV was thought to result in more rapid ventilator weaning. It has subsequently become apparent that when the support level approaches 50% of that required for full ventilatory support, the patient's WOB during VC-IMV can approach that of unsupported spontaneous ventilation. Put another way, the degree of ventilatory muscle rest with VC-IMV is not proportional to the level of ventilatory support provided.[29] Today, it generally is accepted that VC-IMV may prolong ventilator weaning as compared to other methods (e.g., spontaneous breathing trials [SBTs] or pressure support).[26,29]

Advantages of IMV include reduced mean airway pressures (as compared to VC-CMV); maintenance of ventilatory muscle activity, strength, and coordination; and reduction in the need for sedation or administration of paralytic drugs. There is some evidence that the lower mean airway pressures associated with VC-IMV may be helpful in maintaining cardiac output and blood pressure in some patients.[26] During IMV, the patient continues to breathe spontaneously interspersed with mandatory machine breaths and spontaneous breathing is thought to be more physiologic than positive pressure breathing. The level of ventilatory support provided can be easily titrated up and down based on the patient's needs by simply increasing or decreasing the mandatory rate. The level of support provided can range from full ventilatory support, to partial support, to no support, depending on the set mandatory (machine) rate. Rapidly breathing patients may adapt more readily to IMV, without the problem of triggering mandatory breaths at a rapid rate resulting in a respiratory alkalosis, which may occur with patient-triggered VC-CMV. VC-IMV may improve patient tolerance and patient–ventilator synchrony as compared to VC-CMV and the development of autoPEEP is less likely.

Disadvantages of VC-IMV include the $WOB_I$ associated with endotracheal and tracheostomy tubes during spontaneous breathing requiring the addition of PSV or automatic tube compensation (ATC). Spontaneous breathing with high ventilatory workloads may result in ventilatory muscle fatigue and dysfunction, which may prolong the need for mechanical ventilatory support. The addition of PSV or ATC will reduce the WOB, but increase mean airway pressure, which may reduce venous return and impair cardiac output in hemodynamically unstable patients. As noted above, when the level of ventilatory support provided using IMV is decreased to about 50% that needed for full ventilatory support, the patient's WOB can approach that of spontaneous unsupported breathing. Also, as noted, VC-IMV may prolong ventilator weaning and discontinuance as compared to spontaneous breathing trials (SBTs) or PSV.

When used to provide partial ventilatory support, sudden hypoventilation or apnea may result in an acute respiratory acidosis. Lastly, some patients who are experiencing rapid shallow breathing may continue to make respiratory efforts throughout the mandatory breath cycle resulting in an increase in WOB and patient–ventilator asynchrony

Automated modes of ventilation that provide a form of VC IMV include mandatory minute volume ventilation, mandatory minute volume ventilation with automatic tube compensation, mandatory minute volume ventilation with pressure-limited ventilation, and mandatory minute volume ventilation with pressure-limited ventilation and automatic tube compensation available with the Dräger Evita XL and Evita Infinity V500. Automode (available with the Maquet Servo-i and Servo-u) also provides a form of VC-IMV. These newer modes of ventilation are discussed later in this chapter. **Box 6-7** summarizes the advantages and disadvantages of VC-IMV.

## Pressure Control-Intermittent Mandatory Ventilation

**Pressure control-intermittent mandatory ventilation (PC-IMV)** intersperses mandatory pressure-control breaths with spontaneous breaths. The pressure-control breaths may be time or patient triggered and are pressure limited and time cycled to expiration. Spontaneous breaths may be provided with or without pressure augmentation (e.g., pressure-support ventilation [PSV] or automatic tube compensation [ATC]. $F_{IO_2}$ is selected and PEEP/CPAP may also be employed. The respiratory care clinician typically sets the pressure-control level, inspiratory time, and mandatory rate. The clinician also will set the trigger sensitivity and inspiratory rise time for the mandatory pressure-control breaths. For spontaneous breaths, the clinician may add pressure support or automatic tube compensation. Minimal PEEP/CPAP (3 to 5 cm $H_2O$) generally is used to maintain FRC and provide physiologic PEEP. Higher PEEP levels may be required in patients with hypoxemic respiratory failure.

Pressure-control SIMV is currently available as *SIMV pressure control with pressure support or tube compensation* (Covidien PB 840 and PB 980), *PCV+ with pressure support or automatic tube compensation* (Dräger Evita XL), *pressure-control SIMV and pressure-control SIMV+* (Evita Infinity V500), and *pressure-control SIMV with pressure support or tube resistance*

## BOX 6-7 Advantages and Disadvantages of VC-IMV

VC-IMV intersperses volume-targeted mandatory breaths with spontaneous breathing. Mandatory breaths may be time or patient triggered in the case of synchronized intermittent mandatory ventilation (SIMV). Pressure augmentation in the form of pressure support or automatic tube compensation may be provided to overcome the **imposed work of breathing ($WOB_I$)** associated with endotracheal and tracheostomy tubes. PEEP/CPAP may be added in order to improve oxygenation, increase FRC, and prevent cyclic alveolar recruitment–derecruitment as sometimes seen in patients with severe hypoxemic respiratory failure (e.g., ARDS).

### Advantages of VC-IMV

- Incorporates spontaneous breathing that maintains ventilatory muscle activity and may help maintain ventilatory muscle strength and coordination.
- Incorporation of spontaneous breathing allows for more physiologic alveolar and intrathoracic pressures during spontaneous breaths and lower mean airway pressures (as compared to VC-CMV).
- Mandatory respiratory rate can be easily titrated up and down to vary the level of support provided based on the patient's needs.
- May provide partial or full ventilatory support, depending on the set mandatory rate.
  - Level of support provided can be easily titrated from full ventilatory support (mandatory rate ≥ 10 to 12 breaths/min) to no ventilatory support (mandatory rate = 0).
  - Lower levels of support may be beneficial in certain patients to maintain cardiac output and blood pressure.
- Patients often adjust easily to IMV, which may improve patient tolerance and patient–ventilator synchrony.
- PSV or ATC may be added to overcome the $WOB_I$ associated with endotracheal or tracheostomy tubes.
- No need for excessive sedation or administration of neuromuscular-blocking agents.
- Patients who rapidly trigger the ventilator in the VC-CMV mode, resulting in hyperventilation and respiratory alkalosis, may benefit from a trial of VC-IMV.
- Development of autoPEEP may be less likely.

### Disadvantages of VC-IMV

- Patients requiring full ventilatory support and constant tidal volume delivery may do better on VC-CMV.
- Imposed work of breathing ($WOB_I$) due to the artificial airway during spontaneous breathing may be high.
- The addition of PSV or ATC to overcome $WOB_I$ increases mean airway pressure.
- Spontaneous breathing with high ventilatory workloads may result in ventilatory muscle fatigue, especially in patients with rapid shallow breathing and impaired pulmonary mechanics (e.g., reduced compliance, increased resistance).
- With partial ventilatory support and lower set mandatory rates ($f < 8$ to 10 breaths/min) acute respiratory acidosis may occur if the patient becomes apneic or hypoventilates.
- With lower mandatory rates ($f < 6$ to 8 breaths/min or 50% of the full ventilatory support value) WOB can approach that of spontaneous breathing.
- The degree of respiratory muscle rest during VC-IMV is not proportional to the level of ventilatory support provided.
- Some patients have difficulty adjusting to the ventilator and their spontaneous breathing pattern may conflict with the ventilator settings.
- VC-IMV may prolong ventilator weaning.

*compensation* (HAMILTON G-5). The Maquet Servo-i and Servo-u also feature SIMV (pressure control).

There are several more exotic PC-IMV variations that incorporate multiple targeting schemes (e.g., servo, adaptive, and adaptive with servo). Recall that adaptive targeting schemes can maintain a stable tidal volume by adjusting pressure-control levels between breaths as lung mechanics or inspiratory patient effort vary. Servo-targeting schemes vary the support provided by the ventilator proportional to inspiratory effort. Forms of PC-IMV that incorporate adaptive targeting to maintain stable $V_T$ delivery include *SIMV volume control plus*, *SIMV volume control plus with pressure support*, and *SIMV volume control plus with tube compensation* (Covidien PB 840 and PB 980), *SIMV with autoflow* (Dräger Evita XL), *VC-SIMV with autoflow* and *PC-SIMV with volume guarantee* (Evita Infinity V500), and *SIMV pressure-regulated volume control* (Maquet Servo-i and Servo-u). These modes use pressure control with automatic adjustment to achieve a target $V_T$. Other forms of PC-IMV include *bilevel with pressure support, bilevel with tube compensation* (Covidien PB 840 and PB 980)

and *APRV and APRV with tube compensation* (Dräger Evita XL and Evita Infinity V500).

PC-IMV incorporates the advantages and disadvantages of pressure-control ventilation with IMV. As with PC-CMV, mandatory breath $V_T$ will vary with changes in patients' pulmonary mechanics and inspiratory effort. PC-IMV will allow the clinician to set an appropriate and safe inspiratory pressure to maintain $P_{plateau} \leq 28$ to 30 cm $H_2O$ and avoid ventilator-induced lung injury. Tidal volume for pressure-control breaths is determined by the pressure gradient ($\Delta P = PIP - PEEP$), patient effort, inspiratory time ($T_I$), and pulmonary mechanics (compliance and resistance). Normally the PIP is adjusted to achieve a mandatory breath tidal volume in the range of 6 to 8 mL/kg IBW, although larger tidal volumes may be appropriate for some patients.

Inspiratory time ($T_I$) may also affect $V_T$ provided during pressure-control breaths. Typical adult $T_I$ for mandatory pressure-control breaths is in the range of 0.6 to 1.0 seconds, although many patients do well with a slightly longer $T_I$ (e.g., 0.8 to 1.2 seconds). On initial setup, inspiratory time is usually adjusted so that inspiratory flow declines to zero at end inspiration. This should optimize $V_T$ delivery (at the set pressure-control value) and improve distribution of inspired gas. The decreasing flow waveform provided with pressure control will vary inspiratory flow with patient inspiratory effort, which may improve patient comfort and patient–ventilator synchrony. The square wave-like pressure waveform provided will increase mean airway pressure and may improve distribution of inspired gases and oxygenation. As with PC-CMV, higher mean airway pressures may impair venous return and cardiac output in hemodynamically unstable patients. That said, the inclusion of IMV should lower mean airway pressures compared to PC-CMV. Pressure rise time or slope should be adjusted to ensure inspiratory flow provided meets or exceeds the patient's inspiratory demand. Recall, however, that too rapid rise times can result in a pressure spike at the beginning of inspiration.

PC-IMV can provide full or partial ventilatory support by adjusting the mandatory rate. For full ventilatory support, pressures generally are adjusted to achieve an acceptable $V_T$ and mandatory IMV rate is set in the range of 12 to 20 breaths/min. Partial ventilatory support is provided by using a lower IMV rate. Because PC-IMV incorporates spontaneous breathing, ventilatory muscle activity is maintained, which may help preserve ventilatory muscle strength and coordination. Allowing the patient to spontaneously breathe between pressure-control breaths may have other physiologic benefits (e.g., more normal alveolar and intrathoracic pressures during spontaneous breaths). Pressure support provided during spontaneous breaths should be adjusted to minimize the $WOB_I$ associated with the artificial airway. Recall, however, that PSV and ATC will increase mean airway pressure. Some patients adjust easily to IMV, which may further improve patient tolerance and patient–ventilator synchrony. Patients with rapid shallow breathing may have difficulty tolerating PC-IMV and at lower mandatory rates, sudden apnea or hypoventilation can result in acute respiratory acidosis. It should also be recalled that at low mandatory IMV rates, WOB can approach that of spontaneous unsupported breathing. Appropriate levels of PSV should help reduce WOB when low mandatory rates are employed. Like VC-IMV, PC-IMV has not been shown to be a superior mode for ventilator weaning and may prolong the weaning process as comparted to PSV or SBTs.[29]

## Pressure Control-Continuous Spontaneous Ventilation

Forms of pressure control-continuous spontanteous ventilation (PC-CSV) include pressure support, automatic tube compensation and continuous positive airway pressure. While pressure support and CPAP can be used with IMV, they may also be used as stand alone, primary modes.

### Continuous Spontaneous Ventilation (CSV)

Some modes of ventilation allow for spontaneous breathing through the ventilator circuit. Spontaneous breathing during mechanical ventilatory support can be defined by the method a breath is triggered and cycled. With IMV, some breaths are mandatory (i.e., time or patient triggered, but machine cycled) and some breaths are spontaneous (i.e., patient triggered and patient cycled). With continuous spontaneous ventilation (CSV) every breath is patient triggered and patient cycled. Put another way, every breath is spontaneous. Spontaneous breaths during mechanical ventilation can be provided with or without pressure augmentation. The most common forms of pressure augmentation are PSV and automatic tube compensation (ATC). CPAP can be defined as spontaneous breathing with an elevated baseline pressure. Thus, during inspiration CPAP also provides a form of inspiratory pressure augmentation.

### Pressure-Support Ventilation (PSV)

PSV provides patient-triggered, pressure-limited, flow-cycled ventilation. When used as a primary mode of ventilation, PSV is a form of pressure control-continuous spontaneous ventilation (PC-CSV). Every breath is patient triggered and patient cycled and inspiratory pressure augmentation is provided with every breath. Thus, during PSV patients can vary their respiratory rate, inspiratory flow, inspiratory time, and tidal volume. The respiratory care clinician sets the trigger sensitivity and pressure-support level. Most modern critical care ventilators also allow the clinician to set the inspiratory rise time and flow termination criteria (i.e., cycle sensitivity) during PSV. The level of pressure augmentation (i.e., pressure-support level) provided will vary, depending on the clinical goals. As the pressure-support level increases, so will the patient's spontaneous tidal volume. Assuming

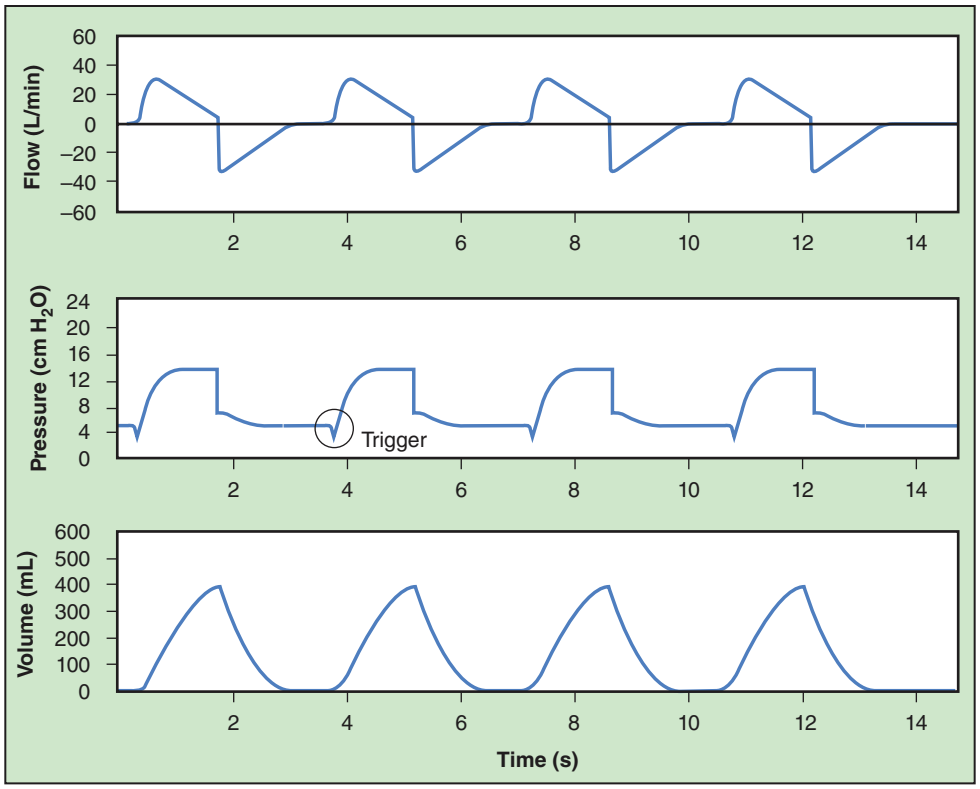


**FIGURE 6-3** Pressure Support.

adequate inspiratory flow rates are provided, as PSV increases, tidal volume increases and WOB declines. **Figure 6-3** illustrates patient-triggered, pressure-limited, flow-cycled pressure-support ventilation (aka PC-CSV).

During PSV, expiration may be passive to ambient pressure (0 cm $H_2O$ baseline) or to an elevated baseline pressure (PEEP/CPAP). Modest levels of pressure support (5 to 15 cm $H_2O$) can be used to overcome the $WOB_I$ due to the ventilator circuit and artificial airway. Low levels of PSV (e.g., 5 to 8 cm $H_2O$) are often combined with CPAP during IMV and during spontaneous breathing trials (SBTs) to evaluate the patient's readiness for ventilator discontinuance and extubation.

While commonly used in conjunction with IMV, PSV can also be used as a primary mode of ventilation. As a primary mode of ventilation, PSV may improve patient–ventilator synchrony and patient comfort. When used as the primary mode of ventilation, the pressure-support level generally is adjusted to achieve a tidal volume in the range of 4 to 8 mL/kg IBW with the patient-triggered respiratory rate $\leq$ 25 breaths/min. Generally speaking, as the pressure-support level increases, WOB decreases.

While often employed during SBTs to overcome the $WOB_I$ due to the endotracheal or tracheostomy tube, PSV may also be used as an alternative ventilator weaning method. When used as a primary weaning method, PSV generally is initiated at a relatively high level to achieve an adequate $V_T$ and respiratory rate (f). When the patient meets readiness criteria, PSV is reduced 2 to 4 cm $H_2O$ in a stepwise fashion followed by assessment for signs of distress (e.g., f > 30 to 35 breath/min, $Spo_2$ < 90%, heart rate [HR] > 120 to 140 bpm, systolic blood pressure [BP] < 90 or > 180 mmHg). If the patient displays signs of distress, PSV is returned to its previous level. In the absence of distress, reductions in the level of PSV continue to the point at which extubation is considered (e.g., PSV of 5 to 8 cm $H_2O$ is well tolerated).

However, if full ventilatory support only requires 10 cm of $H_2O$, then PSV at 5 cm is not truly considered a SBT and some clinicians suggest a trial of ATC without PSV to assess the patients readiness for extubation.

To summarize, PSV may be used as a standalone mode or in conjunction with IMV. When used with IMV, low levels of PSV are often employed to reduce or eliminate the $WOB_I$ of spontaneous breaths in between mandatory breaths. PSV values needed to eliminate the $WOB_I$ will vary with the patient's ventilatory pattern and endotracheal or tracheostomy tube diameter but usually are in the range of 5 to 15 cm $H_2O$. PSV may also be used during SBTs, often in combination with CPAP, to assess the patient's readiness for ventilator discontinuance. PSV is sometimes used as the primary mode of ventilation and may improve patient–ventilator synchrony and comfort, reduce the WOB, and provide an alternative method for ventilator weaning. When used as a primary, standalone mode PSV is a form of PC-CSV.

Automatic tube compensation (ATC) is designed to overcome the $WOB_I$ due to an endotracheal tube or tracheostomy tube during spontaneous breathing. ATC automatically applies inspiratory positive pressure

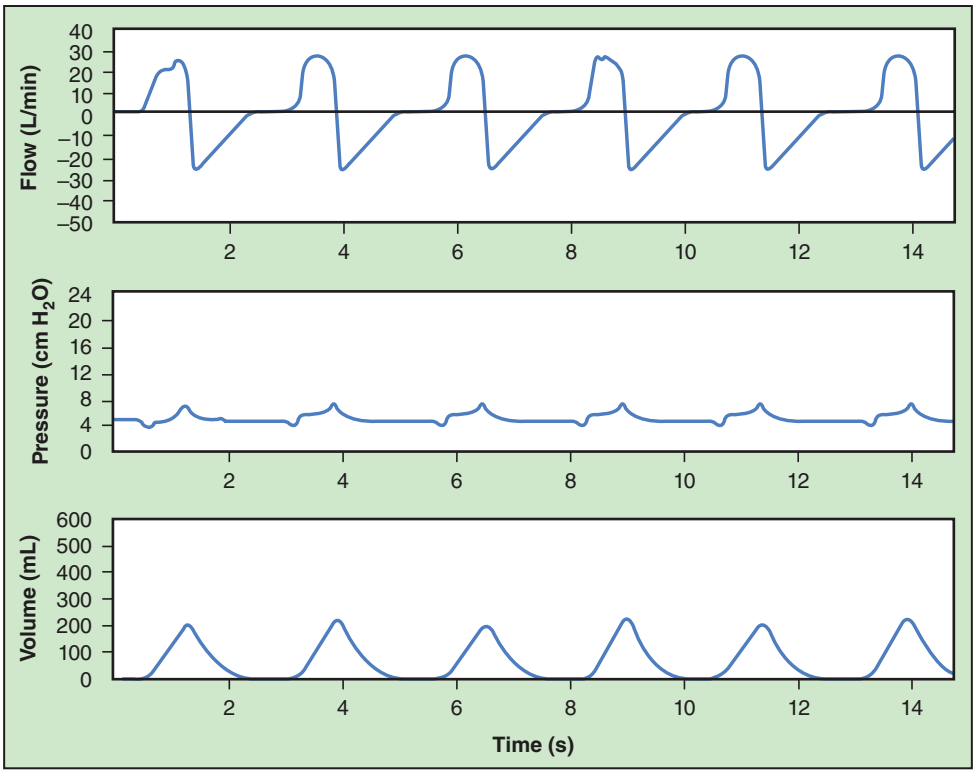


**FIGURE 6-4** Continuous Positive Airway Pressure.

proportional to the measured resistance of the artificial airway. The respiratory care clinician sets the percentage of compensation to be applied, ranging from partial to full compensation. While ATC does reduce the patient's WOB, it has not been shown to improve patient outcomes.[2] ATC incorporates a set point with servo-(s,r) targeting scheme and is commonly used with IMV.[4] Recall that servo-targeting schemes vary the output of the ventilator automatically following a varying input and can vary support provided proportional to inspiratory effort. Setpoint targeting simply refers to the ability of the clinician to set specific parameters (e.g., level of compensation provided). Ventilators that offer ATC include the Covidien PB 840 and PB 980 (as *tube compensation*), Dräger Evita XL and Evita Infinity V500 (as *automatic tube compensation*), and HAMILTON G-5 (as *tube resistance compensation*). When used alone (e.g., IMV rate = 0) ATC is a form of PC-CSV.

## Continuous Positive Airway Pressure

CPAP describes spontaneous breathing at a constant elevated pressure. With CPAP, the patient initiates and terminates each breath. CPAP may be used during continuous spontaneous ventilation (CSV) or with IMV. CPAP may also be combined with PSV. CPAP may be provided through the ventilator or independently using a high-flow, blended and humidified gas source and a PEEP valve. CPAP may be provided by a well-fitted facemask or invasively, via endotracheal or tracheostomy tube. Like PEEP, CPAP increases mean airway pressure, mean intrathoracic pressure, and FRC. **Figure 6-4** illustrates pressure, volume, and flow curves seen with CPAP.

CPAP may increase the lung surface area for gas exchange, improve oxygenation, and help prevent alveolar collapse and atelectasis. CPAP may be useful to maintain alveolar recruitment in patients with acute restrictive lung disease (e.g., mild to moderate pulmonary edema, parenchymal lung injury).[2] With CPAP, pressure is elevated during inspiration and expiration, thus providing a form of inspiratory pressure augmentation that may reduce the WOB during spontaneous ventilation. CPAP is often used during spontaneous breathing trials (SBTs) for evaluation of ventilator discontinuance and extubation. CPAP may also be useful in maintaining FRC in intubated patients, who may otherwise have slight reductions in FRC due to the loss of glottic function; thus, CPAP levels of 3 to 5 cm $H_2O$ for intubated patients may be considered physiologic. CPAP should be used cautiously in patients with obstructive lung disease and those with hemodynamic instability.

## Other Modes of Ventilation

There are a number of alternative modes of ventilation which incorporate feedback mechanisms to adjust the level or type of support provided. In addition, APRV and high frequency ventilation provide alternative modes which may be useful for certain patients (e.g., severe ARDS).

## Adaptive Pressure Control

Adaptive pressure control (APC) provides an adaptive feedback mechanism for pressure control or pressure support. With APC the desired tidal volume (VT) is set but the breath type is pressure control or pressure support. The ventilator then automatically adjusts the pressure level from breath to breath to achieve the targeted VT. This allows the ventilator to maintain a relatively stable VT in the face of changes in compliance, resistance, or patient effort. If delivered VT decreases, the ventilator automatically increases the pressure provided and vice versa. On the other hand, if patient demand and associated effort increases resulting in a larger than desired VT, the ventilator automatically decreases the pressure-control level, which may be inappropriate.

APC provides many of the advantages of pressure-control ventilation while maintaining a relatively stable clinician-selected VT. Decreases in compliance, increases in resistance, or reductions in patient effort will cause the ventilator to increase the pressure automatically. Clinicians must be aware, however, that peak inspiratory pressures (PIP) and plateau pressures ($P_{plateau}$) may rise above acceptable levels as the ventilator attempts to automatically maintain a target VT in the face of changes in ventilatory mechanics or *decreased* patient effort. On the other hand, *increasing* patient effort may result in an inappropriate decreased level of support for patients in distress.

Manufacturers' names for **adaptive pressure control** include *pressure-regulated volume control* (PRVC) provided with the Maquet Servo-i and Servo-u (see below), *auto-flow* provided with the Dräger Evita XL and Evita Infinity V500, *volume control plus* (Covidien PB 840 and PB 980), and *adaptive pressure ventilation* (HAMILTON G5 and C-3). We will discuss a few of these versions of APC below.

## Pressure-Regulated Volume Control

Pressure-regulated volume control (PRVC) is a form of APC first introduced on the Servo 300 ventilator in the 1990s. This form of APC is currently available on the Maquet Servo-i and Servo-u and Yvaire AVEA ventilators as pressure-regulated volume control. PRVC provides volume-targeted pressure-control breaths using an adaptive (a) targeting scheme that automatically adjusts the pressure between breaths to reach the targeted tidal volume in response to varying patient conditions. Delivered VT is measured and compared with target VT and the pressure-control value is then gradually increased or decreased until the target VT is reached. PRVC allows for patient-triggered or time-triggered breaths (aka assist-control ventilation). PRVC with IMV is also offered with the Servo-i and Servo-u ventilators as SIMV pressure-regulated volume control.

PRVC can be classified as pressure control-continuous mechanical ventilation with adaptive targeting ($PC\text{-}CMV_a$) where the "a" notation indicates an adaptive targeting scheme. As a form of APC, PRVC provides relatively stable tidal volume delivery with changes in compliance, resistance, or patient effort. Patients may trigger the ventilator (aka *assist breaths*) and set their own rate. In the absence of a patient trigger within the time interval provided, the ventilator will initiate a time-triggered breath (aka control breath). If the delivered VT for a breath is less than the target, the pressure-control value will automatically increase for the next breath. If VT is greater than target, the pressure-control value will automatically decrease for the next breath.

As noted earlier, adaptive targeting has the advantage of allowing for automatic adjustments in pressure control to achieve a volume target. Adaptive targeting, however, can make inappropriate ventilator adjustments in cases where algorithm assumptions are incorrect, or the assumptions do not match the patient's physiology. For example, an increase in patient effort may be interpreted as an increase in compliance. This may result in an inappropriate decrease in support.

Functionally, the Servo-i and Servo-u ventilators in the PRVC mode will deliver a test breath VT with an inspiratory breath hold to measure the plateau pressure ($P_{plateau}$). The measured $P_{plateau}$ pressure is then used for the next breath and the resultant exhaled VT is compared to the target VT. The pressure is then regulated to provide the clinician-set VT from breath to breath. The pressure will increase or decrease in increments of $\pm$ 3 cm $H_2O$ per breath as needed to achieve the target tidal volume. The pressures possible, however, cannot exceed the clinician-selected peak pressure alarm setting minus 5 cm $H_2O$ (e.g., if the peak pressure alarm is set at 30 cm $H_2O$, the ventilator cannot increase PIP beyond 25 cm $H_2O$).[30]

As with other forms of PC-CMV, PRVC incorporates a decreasing flow waveform and square wave pressure waveform. As compared to VC-CMV with fixed inspiratory flow rates, PRVC shares many of the advantages of PC-CMV in that it may reduce the WOB and improve patient comfort, and increased mean airway pressure may improve oxygenation. Inspiratory gas flow varies with patient inspiratory effort, which may improve patient–ventilator synchrony.

As described above, PRVC is a form of adaptive pressure control (APC) that is available on several other ventilators under different proprietary names (e.g., *auto-flow:* Dräger Evita XL and Evita Infinity V500, *volume control plus:* Covidien PB 840 and PB 980, and *adaptive pressure ventilation:* HAMILTON G5 and C-3).

## Volume Support

*Volume support* (VS) is like PSV with the addition of a clinician-set volume target. Like PSV, volume support requires spontaneous breathing. All breaths are patient triggered, pressure limited, and flow cycled to expiration. Upon initial setup the ventilator delivers a test pulse at 10 cm $H_2O$ above PEEP and measures compliance and exhaled VT. The ventilator than automatically adjusts the

pressure-support level up or down on a breath-to-breath basis to achieve the clinician-selected tidal volume.

Volume support is a form of pressure-control ventilation with adaptive breath targeting. As described earlier, adaptive breath targeting allows the ventilator to automatically vary pressure to achieve the desired $V_T$. Like PSV, the patient triggers and cycles each breath; because of this, VS can be classified as a form of pressure control-continuous spontaneous ventilation, specifically PC-$CSV_a$. With adaptive (a) breath targeting, however, inappropriate changes may occur if algorithm assumptions are violated or do not match the patient's actual physiology. For example, the ventilator cannot distinguish between changes in patient effort and changes in compliance; an increase in patient effort may be misinterpreted as an improvement in compliance and the ventilator may decrease support inappropriately.

In summary, volume support has many of the advantages of pressure support but provides more stable tidal volume delivery in the face of changes in compliance, resistance, or patient effort. Volume support can be classified as PC-$CSV_a$.[4,5] All breaths are initiated and terminated by the patient (i.e., patient triggered and flow cycled). In the absence of a patient trigger, no time-triggered breaths will be provided; an apnea alarm and backup apnea ventilation mode should be employed. For example, in the volume-support mode the Maquet Servo-i ventilator will automatically switch from volume support to volume control in the event of apnea.

Volume support is available on the Servo-i, Servo-u, Covidien PB 840 and PB 980, and Newport e360.

## Mandatory Minute Ventilation (MVV)

Mandatory minute ventilation (MVV) is an older form of automated ventilation that compares the patient's actual minute ventilation ($\dot{V}_E$) to a targeted value and automatically increases or decreases the level of support provided. As originally introduced in 1977, MMV was a form of intermittent mandatory ventilation that automatically increased or decreased the mandatory breath rate to achieve the desired minute ventilation. MMV was initially introduced as a form of automated ventilator weaning. As the patient's level of spontaneous ventilation increased, the ventilator would automatically dial back the number of mandatory breaths delivered. If the patient's spontaneous ventilation decreased, the ventilator would automatically increase the number of mandatory breaths provided to maintain the desired $\dot{V}_E$. Other forms of MMV later introduced would vary the level of pressure support provided (vs. IMV rate) to maintain a stable $\dot{V}_E$.

Advantages of MMV include assuring a more stable level of ventilation during IMV in the face of changes in patients' spontaneous breathing; avoidance of episodes of acute hypoventilation; and providing a smooth, systematic, automated method of weaning ventilatory support. An important disadvantage of MMV is that patients may develop rapid shallow spontaneous breathing, which can result in high $\dot{V}_E$ but inadequate alveolar ventilation. Recall that many patients in respiratory failure develop rapid shallow breathing patterns that maintain a relatively high minute ventilation. This is especially true for patients with acute restrictive pulmonary disease (e.g., severe pneumonia, ARDS). For example, a very sick patient breathing 40 breaths/min with $V_T$ = 150 mL would have a minute ventilation of 6 L/min:

$$\dot{V}_E = V_T \times f = 150\ mL \times 40\ breaths/min = 6000\ mL/min = 6\ L/min$$

In such a case, the MMV system would assume that spontaneous minute ventilation was adequate and dial back the mandatory IMV rate, even though very shallow tidal volumes provide minimal effective alveolar ventilation due to dead space. Recall also that IMV has the potential to prolong ventilator weaning, and spontaneous breathing trials (SBTs) have supplanted IMV as the most appropriate approach to ventilator discontinuance for most patients.

MMV is currently available on the Dräger Evita XL and Evita Infinity V500 as mandatory minute volume ventilation (VC-$IMV_{a,s}$, that is, adaptive and set-point breath targeting) and mandatory minute volume with pressure-limited ventilation (VC-$IMV_{da,s}$ indicates dual adaptive and set-point breath targeting).[31] Despite being available since the late 1970s, MMV has not been shown to consistently improve ventilator weaning success as compared to newer techniques and has not been shown to improve other important patient outcomes.

## Adaptive Support Ventilation (ASV)

Adaptive support ventilation (ASV) is a closed-loop, automatic ventilation mode that combines aspects of pressure control IMV with pressure support (i.e., PC-IMV) to achieve a target minute ventilation ($\dot{V}_E$). ASV incorporates optimal targeting of both mandatory and spontaneous breaths.[4,5] With ASV the pressure-control level is adjusted automatically to achieve a specific tidal volume ($V_T$) at a specific frequency for mandatory breaths.[4,5] Target tidal volume for spontaneous breaths is based on respiratory system mechanics and target minute ventilation.[4,5] Mandatory breaths are time triggered at a preset frequency and inspiratory pressure and are time cycled to expiration (i.e., pressure control). Spontaneous breaths are patient triggered and flow cycled to expiration (i.e., pressure support).

Simply put, ASV allows for the delivery of patient-triggered pressure-supported spontaneous breaths or time-triggered mandatory pressure-control breaths to achieve a minimum minute ventilation at an optimal level of WOB. The ventilator automatically adjusts the level of support provided based on respiratory system mechanics, targeted minute ventilation ($\dot{V}_E$), and clinician-selected level of support. Target minute ventilation is calculated

by the ventilator based on the patient's ideal body weight (IBW) at 0.1 L/min/kg (or 100 mL/min/kg). For example, a patient with an ideal body weight of 70 kg would have a target minute ventilation of 7 L/min ($\dot{V}E = 0.1$ L/min/kg × 70 kg = 7 L/min). The clinician could then select to provide from 20% to 200% of the calculated $\dot{V}E$. If 100% support was selected, in this example the target $\dot{V}E$ would be 7 L/min. A level of support of up to 200% could be selected for patients with increased ventilatory needs. Examples of patients who may have increased ventilatory needs include those with sepsis, increased physiologic dead space, or increased metabolic rate. Less than 100% support could be selected for ventilator weaning.

With ASV, the ventilator uses an algorithm to determine the optimal breathing frequency (f) and tidal volume ($V_T$). The ventilator's goal is to provide tidal volumes and frequencies that are physiologically beneficial for the patient in terms of WOB. The optimal breathing frequency (f) to minimize WOB based on the estimated dead space ($V_D$) and measured expiratory time constant is calculated.[2] Ventilatory dead space ($V_D$) is estimated at 2.2 mL/kg IBW. Tidal volume ($V_T$) is calculated based on the target $\dot{V}E$ and optimal calculated breathing frequency where $V_T = \dot{V}E/f$. The clinician sets the inspiratory pressure-support level, rise time, and expiratory cycle sensitivities for spontaneous breaths.

### CLINICAL FOCUS 6-1 Estimated Minute Volume and Dead Space Volume

A patient with acute respiratory failure is to receive adaptive support ventilation (ASV). The clinician calculates her ideal body weight at 70 kg.

**Question 1. Estimate the required minute ventilation for this patient using the formula integrated into the ASV system.**

The patient's required minute ventilation ($\dot{V}E$) can be estimated using the following formula:

$$\dot{V}E = 100 \text{ mL/min/kg} \times \text{IBW (kg)}.$$

Assuming IBW = 70 kg, this becomes:

$$\dot{V}E = 100 \text{ mL/min/kg} \times 70 \text{ kg} = 7000 \text{ mL/min or } 7 \text{ L/min}.$$

**Question 2. Estimate this patient's dead space volume using the formula integrated into the ASV system.**

Ventilatory dead space volume ($V_D$) is estimated at 2.2 mL/kg:

$$V_D = 2.2. \text{ mL/kg IBW} \times \text{IBW (kg)}.$$

In this example for a 70 kg (IBW) patient the estimated dead space volume would be:

$$V_D = 2.2 \text{ mL/kg} \times 70 \text{ kg} = 154 \text{ mL}.$$

To initiate ASV the clinician enters the patient's ideal body weight, high pressure limit, PEEP, $F_{IO_2}$, rise time, flow cycle, and percentage of predicted minute ventilation to support (i.e., 20% to 200%). The ventilator incorporates algorithms that automatically adjust the respiratory rate, pressure limit, and tidal volume to optimize the patient's WOB based on measurement of specific variables (e.g., flows, times, compliance, resistance, and expiratory time constant) to maintain an appropriate level of support based on calculated $\dot{V}E$.[32] The ventilator uses a test breath to calculate compliance, resistance, and autoPEEP. The ventilator automatically sets minimum and maximum values for $V_T$, mandatory breath frequency, inspiratory pressure, and inspiratory/expiratory time. $V_T$ is adjusted with changes in compliance to maintain a lung-protective strategy. For example, a decrease in compliance may result in a decrease in $V_T$. ASV automatically adjusts mandatory breath frequency (f) and I:E ratio to maintain an expiratory time at least three time constants in length and reduce the risk of autoPEEP.

ASV will alter the amount of support provided to achieve the target $\dot{V}E$. With spontaneously breathing patients, ASV will deliver patient-triggered, pressure-limited, flow-cycled pressure-support breaths while monitoring the patient's lung mechanics and minute ventilation. If the level of spontaneous ventilation is sufficient to meet the target $\dot{V}E$, no mandatory breaths will be delivered. If the level of spontaneous ventilation is insufficient to meet the $\dot{V}E$, the ventilator will automatically increase the level of support provided.

ASV can be an effective approach to ventilation in patients with acute respiratory failure.[2] Patients with normal or near-normal lungs (e.g., opiod drug overdose without aspiration) who require ventilatory support may receive unnecessarily large tidal volumes with ASV.[2] ASV can adjust to changing lung compliance and patient inspiratory effort; however, automatic adjustment may be inappropriate if algorithm assumptions are violated or if they do not match the patient's physiology.[5]

ASV while may provide a safe and effective method for automated ventilator weaning.[32] Because of the algorithms in play, patients with extended expiratory time constants (e.g., long expiratory time as seen in COPD) may receive larger tidal volumes and lower frequencies as compared to patients with shorter time expiratory constants (e.g., short expiratory time as may occur with ARDS).[26] ASV has not been shown to improve specific clinically important patient outcomes.[26]

ASV is available on the HAMILTON G5, C-3, C-1, T-1, and MR-1 ventilators. IntelliVent ASV (HAMILTON S1 ventilator) provides a form of ASV that adds a closed-loop system to control oxygenation based on the ARDSNet PEEP tables and $Spo_2$ to adjust $F_{IO_2}$ and PEEP.[2]

## Airway Pressure-Release Ventilation

Airway pressure-release ventilation (APRV) employs two levels of pressure, which are time triggered and

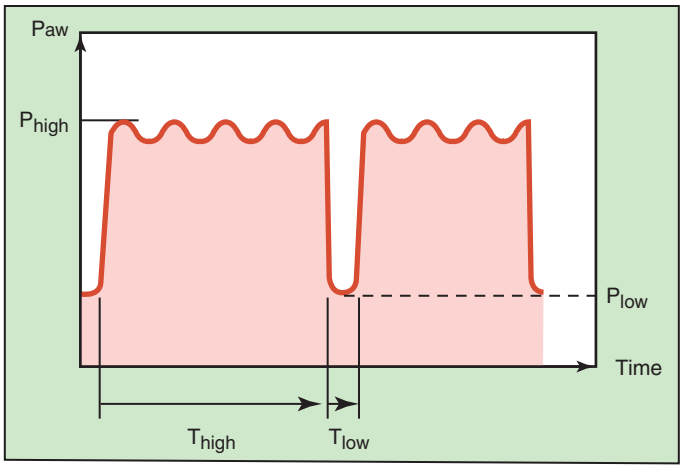


**FIGURE 6-5** Airway Pressure-Release Ventilation.

time cycled. Patients may breathe spontaneously at both levels not unlike providing two levels of CPAP. The high-pressure level may be set to last several seconds (e.g., 3 to 6 sec) to promote alveolar stabilization and alveolar recruitment in patients with severe hypoxemic respiratory failure (e.g., ARDS). The ventilator then cycles to the low-pressure setting for a brief period (e.g., 0.5 to 0.8 sec) to aid in $CO_2$ removal, lower mean airway pressures, and reduce the risk of cardiovascular compromise. **Figure 6-5** illustrates high and low airway pressures and times during APRV.

Ventilator settings during APRV include high airway pressure ($P_{high}$), high-pressure time ($T_{high}$), low airway pressure ($P_{low}$), and low-pressure time ($T_{low}$). $P_{high}$ and $P_{low}$ are the two levels of pressure provided and function like two levels of CPAP in the presence of spontaneous breathing. $T_{high}$ and $T_{low}$ represent the time periods set for each pressure level. $P_{low}$ and $T_{low}$ represent the airway pressure-release level and airway pressure-release time. APRV can be classified as a form of PC-IMV. In the absence of spontaneous breathing, however, APRV functions as time-triggered pressure control-continuous mechanical ventilation (PC-CMV). As noted, $T_{high}$ generally is $>$ $T_{low}$ and in the absence of spontaneous breathing, APRV can provide pressure-controlled inverse-ratio ventilation (PC-IRV).

Tidal volume (VT) provided by the ventilator during APRV is determined by the pressure gradient between the two pressure levels ($\Delta P = P_{high} - P_{low}$), the duration of high pressure ($T_{high}$), and the patient's pulmonary mechanics (i.e., compliance and resistance). Put another way, the transition from $P_{low}$ to $P_{high}$ inflates the lungs while the transition from $P_{high}$ to $P_{low}$ allows the lungs to deflate. The patient's alveolar ventilation and $PaCO_2$ are determined by the VT, frequency of the airway pressure-release maneuver, and level of the patient's spontaneous breathing. For example, if $T_{high}$ is 4.2 seconds and $T_{low}$ is 0.8 seconds, the cycle time would be 5 seconds and provide 12 inspiratory/expiratory cycles per minute.

APRV may decrease peak airway pressures, improve alveolar recruitment, improve oxygenation, and increase ventilation in dependent lung zones in patients with ARDS (as compared to conventional ventilatory support).[26] Because spontaneous breathing is allowed during APRV, there may be some physiologic benefits (e.g., spontaneous breathing may promote recruitment of dependent alveoli, improve gas exchange, and improve cardiac filling). There is also some evidence that APRV has the potential to decrease the need for sedation and administration of paralytic agents, decrease the time on the ventilator, and reduce ICU length of stay as compared to conventional approaches.[26] Like other forms of pressure-control ventilation, tidal volume may vary during APRV with changes in the patient's condition and a minimum minute ventilation is not guaranteed. As with PC-IRV, short expiratory times can result in the development of autoPEEP and higher mean airway pressures can reduce venous return and compromise cardiac output in patients with hemodynamic compromise. APRV generally is not indicated for use in patients with severe obstructive lung disease due to the potential for air trapping and barotrauma. APRV has not been shown to improve mortality or other important outcomes as compared to more conventional modes of ventilation.[2, 26]

APRV is available as *APRV* (Dräger Evita XL, Evita Infinity V500), *Bi-level* (Covidien PB 840 and 980), *BiVent* and *BiVent/APRV* (Maquet Servo-i and Servo-u), *APRV* and *DuoPAP* (HAMILTON G-5 and C-3), and *BiPhasic* (Yvaire AVEA).

## Proportional Assist Ventilation

Proportional assist ventilation (PAV) automatically adjusts the level of ventilatory support based on estimated WOB and feedback measures associated with the neural output of the respiratory center.[2] Specifically, the patient's spontaneous inspiratory effort (as inspiratory gas flow) reflects the patient's respiratory drive. The ventilator calculates delivered volume and estimates resistance

and compliance (as elastance) by applying a brief end-inspiratory pause and expiratory pause every few seconds.[2] Inspiratory pressure is varied automatically depending on the patient's inspiratory effort, calculated WOB, and the clinician-set percentage of support. Inspiratory pressure and inspiratory time may vary breath to breath and within each breath.[2]

Work is simply force times distance; WOB is a function of *pressure times volume* (see **Box 6-8**). The level of support provided can be adjusted from 5% to 95% so that the WOB is in the range of approximately 0.5 to 1.0 J/L.[2] The ventilator monitors the patient's inspiratory flow and calculates the pressure required for ventilation based on the *equation of motion*. Recall that the equation of motion describes the pressure required to overcome the elastic and resistive properties or *loads* of the lung–thorax system. Recall also that compliance is the inverse of elastance and that work is required to overcome these elastic and resistive forces. The elastic forces are proportional to tidal volume and the resistive forces are proportional to the airflow.

The required WOB can be performed by the patient or the ventilator, or both may contribute to the total work necessary. Put another way, the equation of motion describes the elastic and resistive loads contributing to the WOB and predicts the pressures needed to overcome these workloads. The ventilator can perform some or all this work thus *unloading* the ventilatory muscles. In the presence of ventilatory work provided by the ventilator and work provided by the respiratory muscles, the equation of motion can be simplified, where P is the pressure needed to overcome the elastic and resistive loads of the lung. This pressure may be provided by the ventilator or the respiratory muscles, or both.

$$P_{ventilator} + P_{respiratory\ muscles} = elastance \times volume + resistance \times flow$$

As noted, the patient's spontaneous inspiratory flow provides an estimate of the neural output of the respiratory centers and inspiratory effort. Thus, PAV adjusts the level of support based on the patient's inspiratory effort and changing lung mechanics (i.e., compliance and resistance). Pressure may vary from breath to breath depending on changes in the patient's pulmonary mechanics and inspiratory flow demand. Breaths are cycled to expiration by flow, similar to breath cycling with pressure-support ventilation; the flow termination criterion is adjustable. Box 6-8 provides additional information about WOB. Box 3-11 (Chapter 3) provides additional information about the equation of motion.

PAV may improve patient–ventilator synchrony and patient comfort.[2] PAV assumes intact neural control of respiration and no leaks in the system (a system leak can be misinterpreted as increased patient effort and increased inspiratory effort). A runaway phenomenon may occur, resulting in in excessive volume and pressure delivery if the clinician has set the percentage of support too high; if the percentage of support is too low, WOB may be excessive.[2] It must also be noted that PAV does not provide an automatic minimal support level and alarms and backup ventilation modes must be activated in the event of apnea or otherwise absent or minimal patient effort. It

## BOX 6-8 Work of Breathing

Work of breathing (WOB) is the work done by the ventilatory muscles and/or mechanical ventilator to overcome elastic and resistive forces opposing ventilation. Work is *force* × *distance* and work units are *kilograms* × *meters* (kg × m) or *joules* (1 joule = 0.1 kg × m). Pressure is force per unit surface area (force/surface area) while volume is distance cubed ($m^3$ or $cm^3$).

- WOB is a function of the *pressure change* × *volume change* ($\Delta P \times \Delta V$):
  - Work = force × distance.
  - Pressure is force per unit surface area (force/$cm^2$).
  - Surface area is distance$^2$ often reported as $cm^2$.
  - Volume may be recorded in $cm^3$ (i.e., cc or mL).
  - WOB = $\Delta P \times \Delta V$ = force/$cm^2 \times cm^3$ = force × cm = force × distance.
- WOB can be measured as pressure units (cm $H_2O$) × volume units (L) and then converted to kg × m or joules OR normalized to volume (i.e., joules/L) where:

$$1\ joule = 0.1\ kg \times m.$$

$$1\ joule\ per\ liter = joule/L = 0.1\ kg \times m/L$$

- Normally work occurs during inspiration and is performed by the diaphragm and accessory muscles of inspiration; expiration is normally passive requiring only the elastic recoil of the lung tissue (i.e., no work). With severe obstructive lung disease, the accessory muscles of expiration may be engaged increasing WOB during exhalation.
- Normal WOB normalized to volume is about 0.5 to 1.0 joules per liter; > 1.5 joules/L may be an excessive workload.
- Proportional assist ventilation (PAV) is typically set so WOB is 0.5 to 1.0 joules per liter.

must also be noted that calculated WOB may not reflect actual patient effort. For example, a patient may make a large effort that results in little or no volume or flow. In this case, while the patient effort is large, the calculated WOB will not reflect that effort because the volume change is small. PAV is not useful in patients with a weak ventilatory drive or weak respiratory muscles.

PAV is available on the Covidien PB 840 and PB 980 as *spontaneous proportional assist*. The Dräger Evita V 500 offers *spontaneous proportional pressure support*, which allows the clinician to set the amount of resistance to be supported as flow assist and the amount of elastance to be supported as volume assist.[31] The Phillips Respironics V60 ventilator provides a noninvasive form of PAV as proportional pressure support, which may be useful in treating patients with sleep disorders.

Proportional assist ventilation can be classified as a form of pressure control-continuous spontaneous ventilation with servo breath targeting (PC-CSV$_r$).[4] The proportional pressure-support mode available with the Respironics V 60, however, would be best classified as a form of pressure control-intermittent mandatory ventilation (PV-IMV$_{s,r}$).[4] PAV has not yet been shown to significantly improve important clinical outcomes.[2]

## Automode

**Automode** is a form of IMV that incorporates a targeting scheme for both primary and secondary breaths based on the modes selected. Automode uses IMV to synchronize mandatory and spontaneous breaths by automatically switching between two modes of ventilation based on specific feedback measures.[4] This allows the ventilator to automatically titrate the level of support provided between control and support modes dependent on the patient's level of spontaneous ventilation. In the event of apnea, the ventilator will automatically switch to a time-triggered control mode. Automode may be especially useful in patients who have a variable respiratory drive due to fatigue, pain, changing lung mechanics, or intermittent apnea. Automode can be used to provide an automated form of ventilator weaning.

Automode can be set to titrate the level of ventilation provided between the following modes:

- Volume control (VC) and volume support (VS). Used in this fashion, automode can be classified as VC-IMV$_{d,a}$ using dual targeting for VC and adaptive targeting for VS.
- Pressure control (PC) and pressure support (PS). Used in this fashion, automode can be classified as PC-IMV$_{s,s}$ using set-point targeting for PC and PS.
- Pressure-regulated volume control (PRVC) and volume support (VS). Used in this fashion, automode can be classified as PC-IMV$_{a,a}$ using adaptive targeting for both PRVC and VS.

As noted, automode can be set to the alternate between PRVC and VS with a target minute ventilation based on the set tidal volume and respiratory rate. Used in this manner, the ventilator monitors the patient's tidal volume and automatically adjusts inspiratory pressure between breaths to achieve an average exhaled tidal volume at the set target. If the spontaneous respiratory rate does not achieve the minimum minute ventilation target, mandatory time-triggered breaths are provided.

Inappropriate sensitivity settings, resulting in autotriggering, can mislead the ventilator regarding the level of spontaneous breathing present. As with other modes of ventilation, attention to appropriate alarm settings is required. Automode is available on the Maquet Servo-i and Servo-u.

## Neurally Adjusted Ventilatory Assist (NAVA)

NAVA incorporates an esophageal catheter with a multiple array electrode to detect the electrical discharge from the diaphragm (Edi). Edi provides a reflection of the respiratory center's neural output to the diaphragm.[28] This diaphragmatic signal is used to trigger, adjust flow, and cycle the ventilator.[2] Because the strength of the diaphragmatic signal varies throughout inspiration, pressure will also vary throughout inspiration.[28] NAVA may provide better coordination between the patient's central respiratory drive and the ventilator's inspiratory trigger, flow, and cycle. The degree of support provided varies with the amplitude of the diaphragmatic signal and assist level set by the respiratory care clinician.[6] Tidal volume will vary from breath to breath in proportion to the patient's inspiratory demand. NAVA can be classified as a form of pressure control-continuous spontaneous ventilation with servo breath targeting (PC-CSVr), not unlike proportional assist ventilation (PAV).

Up to 25% of ventilator patients experience patient–ventilator asynchrony.[33] Patient–ventilator asynchrony may lead to patient discomfort, increased WOB, diaphragmatic dysfunction, the need for increased sedation, and delayed liberation from the ventilator. NAVA was developed to provide spontaneously breathing patients greater control of their ventilatory pattern during mechanical ventilatory support.[28] NAVA's intent is to achieve neural-ventilatory coupling, which should improve trigger synchrony and cycle synchrony. Neural–ventilatory coupling refers to the time between the spontaneous breath and the delivery of a mechanical breath. Neural–ventilatory coupling is faster with NAVA than with conventional flow or pressure-triggered ventilatory support.[26] Another advantage of NAVA is ventilator triggering should not be adversely affected in patients with flow limitations and autoPEEP and this may be helpful in patients with COPD.[2]

As described, the degree of support provided with NAVA varies with the amplitude of the diaphragmatic signal and the assist level set by the clinician. As the set

NAVA level is increased, the inspiratory pressure provided in proportion to the diaphragmatic signal also increases.[28] Initially, NAVA settings should be adjusted to produce the same or slightly lower inspiratory pressures as the patient was receiving during conventional ventilation. Settings may then be adjusted until a comfortable and consistent tidal volume is achieved while observing the diaphragmatic signal displayed on the ventilator screen. In general, as NAVA levels are increased, peak pressure and tidal volume will increase, although this is dependent on patient effort and the strength of the diaphragmatic signal.

The ventilator can be set to cycle to expiration when the diaphragmatic signal decreases to 40% to 70% of its maximum signal strength. Normally, the diaphragmatic signal decreases as inspiratory effort decreases, and expiration begins. The goal is to avoid continued inflation when the patient's central respiratory control centers have switched to the expiratory phase. Cycling criteria is normally set at 70% of peak inspiratory diaphragmatic activity. With inadequate levels of support, the patient may exhibit signs of distress with increased respiratory rate; ventilatory muscle fatigue may ensue. If support provided is greater than necessary, large tidal volumes may result with suppression of the diaphragmatic signal. Optimal NAVA support will allow the patients to comfortably choose their respiratory rate and tidal volume and maintain adequate alveolar ventilation while unloading the respiratory muscles.

Drawbacks of NAVA include the expense and invasive nature of the esophageal catheter, which may cause discomfort; catheter displacement and signal loss are other potential problems. Contraindications for the placement of an esophageal catheter precludes the use of NAVA. In the case of the loss of the catheter signal, the ventilator will automatically switch to conventional, patient-triggered pressure-support mode.[28]

Spontaneous breathing is required with NAVA, and it should not be used in patients who are heavily sedated or otherwise have respiratory center depression. NAVA is also contraindicated in patients with spinal cord injury, brain center damage, absent phrenic nerve activity, neuromuscular transmission problems or blockade, or apnea.[28] Should a patient become apneic during NAVA, the ventilator will automatically switch to time-triggered pressure control.[28] NAVA also depends on adequate neurotransmission via the phrenic nerve to the diaphragm and an intact vagal reflex.[28] It should be noted that lung transplant patients may not have an intact vagal reflex and are not candidates for NAVA.

As with any ventilatory mode, proper alarm settings are an important consideration. In addition to an audible alarm for diaphragmatic signal loss (e.g., catheter displacement) or apnea, alarms are also available for high pressure, PEEP, minute ventilation, and rate.[28] As noted above, NAVA requires spontaneous breathing with an intact ventilatory drive and is not appropriate for patients who are heavily sedated or have other CNS problems that depress spontaneous ventilation. NAVA does not provide a minimal support level and alarms and apnea backup ventilation modes must be employed. Also, as noted should apnea occur the ventilator will automatically switch to time-triggered pressure control (PC-CMV) as a safety feature. The respiratory care clinician can set the backup PC-CMV pressure, rate, and inspiratory time.[28]

NAVA has been safely used in adults, children, and neonates and there is evidence that NAVA may improve patient–ventilator trigger and cycle synchrony and reduce the need for sedation.[2] Patients may be more comfortable as NAVA allows them to determine their own ventilatory pressures, volumes, and respiratory rates.[28] The level of support provided varies based on the patients' respiratory drive. Outcomes data that NAVA improves important clinical outcomes such as liberation from the ventilator or survival are not currently available.[26] NAVA is available on the Maquet Servo-i and Servo-u.

Recently an option to provide noninvasive ventilatory support using NAVA has been developed and newer Servo ventilators allow NAVA to be used to provide invasive *or* noninvasive ventilatory support.[28]

**RC Insight**

Newer modes of ventilation have been shown to be safe and effective; however, they do not significantly improve important patient outcomes.

## High-Frequency Ventilation

High-frequency ventilation (HFV) employs very rapid respiratory rates (> 60 to 3000 breaths/min) and very small tidal volumes at or below that of anatomic dead space volume. HFV has been used in neonatal, pediatric, and adult patients as a lung-protective strategy. Its primary use in adults is as a rescue mode for patients with severe ARDS who have failed to respond to conventional ventilation using a lung-protective strategy.

Routine use of HFV for patients with ARDS is not supported by current evidence.[2] HFV has been suggested for several other conditions including bronchopleural fistula, neonatal respiratory distress syndrome (RDS), burns with inhalational injury, and head trauma with increased intracranial pressure (ICP). HFV can successfully ventilate patients with large air leaks (e.g., tracheoesophageal fistula, bronchopleural fistula) and may be helpful in cases of major airway disruption that cannot be successfully managed with conventional ventilation. HFV has been used extensively to support neonates with RDS and in those with pulmonary air leaks and bronchopulmonary dysplasia with generally

good results.[2] Currently there are four major types of HFV available as described below.

*High-frequency positive-pressure ventilation (HFPPV)* as applied to adults uses tidal volumes in the range of 100 to 200 mL with respiratory rates of 60 to 120 breaths/min. HFPPV can be accomplished using current conventional ventilators and can be effective in ventilating patients with large air leaks. HFPPV is rarely used in the modern intensive care unit.

*High-frequency percussive ventilation (HFPV)* was developed by Forrest Bird in the mid-1980s. HFPV incorporates a sliding Venturi device or Phasitron and combines high-frequency oscillatory pulses (200 to 900 beats per minute) and small tidal volumes with more traditional pressure-control ventilation. HFPV may improve oxygenation and ventilation and reduce the risk of barotrauma and hemodynamic compromise. HFPV may also be useful in promoting secretion clearance. HFPV has been advocated for ventilation of burn patients with inhalational injury to maintain lower peak airway pressures, facilitate clearance of soot and secretions, and to facilitate reinflation of collapsed alveoli.[34] HFPV may reduce the incidence of pneumonia in patients with smoke inhalation and decrease ICP in patients with head injuries.

HFPV is available for critical-care applications as the Percussionaire VDR-4 volumetric diffusive respirator (Percussionaire Corporation). The Percussionaire IPV-1C is primarily a therapy device to aid in secretion removal, although it may be used in-line with other ventilators.

*High-frequency jet ventilation (HFJV)* employs a jet delivered through a special endotracheal tube adapter. HFJV uses constant gas flow interrupters that are time cycled and pressure limited.[35] Tidal volume is dependent on amplitude, jet driving pressure, jet orifice size, length of inspiratory jet valve time on, and the patient's compliance and resistance. HFJV is used in conjunction with a conventional ventilator, which can provide adjustable $F_{IO_2}$, PEEP, and 2 to 10 sigh breaths/min.[35] The clinician selects peak inspiratory pressure (PIP), jet frequency, and inspiratory jet valve time on.[35]

HFJV is available with the Bunnell Life Pulse jet ventilator, which can deliver frequencies in the range of 240 to 660 cycles per minute. HFJV is commonly employed in preterm neonates with RDS, although evidence that routine use of HFJV improves patient outcomes as compared to conventional ventilation is lacking.

*High-frequency oscillatory ventilation (HFOV)* uses very high frequencies in the range of 180 to 900 cycles/min (3 to 15 Hz; 1 Hz = 60 cycles/min) and very small tidal volumes (50 to 250 mL). HFOV is the most commonly used form of high-frequency ventilation in neonates and adults. HFOV creates a rapidly oscillating bias flow that affects gas transport through complex, incompletely understood mechanisms.[2] These mechanisms may include conventional bulk flow, Taylor dispersion, pendeluft, asymmetric velocity profiles, cardiogenic mixing, and/or enhanced molecular diffusion.[27] HFOV provides relatively high mean alveolar pressures with minimal fluctuation (as compared to conventional mechanical ventilation).[2] This may help prevent cyclic alveolar inflation—deflation (i.e., cyclic recruitment–derecruitment), which may contribute to alveolar injury in patients with ARDS. HFOV may also minimize alveolar overdistention and help maintain alveolar patency.[2]

HFOV has frequently been used in preterm neonates in respiratory failure and may be useful as rescue therapy when PIP $\geq$ 28 to 30 cm $H_2O$ or when mean airway pressure $>$ 10 cm $H_2O$.[35] In adults, HFOV is primarily used as a rescue mode for ARDS patients with refractory hypoxemia that has failed to respond to conventional mechanical ventilation using a lung-protective strategy.

HFOV is available for ventilation of neonates, infants, and small children using the Vyaire 3100A. The Vyaire 3100B is designed to provide HFOV for adults and larger children ($>$ 35 kg).

In summary, high-frequency ventilation may be provided using high-frequency positive-pressure ventilation (HFPPV), high-frequency percussive ventilation (HFPV), high-frequency jet ventilation (HFJV), and high-frequency oscillatory ventilation (HFOV). HFOV has been the most commonly employed method to provide high-frequency ventilation in neonates and adults.

HFV should be only employed by skilled clinicians well familiar with its use. Management of ventilatory parameters with HFV can be complex. HFV may cause auto PEEP due to reduced expiratory times and probably should be avoided in patients with obstructive lung disease.

HFV can be safe and effective in maintaining oxygenation and ventilation in various settings.[26] However, no form of HFV has been shown to be consistently superior to conventional ventilation in reducing mortality or improving outcomes. Chapter 3 provides additional information regarding HFV. Chapter 11 describes the use of HFOV for adults with ARDS.

## Initial Ventilator Settings

Once the decision has been made to initiate mechanical ventilation, several important choices must be made. As noted, mechanical ventilatory support can be invasive or noninvasive. Initiation of NIV was discussed earlier in this chapter and additional information is provided in Chapter 10. Invasive mechanical ventilation requires establishment of an artificial airway, and mechanical ventilation is most commonly initiated following oral endotracheal intubation.

An appropriate ventilator must be available based on the patient's needs and the expertise and experience of the respiratory care clinician. The clinician must then choose the mode of ventilation and make important decisions about the tidal volume, respiratory rate, breath trigger, inspiratory pressures, flows, and time. The clinician must also choose an appropriate $F_{IO_2}$ and whether to implement PEEP or CPAP. Humidification,

alarms, limits, and backup apnea ventilation must then be selected. Each of these choices is discussed below.

## Mode

While there are several mode choices that may be appropriate in specific situations, we recommend that the initial mode for most adult and pediatric patients be volume control-continuous mandatory ventilation (VC-CMV) allowing for patient-triggered or time-triggered ventilation. This mode is commonly referred to as assist-control volume ventilation. VC-CMV assures that the patient will receive a minimum minute ventilation ($\dot{V}_E$) based on the set tidal volume ($V_T$) and respiratory rate (f). The set $V_T$ is delivered consistently, even in the face of changes in the patient's compliance or resistance. Allowing for patient triggering enables the patient to set his or her respiratory rate at a value above the minimum set rate. In the event of apnea, sedation, or respiratory center depression $V_T$, f, and $\dot{V}_E$ are assured. VC-CMV also provides full ventilatory support and when properly applied may significantly reduce the WOB.

The main disadvantages of VC-CMV are the variability of PIP and $P_{plateau}$, introducing the possibility of inappropriately high pressures being delivered to the patient. Patient triggering sometimes results in an unacceptably high ventilatory rate resulting in a respiratory alkalosis, especially in patients who are anxious or in pain. Inappropriately high triggering rates can also cause inadequate expiratory time resulting in air trapping and autoPEEP. VC-CMV is also provided using a fixed inspiratory flow rate, which can result in an increased WOB in spontaneously breathing patients if the set inspiratory flow does not meet or exceed the patient's inspiratory demand. Improper ventilator settings can also lead to patient–ventilator asynchrony. That said, VC-CMV generally is the best initial choice for most critically ill adult patients.

An acceptable alternative to VC-CMV for initial mode choice is PC-CMV set to allow patient-triggered or time-triggered breath initiation. This mode is commonly referred to as assist-control pressure-control ventilation (PCV). With PC-CMV, inspiratory pressure will not exceed the set pressure-control level, thus assuring that PIP and $P_{plateau}$ remain in a safe range, despite changes in the patient's respiratory mechanics. PC-CMV also incorporates a variable inspiratory flow, which may be more comfortable and better tolerated by some patients. The major disadvantage of PC-CMV is that delivered $V_T$ will vary with changes in the patient's compliance, resistance, or inspiratory effort. Adjustment of PC-CMV to ensure tidal volume delivery also requires that the respiratory care clinician fully understand the interactions between inspiratory pressure, inspiratory time, respiratory mechanics, and patient effort. If apnea is present, PC-CMV will provide time-triggered ventilation (aka controlled ventilation). Volume-targeted forms of PC-CMV (e.g., PRVC) provide good options for clinicians familiar with these modes.

A third option sometimes appropriate for initial choice of mode in spontaneously breathing patients with an intact respiratory drive is PSV. Used as a primary standalone mode, PSV may be classified as pressure control-continuous spontaneous ventilation (PC-CSV). PSV generally is well tolerated by spontaneously breathing patients and the pressure level can be adjusted to achieve a desired tidal volume. PSV allows the patient to initiate and terminate each breath and it delivers a variable flow based on the patient's inspiratory effort. Thus, PSV may improve patient–ventilator synchrony and comfort while reducing the WOB. Two major drawbacks of PSV as a primary mode of ventilation are present. If apnea or bradypnea occur, there is no backup ventilatory rate provided. Attention to ventilator alarms and properly setting apnea backup ventilation is very important. As with other forms of pressure control, tidal volume will vary with changes in compliance, resistance, or patient effort.

SIMV is also a serviceable option for initial ventilator setup and can be provided as volume control-intermittent mandatory ventilation (VC-IMV) or pressure control-intermittent mandatory ventilation (PC-IMV). SIMV, when properly applied, can provide full ventilatory support, while allowing the patient to breathe spontaneously in between mandatory breaths. Spontaneous breaths can be pressure augmented using pressure support or automatic tube compensation to reduce the WOB associated with the artificial airway. While SIMV has largely fallen out of favor in recent years, it can be useful as an alternative for patients with rapid spontaneous respiratory rates that would otherwise trigger the ventilator much too frequently when using a mode in which every patient trigger results in a mandatory breath. It is used by some clinicians in patients with status asthmaticus to limit the minute ventilation to around 10 L/min and minimize air trapping.

Following initiation of mechanical ventilation and patient stabilization using one of the above modes, the respiratory care clinician must thoroughly assess the patient. It may then become apparent that an alternative mode should be considered.

## Tidal Volume and Rate

Tidal volume, respiratory rate, and minute ventilation determine the effectiveness of the ventilatory support provided. Each of these parameters may be set directly or indirectly as described below.

### Normal Tidal Volume, Rate, and Minute Ventilation

A normal adult's resting spontaneous tidal volume ($V_T$) is about 5 to 7 mL/kg of ideal body weight (IBW) or about 400 to 700 mL with a respiratory rate (f) in the range of 12 to 18 breaths/min. Minute ventilation ($\dot{V}_E$) is simply tidal volume ($V_T$) × rate (f):

$$\dot{V}_E = V_T \times f$$

Assuming a normal adult tidal volume (500 mL) and respiratory rate (12 breaths/min), minute ventilation would be:

$$\dot{V}E = VT \times f = 500 \text{ mL} \times 12 \text{ breaths/min} = 6000 \text{ mL/min or } 6 \text{ L/min.}$$

The normal range (for adults) for $\dot{V}E$ is 5 to 10 L/min or about 100 mL/kg IBW. Note that there are several formulas for estimating IBW (e.g., Broca formula, Devine formula, and Hamwi formula). We use the formulas suggested by ARDSNet, which are based on the Devine formula for IBW calculation:

**Males:** IBW = 50 + 2.3 (height in inches – 60)

**Females:** IBW = 45.5 + 2.3 (height in inches – 60)

Note: ARDSNet uses the term predicted body weight or PBW instead of IBW; the terms can be used interchangeably. **Table 6-3** illustrates the calculation of tidal volume and minute ventilation based on ideal body weight.

## Initial Ventilator Settings for Tidal Volume and Rate

With VC-CMV using set-point breath targeting (aka *assist-control volume ventilation*) the clinician sets the desired VT and f. For ventilator initiation in the VC-CMV mode, we suggest an initial tidal volume of 8 mL/kg IBW with a rate of 12 to 16 breaths/min for most patients. Tidal volume should be then adjusted (if necessary) to maintain a $P_{plateau} \leq 28$ to 30 cm $H_2O$. Slightly larger tidal volumes (e.g., 8 to 10 mL/kg) may be acceptable if $P_{plateau} \leq 28$ to 30 cm $H_2O$.[3] ARDS patients may require smaller tidal volumes (e.g., 6 mL/kg IBW or less) to maintain $P_{plateau} \leq 28$ to 30 cm $H_2O$. Patients with neuromuscular diseases may require larger tidal volumes to prevent atelectasis. The spontaneously breathing patient may trigger the ventilator at a rate greater than the set minimum rate. If smaller tidal volumes are required to maintain $P_{plateau} \leq 28$ to 30 cm $H_2O$ (e.g., ARDS, severe pneumonia), higher initial respiratory rates may be required.

For PC-CMV using set-point breath targeting (aka assist-control pressure-control ventilation [PCV]) we suggest an initial pressure-control setting of 12 to 15 cm $H_2O$ (above PEEP) followed by immediate observation of the resultant tidal volume. The pressure-control level is then quickly adjusted up or down to achieve the desired VT while ensuring $P_{plateau} \leq 28$ to 30 cm $H_2O$. Initial rate is set in the range of 12 to 16 breaths/min. Spontaneously breathing patients may trigger the ventilator at a rate greater than the set minimum rate. If smaller tidal volumes are required to maintain $P_{plateau} \leq 28$ to 30 cm $H_2O$ to prevent alveolar overdistention (e.g., ARDS), higher initial respiratory rates may be required.

For PC-CSV using set-point breath targeting (aka standalone pressure-support ventilation [PSV]), we suggest an initial PSV setting of 12 to 15 cm $H_2O$ (above PEEP) followed by immediate observation of the resultant tidal volume. PSV is then adjusted to achieve an acceptable tidal volume, usually in the range of 4 to 8 mL/kg IBW and resulting in a patient-triggered respiratory rate of ≤ 25 breaths/min. Typically, this requires PSV levels of ≤ 20 cm $H_2O$ (above PEEP). Recall that with PSV all breaths are patient triggered and no time-triggered rate is set. In the event of apnea, an automatic backup apnea ventilation function should be set, as well as setting other appropriate alarms and limits.

With VC-IMV and PC-IMV, mandatory breath tidal volume, pressure, and rate are set in a similar fashion as volume control- and pressure control-continuous mandatory ventilation (VC-CMV and P-CMV) as described above.

## Inspiratory Pressure

High inspiratory pressures are associated with barotrauma and lung injury. In general, $P_{plateau} \leq 28$ to 30 cm $H_2O$ is thought to reduce the likelihood of ventilator-induced lung injury and lower plateau pressures are associated with better patient outcomes. It should be noted, however, that patients with decreased thoracic compliance (e.g., chest wall deformity, obesity, and ascites) may tolerate $P_{plateau} > 28$ to 30 cm $H_2O$ without causing alveolar overdistention.

With VC-CMV, peak inspiratory pressure (PIP) and plateau pressure ($P_{plateau}$) will vary with changes in patients' compliance and resistance. In general, PIP should be ≤ 40 cm $H_2O$ while maintaining $P_{plateau} \leq 28$ to 30 cm $H_2O$. Ventilator adjustments that may reduce PIP during volume ventilation include lowering the set tidal volume, decreasing the inspiratory peak flow, and changing the inspiratory flow waveform from a square wave to a down ramp. $P_{plateau}$ can be reduced by lowering the set tidal.

With PC-CMV, PC-CSV, and PC-IMV the pressure-control level is set by the clinician to achieve an acceptable VT while maintaining $P_{plateau} \leq 28$ to 30 cm $H_2O$.

## Intermittent Sigh Breaths

Normal spontaneously breathing subjects take an intermittent deep breath or sigh every 6 to 10 minutes. Monotonous shallow tidal breathing (< 7 mL/kg IBW) without an intermittent deep breath may cause progressive atelectasis, and intermittent deep breaths (sighs) will reverse this trend. Often modern critical care ventilators incorporate a sigh function, which may be set by the clinician to deliver an intermittent deep breath or sigh volume at a specific interval. Traditionally, sigh breaths were set at 1.5 to 2 times the tidal volume to be delivered every 6 to 10 minutes. We suggest that almost all patients receive a minimal level of PEEP (e.g., 5 to 8 cm $H_2O$), which should make institution of intermittent sigh breaths unnecessary. That said, recruitment maneuvers are sometimes used in patients with ARDS and function somewhat like an intermittent sigh. There is also some evidence that the use of intermittent sighs may improve alveolar recruitment in ARDS.[2] Chapters 7 and 8 provide additional discussion of the use of recruitment maneuvers in ARDS.

**TABLE 6-3**
**Tidal Volume and Minute Ventilation Based on Ideal Body Weight**

| Males | | Tidal volume ($V_T$) | | | | $\dot{V}_E$ |
|---|---|---|---|---|---|---|
| Height (in) | IBW (kg) | 4 mL/kg | 6 mL/kg | 8 mL/kg | 10 mL/kg | 100 mL/kg |
| 60 | 50 | 200 | 300 | 400 | 500 | 5000 |
| 61 | 52.3 | 209.2 | 313.8 | 418.4 | 523 | 5230 |
| 62 | 54.6 | 218.4 | 327.6 | 436.8 | 546 | 5460 |
| 63 | 56.9 | 227.6 | 341.4 | 455.2 | 569 | 5690 |
| 64 | 59.2 | 236.8 | 355.2 | 473.6 | 592 | 5920 |
| 65 | 61.5 | 246 | 369 | 492 | 615 | 6150 |
| 66 | 63.8 | 255.2 | 382.8 | 510.4 | 638 | 6380 |
| 67 | 66.1 | 264.4 | 396.6 | 528.8 | 661 | 6610 |
| 68 | 68.4 | 273.6 | 410.4 | 547.2 | 684 | 6840 |
| 69 | 70.7 | 282.8 | 424.2 | 565.6 | 707 | 7070 |
| 70 | 73 | 292 | 438 | 584 | 730 | 7300 |
| 71 | 75.3 | 301.2 | 451.8 | 602.4 | 753 | 7530 |
| 72 | 77.6 | 310.4 | 465.6 | 620.8 | 776 | 7760 |
| 73 | 79.9 | 319.6 | 479.4 | 639.2 | 799 | 7990 |
| 74 | 82.2 | 328.8 | 493.2 | 657.6 | 822 | 8220 |
| **Females** | | **Tidal volume ($V_T$)** | | | | **$\dot{V}_E$** |
| Height (in) | IBW (kg) | 4 mL/kg | 6 mL/kg | 8 mL/kg | 10 mL/kg | 100 mL/kg |
| 60 | 45.5 | 182 | 273 | 364 | 455 | 4550 |
| 61 | 47.8 | 191.2 | 286.8 | 382.4 | 478 | 4780 |
| 62 | 50.1 | 200.4 | 300.6 | 400.8 | 501 | 5010 |
| 63 | 52.4 | 209.6 | 314.4 | 419.2 | 524 | 5240 |
| 64 | 54.7 | 218.8 | 328.2 | 437.6 | 547 | 5470 |
| 65 | 57 | 228 | 342 | 456 | 570 | 5700 |
| 66 | 59.3 | 237.2 | 355.8 | 474.4 | 593 | 5930 |
| 67 | 61.6 | 246.4 | 369.6 | 492.8 | 616 | 6160 |
| 68 | 63.9 | 255.6 | 383.4 | 511.2 | 639 | 6390 |
| 69 | 66.2 | 264.8 | 397.2 | 529.6 | 662 | 6620 |
| 70 | 68.5 | 274 | 411 | 548 | 685 | 6850 |
| 71 | 70.8 | 283.2 | 424.8 | 566.4 | 708 | 7080 |
| 72 | 73.1 | 292.4 | 438.6 | 584.8 | 731 | 7310 |
| 73 | 75.4 | 301.6 | 452.4 | 603.2 | 754 | 7540 |
| 74 | 77.7 | 310.8 | 466.2 | 621.6 | 777 | 7770 |

Males: IBW = 50 + 2.3 (height in inches – 60).
Females: IBW = 45.5 + 2.3 (height in inches – 60).

Note: ARDSNet uses the term *predicted body weight or PBW* instead of IBW; the terms can be used interchangeably. Set ventilator tidal volumes may be rounded, as appropriate.

## Breath Trigger

Patient-triggered breaths may be (negative) pressure or flow triggered. With pressure triggering, a patient inspiratory effort decreases the ventilator circuit pressure to a clinician-selected level, thus triggering inspiration. With flow triggering, a constant flow of gas during the expiratory phase is disrupted by the patient's inspiratory effort, triggering inspiration. In either case, the trigger sensitivity should be adjusted to minimize trigger work while avoiding **autotriggering**. For pressure triggering, the trigger generally is set between −0.5 and −1.5 cm $H_2O$, although some circuits may require trigger sensitivity be set at −2.0 cm $H_2O$ to avoid autotriggering.[2,27] With flow triggering the trigger sensitivity generally is set at the range of 1 to 2 L/min below the baseline or bias flow, although some systems may require flow triggers as high as 3 to 4 L/min below baseline or bias flow to avoid autotriggering.[2,27] Inappropriate trigger sensitivity settings and autoPEEP can increase trigger work. Trigger asynchrony occurs when the patient's inspiratory effort becomes decoupled from the ventilator trigger. With the current generation of critical care ventilators there are no clinically important differences between a pressure and flow trigger.[2,27] NAVA may also improve patient–trigger synchrony.

### RC Insight

Patient-trigger sensitivity should be adjusted to minimize trigger work without autocycling.

## Inspiratory Phase, Expiratory Phase, and I:E Ratio

Various ventilator controls will effect inspiratory time, expiratory time, and I:E ratio, and these effects vary depending on the mode of ventilation employed. Initial ventilator settings are discussed further below.

### Volume Control

With VC-CMV and VC-IMV using set-point breath targeting (aka assist-control volume ventilation and volume SIMV), the clinician sets the desired $V_T$ and f for mandatory breaths. With these modes, the clinician also sets either the peak flow and flow waveform or the inspiratory time and flow waveform. For assist-control ventilation, the clinician also sets trigger sensitivity. In ventilators with a peak flow control, peak flow, flow waveform, and tidal volume determine inspiratory time. As peak flow increases, inspiratory time decreases and vice versa. In ventilators with an inspiratory time setting, inspiratory time, tidal volume, and flow waveform determine peak flow. Inspiratory time is set directly in these ventilators and inspiratory flow varies to ensure tidal volume delivery within the set inspiratory time.

Many ventilators allow the clinician to choose between a square wave (constant flow) flow waveform and a down ramp (decreasing flow waveform). In ventilators with peak flow controls, a square wave will result in a shorter inspiratory time, higher PIP, and lower mean airway pressure (as compared to a down ramp). In ventilators with peak flow controls, a down-ramp waveform will result in a longer inspiratory time, lower PIP, and higher mean airway pressure (as compared to a square wave). Ventilators with inspiratory time controls will vary the inspiratory flow based on the set tidal volume and inspiratory time. Changes in flow waveform in these ventilators will affect PIP and mean airway pressure. In general, flow waveforms that increase mean airway pressure will tend to decrease PIP and vice versa.

For VC-CMV, inspiratory time and respiratory rate determine the expiratory time and I:E ratio. In general, an I:E ratio of 1:2 or lower is preferred. For VC-IMV, mandatory and spontaneous breaths are interspersed allowing the patient to initiate a spontaneous inspiration following a mandatory breath. Thus, the patient has control of his or her spontaneous inspiratory time, spontaneous expiratory time, and spontaneous I:E ratio.

We suggest an initial mandatory breath peak flow setting for VC-CMV and VC-IMV of 60 L/min with a range of 40 to 80 L/min for adult patients.[27] In ventilators with an inspiratory time setting, we suggest an initial inspiratory time of 0.8 seconds with a range of 0.6 to 1.0 seconds for adult patients,[27] although many patients do well with a slightly longer $T_I$ (e.g., 0.8 to 1.2 seconds). We also suggest using a down-ramp flow waveform for initial ventilator setup. This may later be adjusted based on patient assessment results. **Box 6-9** summarizes

### BOX 6-9 Initial Ventilator Settings for Assist-Control Volume Ventilation (VC-CMV)

Initial ventilator settings for most adults receiving volume ventilation in the assist-control mode are summarized as follows.

| Ventilator Control | Initial Setting |
|---|---|
| Tidal volume ($V_T$) | 8 mL/kg IBW (range 6 to 8 mL/kg); adjust to ensure $P_{plateau} \leq$ 28 to 30 cm $H_2O$. ARDS patients may require smaller tidal volumes to maintain $P_{plateau} \leq$ 28 to 30 cm $H_2O$. Some patients with neuromuscular disease may require larger tidal volume. |
| Rate | For assist-control (patient- or time-triggered ventilation), set the rate in the range of 12 to 14 breaths/min. |

(*Continues*)

## BOX 6-9 Initial Ventilator Settings for Assist-Control Volume Ventilation (VC-CMV) (*Continued*)

| | |
|---|---|
| Peak flow or inspiratory time | For ventilators with *peak flow control* begin at 60 L/min (range 40 to 80 L/min). Adjust peak flow to ensure inspiratory flow meets or exceeds patient inspiratory demand. For ventilators with *inspiratory time control*, begin with an inspiratory time setting of 0.8 sec (range 0.6 to 1.0 sec). Adjust inspiratory time to ensure resultant flows meet or exceed patient demand and avoid patient–ventilator asynchrony. |
| Trigger sensitivity | Set pressure trigger –0.05 to –1.5 cm $H_2O$. For flow, trigger set sensitivity at 1 to 2 L/min below baseline flow. Adjust trigger sensitivity to minimize trigger work without autocycling. |
| Flow waveform | Begin with a decreasing flow waveform (down ramp). A decreasing flow waveform will reduce PIP and increase inspiratory time (in ventilators with a peak flow control) and mean airway pressure and may improve distribution of inspired gases. Consider square wave to decrease inspiratory time and decrease mean airway pressures. |
| $F_{IO_2}$ ($O_2$ percentage) | Begin with 100% $O_2$ for patients in obvious distress or conditions that may require high initial $O_2$ concentrations (e.g., multiple trauma, severe pneumonia, ARDS, carbon monoxide poisoning, pulmonary edema, and post-resuscitation cardiac arrest). If recent arterial blood gases and the patient's condition (e.g., COPD) suggest that 100% $O_2$ will not be necessary, you may begin with a moderate to high $F_{IO_2}$ (e.g., 0.40 to 0.70.) Careful assessment and monitoring (including continuous $Spo_2$) should guide appropriate adjustment in $F_{IO_2}$ to obtain adequate arterial oxygenation at a safe oxygen concentration. |
| PEEP | Initial PEEP setting for most patients is 5 cm $H_2O$. |
| Humidification | For heated humidification, adjust to obtain a temperature at the proximal airway of 35° to 37°C. A heat moisture exchanger may suffice for some patients. |
| Alarms and limits | Set appropriate volume and pressure alarms and limits to ensure safe and effective ventilation (see **Table 6-4**) |

## TABLE 6-4 Initial Ventilator Alarm Settings for Adult Patients*

| Alarm | Initial setting | Adjusted value |
|---|---|---|
| Low-pressure limit | 8 cm $H_2O$ | 5 to 10 cm $H_2O$ below PIP |
| High-pressure limit | 40 cm $H_2O$ | 10 cm $H_2O$ above PIP; avoid PIP exceeding 40 cm $H_2O$ |
| Low PEEP/CPAP | 3 to 5 cm $H_2O$ below initial PEEP setting to begin | 2 cm $H_2O$ below PEEP/CPAP |
| Low $V_T$ | 100 mL below set $V_T$ | 100 mL below actual $V_T$ |
| Low $\dot{V}_E$ | 1 to 2 L/min below set $\dot{V}_E$ | 1 to 2 L/min < actual $\dot{V}_E$ |
| High $\dot{V}_E$ | 5 L/min or 50% above set $\dot{V}_E$ | 5 L/min or 50% above actual $\dot{V}_E$ |
| Apnea | 20 seconds | 20 seconds |
| Apnea backup ventilation | Set $V_T$ and f for full ventilatory support in the event of apnea | Set $V_T$ and f for full ventilatory support in the event of apnea |
| High oxygen percentage | 5% > set $O_2$% | 5% > actual $O_2$% |
| Low oxygen percentage | 5% < set $O_2$% | 5% < actual $O_2$% |
| Humidifier temperature | 35° to 37°C | 35° to 37°C |
| Low humidifier temperature alarm | 2°C below set temperature | 2°C < actual temperature |
| High humidifier temperature alarm | 1°C above set temperature | 1°C above set temperature; do not exceed delivered temperature > 37°C |

*The initial alarm settings should be set prior to patient connection to the ventilator. Ventilator alarms and limits should then be adjusted based on the patient's response.

Data from Hyzy RC. Modes of mechanical ventilation. In: Parsons PE, Finlay G (eds.) *UpToDate*; October 2018.

initial ventilator settings for most adult patients when using assist-control volume ventilation (aka patient- or time-triggered VC-CMV). **Clinical Focus 6-2** provides an example using VC-CMV.

## Pressure Control

With PC-CMV and PC-IMV using set-point breath targeting (aka assist-control pressure-control ventilation [PCV] and pressure-control SIMV) the clinician sets the inspiratory pressure, inspiratory time, and rate (f) for mandatory breaths. With these two modes, the inspiratory pressure waveform is a square wave while the inspiratory flow waveform is a decreasing flow that varies with the patient's inspiratory effort. As noted above, inspiratory pressure is set to achieve the desired tidal volume while maintaining $P_{plateau} \leq 28$ to 30 cm $H_2O$. The inspiratory time setting and rate determine the expiratory time and I:E ratio. Inspiratory time may be set initially in the range of 0.6 to 1.0 seconds. For example, with an inspiratory time of 1.0 second and respiratory rate of 15 breaths per min, the respiratory cycle time will be 4 sec (60/15 = 4 sec); expiratory time will be 3 sec resulting in an I:E ratio of 1:3. Pressure-control inverse-ratio ventilation (PC-IRV) may begin with an I:E ratio 1:1 and increase the I:E ratio based on patient response. We suggest that more conventional modes of lung-protective ventilation with appropriate levels of PEEP be applied before attempting PC-IRV.

With PC-CMV, the patient may trigger the ventilator more frequently than the set rate. In such cases, the inspiratory time will remain constant, while the expiratory time will decrease and I:E ratio will increase. With PC-IMV, the patient may intersperse spontaneous breaths with mandatory breaths. In such cases, the patient will have control over his or her spontaneous inspiratory time, spontaneous expiratory time, and spontaneous I:E ratio. **Box 6-10** summarizes initial ventilator settings for most adult patients when using assist-control pressure-control ventilation (aka patient- or time-triggered PC-CMV). **Clinical Focus 6-3** provides an example of a ventilator initiation using PC-CMV.

With PSV (aka PC-CSV), when used as a primary mode of ventilation, the clinician sets the inspiratory pressure-support level to achieve a desired tidal volume. The patient triggers and cycles each breath and thus controls his or her inspiratory time, expiratory time, I:E ratio, and rate.

### RC Insight

Pressure-control ventilation is a good option for patients with ARDS to maintain safe airway pressures, while providing effective ventilation.

## Pressure Rise Time or Slope

Most modern ventilators allow for adjustment of rise time (aka pressure slope) and expiratory sensitivity during PSV and these adjustments will alter the inspiratory pressure and flow waveforms. The inspiratory pressure rise time control adjusts the rate at which gas flow increases during inspiration. Normally, the rise time is adjusted so

### CLINICAL FOCUS 6-2 Initiating Assist-Control Volume Ventilation (aka VC-CMV)

A 50-year-old man presented to the emergency department complaining of shortness of breath, cough, yellow-colored sputum, and fever with chills for 2 weeks. The patient was extremely short of breath and on examination, the respiratory care clinician noted respiratory accessory muscle use, diaphoresis, and course crackles upon auscultation. Vital signs were heart rate of 126, respirations of 35, blood pressure 160/92 mmHg, $Spo_2$ 84% (while breathing room air), and oral temperature of 102° F. Chest radiographs demonstrated bilateral infiltrates. Arterial blood gas was obtained after the patient was placed on a nasal cannula at 5 L/min:

pH: 7.24

$Paco_2$: 68 mmHg

$Pao_2$: 48 mmHg

$Sao_2$: 0.83

$HCO_3^-$: 27 mEq/L

NIV was considered; however, the decision was made to initiate invasive mechanical ventilatory support.

**Question 1: What initial mode of ventilation is appropriate for this patient?**

Assist-control volume ventilation (aka VC-CMV) to provide full ventilatory support is a good initial choice for most patients. Assist-control pressure-control ventilation (PC-CMV) or volume control-SIMV (VC-SIMV) could also be used to provide full ventilatory support for this patient.

**Question 2: With assist-control volume ventilation, what are appropriate choices for initial tidal volume ($V_T$) and respiratory rate (f)?**

Initial tidal volume should be 8 mL/kg IBW (range 6 to 8 mL/kg) with a respiratory rate of 12 to 14 breaths/min. A rate in the range of 8 to 12/min may be necessary to ensure adequate expiratory time. Ideal body weight can be estimated based on the patient's height using the following formula for males:

$$IBW = 50 + 2.3 \text{ (height in inches} - 60)$$

(*Continues*)

## CLINICAL FOCUS 6-2 Initiating Assist-Control Volume Ventilation (aka VC-CMV) (*Continued*)

If this patient is 5 ft 10 in tall (70 in) his estimated IBW would be:

$$IBW = 50 + 2.3\,(70 - 60) = 73 \text{ kg (or 168 lb).}$$

$V_T$ (desired) will be 8 mL/kg × 73 kg = 584 mL.

**Question 3. What's an appropriate initial respiratory rate for this patient?**

While an initial respiratory rate of 12 to 14 breath/min should suffice, the respiratory care clinician can estimate the rate (f) based on the desired $V_T$ and minute ventilation ($\dot{V}_E$), where:

$$\dot{V}_E = V_T \times f$$

and

$$f = \dot{V}_E \div V_T$$

Given the patient's IBW of 73 kg, the target minute ventilation can be estimated at 100 mL/kg/min:

$$\text{Desired } \dot{V}_E = IBW \times 100 \text{ mL/kg/min} = 73 \text{ kg} \times 100 \text{ mL/kg/min} = 7300 \text{ mL/min (7.3 L/min).}$$

Given a tidal volume of 584 mL, the rate needed to achieve this minute ventilation would be:

$$f = \dot{V}_E \div V_T = 7300 \text{ mL} \div 584 \text{ mL} = 12.5 \text{ breaths/min.}$$

The respiratory care clinician would then set the rate at 12 or 13 breaths/min. A rate as low as 8 to 12 breaths/min may be necessary to increase expiratory time and avoid air trapping. Initial $F_{IO_2}$ of 0.50 to 0.70 with a PEEP of ≤ 5 cm $H_2O$ (or as needed to offset autoPEEP) is a good place to start followed by rapid adjustment based on $Spo_2$. Initial peak flow (e.g., ≥ 80 L/min) and inspiratory time (e.g., should allow for an expiratory time sufficient to allow complete exhalation, and avoid air trappingg and autoPEEP. As a point of interest, if initial time volume is 8 mL/kg IBW and initial rate is 12.5 breaths/min for any patient, the target minute ventilation will be 100 mL/kg.

## BOX 6-10 Initial Ventilator Settings for Assist-Control Pressure-Control Ventilation (PC-CMV)

Initial ventilator settings for most adults receiving pressure-control ventilation (PCV) in the assist-control mode are summarized as follows.

| Ventilator Control | Initial Setting |
|---|---|
| Pressure control | Begin at 15 to 20 cm $H_2O$ and adjust to obtain an expired tidal volume of 8 mL/kg IBW (range 6 to 8 mL/kg). Do not exceed $P_{plateau}$ > 28 to 30 cm $H_2O$. ARDS patients may require smaller tidal volumes as described in the ARDS Clinical Network Mechanical Ventilation Protocol Summary.[a] |
| Inspiratory time | Begin with an inspiratory time setting of 0.8 sec (range 0.6–1.0 sec, although many patients do well with $T_I$ 0.8 to 1.2 sec. Adjust inspiratory time to ensure resultant flow meets or exceeds patient demand; avoid patient–ventilator asynchrony. If possible, the inspiratory time and pressure-control settings should allow the inspiratory flow to decrease to zero prior to the initiation of the expiratory phase, as observed on the ventilator's graphics flow–time display. |
| Rate | For assist-control (patient- or time-triggered ventilation) set the rate in the range of 12 to 14 breaths/min. |
| Trigger sensitivity | Set pressure trigger –0.05 to –1.5 cm $H_2O$. For flow, trigger set sensitivity at 1 to 2 L/min below baseline flow. Adjust trigger sensitivity to minimize trigger work without autocycling. |
| Flow waveform and pressure rise time or slope | PCV results in a square wave pressure pattern and a decreasing flow waveform. Pressure rise time should be adjusted based on observation of the ventilator graphics pressure–time curve to ensure that there is not a pressure overshoot or spike at the beginning of inspiration, but that pressure rises quickly enough to meet the patient's spontaneous inspiratory demand in spontaneously breathing patients. |
| $F_{IO_2}$ ($O_2$ percentage) | Begin with 100% $O_2$ for patients in obvious distress or conditions that may require high initial $O_2$ concentrations (e.g., multiple trauma, severe pneumonia, ARDS, carbon monoxide poisoning, pulmonary edema, and post-resuscitation cardiac arrest). If recent arterial blood gases and the patient's condition (e.g., COPD) suggest that 100% $O_2$ will not be necessary, you may begin with a moderate to high $F_{IO_2}$ (e.g., 0.40 to 0.70.) Careful assessment and monitoring, (including continuous $Spo_2$) should guide appropriate adjustment in $F_{IO_2}$ to obtain adequate arterial oxygenation at a safe oxygen concentration. |
| PEEP | Initial PEEP setting for most patients is 5 cm $H_2O$. |
| Humidification | For heated humidification adjust to obtain a temperature at the proximal airway of 35°C–37°C. A heat moisture exchanger (HME) may suffice for some patients. |
| Alarms and limits | Set appropriate volume and pressure alarms and limits to ensure safe and effective ventilation (see Table 6-4). |

[a]The ARDSNet Protocol may be found at the ARDSNet website: www.ardsnet.org/files/ventilator_protocol_2008-07.pdf.

## CLINICAL FOCUS 6-3 Initiating Assist-Control Pressure-Control Ventilation (aka PC-CMV)

The decision is made to intubate and ventilate a female ARDS patient using assist-control pressure control ventilation (aka PC-CMV). The patient is 65 inches (165 cm) in height.

**Question 1. What is an appropriate initial tidal volume goal for this patient?**

Initial tidal volume should be 8 mL/kg IBW with a respiratory rate to achieve an appropriate minute ventilation ($\dot{V}_E$). Ideal body weight can be estimated based on the patient's height using the following formula for females:

$$IBW = 45.5 + 2.3 \text{ (height in inches} - 60)$$

If this patient is 65 in tall, her estimated IBW would be:

$$IBW = 45.5 + 2.3 \text{ (65} - 60) = 57 \text{ kg (or 125 lb).}$$

$V_T$ (desired) will be 8 mL/kg × 57 kg = 456 mL.

**Question 2. What is an appropriate initial respiratory rate for this patient?**

While an initial respiratory rate of 12 to 14 breath/min may suffice, the respiratory care clinician can estimate the rate (f) based on the desired $V_T$ and minute ventilation ($\dot{V}_E$) where:

$$\text{and } f = \dot{V}_E \div V_T$$

Given the patient's IBW of 57 kg, the target minute ventilation can be estimated at 100 mL/kg/min:

$$\text{Desired } \dot{V}_E = IBW \times 100 \text{ mL/kg/min} = 57 \text{ kg} \times 100 \text{ mL/kg/min} = 5700 \text{ mL/min (5.7 L/min).}$$

Given a target tidal volume of 456 mL, the rate needed to achieve this minute ventilation would be:

$$f = \dot{V}_E \div V_T = 5700 \text{ mL} \div 456 \text{ mL} = 12.5 \text{ breaths/min.}$$

The respiratory care clinician would then set the rate at 12 or 13 breaths/min.

**Question 3. What is an appropriate initial pressure control, inspiratory time, and PEEP for this patient?**

Pressure control can be initially set at 15 cm $H_2O$ above PEEP; initial PEEP should be set at 5 cm $H_2O$. Tidal volume delivery should then be immediately assessed, and pressure-control level adjusted to achieve the target $V_T$ of about 460 mL, while at the same time assuring that $P_{plateau} < 30$ cm $H_2O$. The ARDSNet Protocol[a] suggests that $V_T$ then be reduced by 1 mL/kg at intervals of ≤ 2 hours until $V_T$ is 6 mL/kg, or about 340 mL for this patient. As $V_T$ is reduced, appropriate increases in rate (up to 35 breaths /min) should be made to maintain $\dot{V}_E$.

[a]The ARDSNet Protocol may be found at the ARDSNet website: www.ardsnet.org/files/ventilator_protocol_2008-07.pdf.

that there is not a pressure spike on the pressure–time scalar at the beginning of inspiration. Rise time should also be adjusted such that initial gas flow to the patient meets or exceeds the patient's inspiratory demand. With PSV inspiratory gas flow declines until the flow termination criteria is met (e.g., 5% to 25% of peak inspiratory flow). Expiratory sensitivity allows for adjustment of the flow termination criterion to ensure the ventilator and patient cycle are in sync in terms of the beginning of the expiratory phase and cycle asynchrony does not occur.

With pressure-control ventilation, the clinician can set the rise time; the cycle variable is time.

### Inspiratory Pause

With VC-CMV and VC-IMV using set-point breath targeting (aka assist-control volume ventilation and volume SIMV) the clinician may set an inspiratory pause or inspiratory hold. Clinicians and automated monitoring systems routinely use a brief inspiratory pause (0.5 to 2.0 sec) to measure patients' $P_{plateau}$ and calculate compliance and resistance.

The application of an inspiratory pause will increase inspiratory time, decrease expiratory time, increase I:E ratio, and increase mean airway pressure. A brief inspiratory pause (e.g., 10%) may improve distribution of inspired gases, improve $PaO_2$, and improve aerosol medication delivery.[27] An inspiratory pause may also be used to ensure a full inspiration (e.g., 1-sec inspiratory pause) before a chest radiograph is obtained.[27] Caution should be employed beyond intermittent use of an inspiratory pause to measure $P_{plateau}$ in spontaneously breathing patients to avoid causing or worsening patient–ventilator asynchrony. An inspiratory pause will also increase mean airway pressure, which could be problematic in patients with hemodynamic instability.

### Expiratory Time

Expiratory time for continuous mandatory ventilation is a function of inspiratory time, and respiratory rate. Depending on the ventilator employed and the mode in use, inspiratory time may be set directly OR be determined by the tidal volume, peak flow, and flow waveform. Expiratory time should allow for complete exhalation of inspired gases prior to the initiation of the next breath. This is especially important in patients with obstructive lung disease (e.g., asthma, COPD) to avoid the development of autoPEEP and pulmonary over inflation. AutoPEEP may also cause patients to have difficulty triggering the ventilator. Steps to correct for autoPEEP include using smaller tidal volumes, decreasing inspiratory time, increasing expiratory time, and reducing mandatory breath rate. Small

amounts of extrinsic PEEP to balance autoPEEP may be useful in patients have triggering difficulty.

## I:E Ratio

For ventilator initiation, we recommend that adjustments in inspiratory time, expiratory time, and respiratory rate achieve an initial I:E ratio of 1:2 or lower. Methods to alter expiratory time and I:E ratio will vary, depending on the mode in use and available controls (e.g., peak flow, respiratory rate, and inspiratory time). **Box 6-11** summarizes initial ventilator settings for most adult patients when using volume control or pressure control intermittent mandatory ventilation (aka VC-SIMV or PC-SIMV). **Clinical Focus 6-4** provides an example using IMV/SIMV.

## $F_{IO_2}$ (Oxygen Percentage)

In general, the safest option for initial oxygen concentration ($F_{IO_2}$) is 1.0 (100% $O_2$) followed by patient assessment, observation of changes in pulse oximetry values ($S_{PO_2}$), and arterial blood gas measurement.[2] Beginning with 100% oxygen is especially important in patients for whom little information is available or

### BOX 6-11 Initial Ventilator Settings for Intermittent Mandatory Ventilation (VC-IMV or PC-IMV)

Intermittent mandatory ventilation (IMV) intersperses mandatory breaths with spontaneous breathing. Spontaneous breaths may be pressure supported using pressure-support ventilation (PSV) or automatic tube compensation (ATC). IMV is most commonly provided as volume-SIMV (aka VC-SIMV), although many modern critical care ventilators allow for the use of pressure control-SIMV (aka PC-IMV) or various other targeting schemes. With SIMV, the ventilator is often initially adjusted to provide full ventilatory support. Initial ventilator settings for VC-IMV and PC-IMV are described below.

| Ventilator Control | Initial Setting |
|---|---|
| Tidal volume ($V_T$) and inspiratory pressure | For VC-IMV initial $V_T$ may be set at 8 mL/kg IBW (range 6 to 8 mL/kg); adjust to ensure $P_{plateau} \leq$ 28 to 30 cm $H_2O$. For PC-IMV set initial pressure-control value in the range of 15 to 20 cm $H_2O$ and adjust to achieve an adequate $V_T$. |
| Rate | Initially set the IMV rate in the range of 12 to 14 breaths/min to achieve full ventilatory support. |
| Peak flow or inspiratory time | For volume ventilators with peak flow control begin at 60 L/min (range 40 to 80 L/min). Adjust peak flow to ensure mandatory breath inspiratory flow meets or exceeds patient inspiratory demand. For ventilators with inspiratory time control, begin with an inspiratory time setting of 0.8 sec (range 0.6 to 1.0 sec although some patients do well with a $T_I$ 0.8 to 1.2 sec.) Adjust inspiratory time to ensure resultant flows meet or exceed patient demand and avoid patient–ventilator asynchrony. |
| Trigger sensitivity | Set pressure trigger –0.05 to –1.5 cm $H_2O$. For flow, trigger set sensitivity at 1 to 2 L/min below baseline flow. Adjust trigger sensitivity to minimize trigger work without autocycling. |
| Flow waveform for the mandatory breaths | For VC-IMV begin with a decreasing flow waveform (down ramp) and adjust, if needed. PC-IMV provides a square wave-like pressure pattern with a decreasing flow waveform. The pressure waveform may be modified by adjusting the pressure rise time or slope. |
| Pressure support | PSV generally is provided for spontaneous breaths in the range of 5 to 15 cm $H_2O$ to overcome the $WOB_I$ due to artificial airways. Automatic tube compensation (ATC) is also available on most modern critical care ventilators when used in the IMV/SIMV mode. |
| $F_{IO_2}$ ($O_2$ percentage) | Begin with 100% $O_2$ for patients in obvious distress or conditions that may require high initial $O_2$ concentrations (e.g., multiple trauma, severe pneumonia, ARDS, carbon monoxide poisoning, pulmonary edema, and post-resuscitation cardiac arrest). If recent arterial blood gases and the patient's condition (e.g., COPD) suggest that 100% $O_2$ will not be necessary, you may begin with a moderate to high $F_{IO_2}$ (e.g., 0.40 to 0.70). Careful assessment and monitoring (including continuous $S_{PO_2}$) should guide appropriate adjustment in $F_{IO_2}$ to obtain adequate arterial oxygenation at a safe oxygen concentration. |
| PEEP | Initial PEEP setting for most patients is 5 cm $H_2O$. |
| Humidification | For heated humidification adjust to obtain a temperature at the proximal airway of 35°C to 37°C. A heat moisture exchanger (HME) may suffice for some patients. |
| Alarms and limits | Set appropriate volume and pressure alarms and limits to ensure safe and effective ventilation (see Table 6-4). |

## CLINICAL FOCUS 6-4 Initiating Volume SIMV (VC-IMV)

A 38-year-old male arrived unresponsive in the emergency department. He was suspected of taking an overdose of an unknown substance. An arterial blood gas sample taken on room air reveals:

pH: 7.15

$Paco_2$: 80 mmHg

$Pao_2$: 38 mmHg

$Sao_2$: 0.78

$HCO_3^-$: 28 mEq/L

The decision is made to intubate and ventilate this patient using volume SIMV (aka VC-IMV). The patient is approximately 72 inches in height (6 ft).

**Question 1. What are appropriate initial ventilator settings for rate (f) and tidal volume ($V_T$) this patient?**

Initial $V_T$ should be 8 mL/kg IBW. The patient's ideal body weight can be calculated using the following formula for males:

$$IBW = 50 + 2.3 \text{ (height in inches} - 60)$$

$$IBW = 50 + 2.3\ (72 - 60) = 77.6 \text{ kg (or 168 lb).}$$

$V_T$ (desired) will be 8 mL/kg × 77.6 kg = 620.8 mL.

SIMV rate can be set in the range of 12 to 14 breaths/min to achieve a $\dot{V}_E$ of 100 mL/min/kg IBW or 7760 mL/min.

**Question 2. What are appropriate initial ventilator settings for this patient for peak flow, flow wave form, trigger sensitivity, and $F_{IO_2}$?**

The peak flow should be initially set at 60 L/min (range 40 to 80 L/min) and then adjusted to ensure that peak flow meets or exceeds the patient's inspiratory flow demand. In ventilators with inspiratory time control, an initial setting of 0.8 seconds (range 0.6 to 1.0 sec) is a good place to start.

Most modern critical care ventilators allow the respiratory care clinician to choose between a square wave and down ramp flow waveform. We suggest Initiating ventilation with a down ramp. This may then be adjusted following ventilator initiation.

Trigger sensitivity should be adjusted to ensure minimal trigger work without autocycling. This generally corresponds to a pressure trigger of 0.5 to −1.5 cm $H_2O$ or flow trigger of 1 to 2 L/min below baseline bias flow.

This patient was experiencing severe hypoxemia while breathing room air. $F_{IO_2}$ should be initiated at 1.0 or 100% $O_2$.

**Question 3. What is an appropriate initial ventilator setting for PSV?**

SIMV allows for spontaneous breathing to be interspersed with mandatory IMV breaths. Some form of pressure augmentation should be provided with SIMV to compensate for the $WOB_I$ due to the endotracheal tube. Pressure augmentation may be provided using PSV or automatic tube compensation. For PSV an initial setting of 5 to 15 cm $H_2O$ is appropriate. Following ventilator initiation, the PSV needed to overcome the resistance of the endotracheal tube can be estimated as follows:

$$PSV = (PIP - P_{plateau}) \times \text{the patient's spontaneous inspiratory flow rate.}$$

Following ventilator initiation, the patient's peak inspiratory pressure (PIP) was 35 cm $H_2O$ and plateau pressure ($P_{plateau}$) was 21 cm $H_2O$. During spontaneous breathing in between mandatory SIMV breaths, the patient's spontaneous inspiratory flow rate was 0.5 L/sec or 30 L/min.

PSV needed to overcome the $WOB_I$ for this patient was:

$$PSV = (PIP - P_{plateau}) \times \text{the patient's spontaneous inspiratory flow rate.}$$

$$PSV = (35 \text{ cm } H_2O - 21 \text{ cm } H_2O) \times 0.5 \text{ L/sec} = 7 \text{ cm } H_2O.$$

those in obvious distress. Disease states or conditions that may require high initial oxygen concentrations include severe pneumonia, ARDS, cardiac arrest following resuscitation, severe trauma, acute pulmonary edema, near-drowning, smoke inhalation, suspected aspiration, and carbon monoxide poisoning.[27] Many of these conditions increase pulmonary shunt, which generally is less responsive to oxygen therapy. $F_{IO_2}$ should then be quickly reduced (if possible) to avoid the development of absorption atelectasis and oxygen toxicity. In many patients $F_{IO_2}$ may be rapidly titrated downward based on $Spo_2$ monitoring and clinical assessment. The end goal is to achieve an adequate arterial oxygen level ($Pao_2 \geq 60$ mmHg, $Sao_2 \geq 0.90$) at a safe $F_{IO_2}$ ($\leq 0.50$ to 0.60). PEEP or CPAP may help achieve this goal.

Some patients require mechanical ventilatory support due to extra pulmonary conditions (e.g., anesthesia, drug overdose, head trauma, neuromuscular disease, and spinal cord injury). These patients may have normal or near-normal lungs and may respond well to low to moderate initial concentrations of oxygen (e.g., $F_{IO_2}$ of 0.40 to 0.50). Certain disease states associated with low $\dot{V}/\dot{Q}$ (but not shunt) also often respond well to low to moderate concentrations of oxygen therapy. These include asthma, emphysema, chronic bronchitis, and COPD. There may also be patients for whom a great

deal of information is available including recent arterial blood gases, suggesting adequate arterial oxygenation can be achieved with low to moderate concentrations of oxygen. In such cases, the clinician may choose to begin with a moderate concentration of oxygen (e.g., 40% to 50%) based on prior blood gases and the patient's clinical condition. That said, when in doubt begin with 100% $O_2$ and titrate down based on the patient's oxygen saturation.

**RC Insight**

In general, the safest option for initial oxygen concentration is 100% $O_2$.

### PEEP and CPAP

As described earlier, patients with acute restrictive pulmonary disease (e.g., ARDS, severe pneumonia, or pulmonary edema) may develop hypoxemia due to unstable alveolar units that are collapsed. PEEP and CPAP can restore FRC, improve and maintain lung volumes, and improve oxygenation in such patients. PEEP/CPAP should be considered in such patients with inadequate arterial oxygen levels ($Pao_2 < 60$ mmHg, $Sao_2 < 0.90$) on moderate to high oxygen concentrations ($Fio_2 \geq 0.40$). Smaller tidal volumes and appropriate levels of PEEP are used in patients with ARDS to avoid VILI. With ARDS, properly applied PEEP can stabilize unstable lung units and avoid repetitive inflation and deflation of alveoli, thus reducing the likelihood of additional injury.

Minimal PEEP/CPAP (3 to 5 cm $H_2O$) generally is used to maintain FRC and provide physiologic PEEP. PEEP/CPAP may also be useful to offset autoPEEP and reduce trigger work in some patients. PEEP and CPAP must be used cautiously in patients with an already elevated FRC as may occur with obstructive lung disease (e.g., COPD, acute asthma).

There are several approaches to the use of PEEP. These include minimal PEEP, optimal or best PEEP, compliance titrated PEEP, and the use of pressure–volume curves as part of a lung-protective strategy. For initial ventilator setup, however, we suggest that almost all patients initially receive 5 cm $H_2O$ of PEEP/CPAP.

### Alarms and Limits

Modern critical care ventilators have sophisticated alarms and monitoring systems. Ventilator alarms audibly and visually notify ICU personnel that specific parameters are not met, and the patient–ventilator system should be assessed. Ventilator malfunction alarms are normally set by the manufacturer, and include alarms for power loss, gas supply loss, electronic malfunction, or pneumatic malfunction. Certain patient status alarms can be set by the respiratory care clinician. These include alarms for maximum inspiratory pressure, low pressure, low PEEP, high and low tidal volume, high and low minute ventilation, high and low respiratory rate, oxygen percentage, humidification (temperature), and apnea.[27] The respiratory care clinician should adjust the ventilator alarms to ensure patient safety without becoming a nuisance that may be ignored.

Limits should be adjusted prior to ventilator initiation. The high-pressure limit and high-pressure alarm may can be set at 40 cm $H_2O$ prior to connecting the patient to the ventilator to ensure that excessive pressures are not unintentionally delivered. Pressures are then reassessed and readjusted following initiation of mechanical ventilation with the goal of maintaining safe inspiratory pressures (e.g., $P_{plateau} \leq 28$ to 30 cm $H_2O$, PIP $\leq$40 cm $H_2O$). Ventilator adjustments can be made to reduce $P_{plateau}$ and PIP if necessary following ventilator initiation. Table 6-4 lists suggested initial alarm settings for adult mechanical ventilation.

### Humidification

Humidification should be provided for all patients receiving invasive mechanical ventilatory support. Clinical practice guidelines for heated humidifiers suggest an inspired gas temperature of 35°C ± 2°C to provide humidity of 33 to 44 mg $H_2O$/L at the patient Y connection. Heat and moisture exchangers (HME) may be appropriate for some patients. HMEs should not be used in patients receiving low tidal volumes as they add additional mechanical dead space. HMEs are also not recommended for use with noninvasive ventilation.

### Patient Assessment

Following initiation of mechanical ventilation, the patient and patient–ventilator system should be carefully assessed. This should include physical assessment, breath sounds, oximetry, heart rate, blood pressure, and observation of the cardiac monitor for cardiac rhythm. The patient–ventilator system should be assessed for ventilatory pressures, volumes, and flows. Arterial blood gases are usually obtained following initial patient stabilization. Following assessment, necessary changes in ventilatory parameters should be made to ensure patient safety, comfort, oxygenation, and ventilation. Chapter 7 describes patient stabilization and ventilator adjustments following ventilator initiation.

## Management of Specific Disease States and Conditions

Management of patients with specific disease states and conditions can be complex. A few of the key factors that should be considered for mechanical ventilation in specific situations are described below.

## Asthma

Ventilation of patients with severe asthma can be extremely challenging. Lower tidal volumes (e.g., 6 to 8 mL/kg IBW) should be used to reduce airway pressures and avoid barotrauma; $P_{plateau}$ should be maintained $\leq$ 30 cm $H_2O$.[36,37] Care must be taken to ensure adequate I:E ratios and sufficient expiratory time to allow for complete exhalation in the presence of airway obstruction. Lower respiratory rates (e.g., 10 to 12 breaths/min) and higher inspiratory flow (e.g., 60 to 80 L/min) should be employed.[36,37] Patient–ventilator asynchrony should be avoided, and adjustment of tidal volume, respiratory rate, inspiratory flow, inspiratory time, and trigger sensitivity may be necessary. PEEP may be set at $\leq$ 5 cm $H_2O$ or at 50% to 80% of measured autoPEEP, if present. Some patients may require the use of paralytic agents to control ventilation and permissive hypercapnia may sometimes be used to ensure airway pressures are not excessive. Oxygen concentrations should be adjusted to achieve adequate arterial oxygenation (e.g., $Spo_2 \geq 90\%$).

## Acute Exacerbation of COPD

Mechanical ventilatory support may be necessary for patients with severe exacerbation of COPD.[36,38] NIV is often a good option for these patients in the presence of acute respiratory acidosis. Other indications for NIV include severe dyspnea with respiratory muscle fatigue, increased WOB, or persistent hypoxemia unresponsive to supplemental oxygen therapy [36,38] NIV can be delivered by facemask, nasal mask, or nasal pillows. Initial settings may include patient-triggered breaths with inspiratory pressure in the range of 8 to 20 cm $H_2O$ and end-expiratory pressure in the range of 3 to 5 cm $H_2O$.[36,38] Inspiratory pressure is then adjusted based on measured tidal volume and respiratory rate.

Some patients may be unable to tolerate NIV and require invasive mechanical ventilation. Initial ventilator settings generally include assist-control volume ventilation with a tidal volume in the range of 6 to 8 mL/kg, backup rate of 10 to 12 breaths/min, and inspiratory flow of 60 to 80 L/min.[36,38] Lower tidal volumes (e.g., 6 mL/kg), lower rates (e.g., 8 to 10), and higher initial peak flow ($\geq$ 80 L/min or inspiratory time of 0.6 to 0.80 sec) may be necessary to allow for sufficient expiratory time. Care should be taken to avoid excessive pressures (e.g., maintain $P_{plateau} \leq$ 30 cm $H_2O$). Trigger sensitivity should be set to minimize trigger work without autotriggering. Adequate expiratory time should be provided to avoid air trapping and autoPEEP. Moderate $F_{IO_2}$s will often suffice (e.g., 0.40 to 0.50). $F_{IO_2}$ is adjusted to maintain adequate arterial oxygen levels (e.g., $Spo_2 \geq 92\%$, $Pao_2 \geq 60$ mmHg). Patients who rapidly trigger the ventilator in the assist-control mode may do well with SIMV. If SIMV is employed, tidal volume, inspiratory peak flow, and inspiratory time should be set at values similar to those used for assist-control volume ventilation. Pressure support (5 to 10 cm $H_2O$) should be added to reduce the $WOB_I$ due to the endotracheal tube. In the presence of autoPEEP resulting in triggering difficulty, small amounts of extrinsic PEEP (3 to 5 cm $H_2O$) may be applied, generally at about 50% to 80% of the measured autoPEEP level.

## Severe Pneumonia

Mechanical ventilation may be necessary in pneumonia patients with severe respiratory failure to maintain oxygenation, ventilation, and acid-base balance. [36,39] Assist-control volume ventilation (VC-CMV) or volume-SIMV with pressure support will be effective for most patients. Initial $V_T$ and f may be set at 8 mL/kg IBW and 14 to 16 breaths/min (respectively) with sufficient inspiratory flow and time settings (e.g., 60 to 80 L/min or 0.6 to 0.8 sec) to meet or exceed the patient's inspiratory demand.[36,39] Unless recent blood gases and the patient's condition indicate otherwise, it is usually best to begin $F_{IO_2}$ at 1.0 and PEEP of 5 cm $H_2O$. $F_{IO_2}$ and PEEP are then titrated to achieve an adequate arterial oxygenation at a safe $F_{IO_2}$. Respiratory rate and tidal volume are adjusted to maintain adequate alveolar ventilation, while avoiding excessive pressures (e.g., keep $P_{plateau} <$ 30 cm $H_2O$). A lung-protective ventilation strategy is then employed (see ARDS below).[36,39]

## Acute Respiratory Distress Syndrome

Patients with severe ARDS often require intubation and mechanical ventilation. Initially, very high oxygen concentrations may be required, and it generally is best to begin ventilation with 100% $O_2$. As soon as is feasible, $F_{IO_2}$ and PEEP are titrated to achieve adequate oxygenation at a safe $F_{IO_2}$. Lower tidal volumes are used as part of a lung-protective strategy to avoid ventilator-associated lung injury.[36,39] Ventilation is usually initiated to achieve full ventilatory support. Assist-control volume ventilation (aka VC-CMV) or assist-control pressure/control ventilation (aka PC-CMV) generally is effective. Initial tidal volume may be set at 8 mL/kg IBW and respiratory rate adjusted to achieve an adequate minute ventilation (e.g., 100 mL/min/ kg IBW). [36,39] Tidal volume is then progressively reduced to 7 mL/kg and then to 6 mL/kg over the next 1 to 3 hours.[36,39] As tidal volume is reduced, respiratory rate is increased to maintain minute ventilation. Respiratory rate may be adjusted up to 35 breaths/min. Additional tidal volume adjustments may be made to maintain $P_{plateau} <$ 30 cm $H_2O$. PEEP is employed to facilitate alveolar recruitment and reduce end expiratory alveolar collapse. Several PEEP strategies have been suggested for ARDS patients. A good strategy for most patients is to adjust the PEEP to the lowest level that results in an adequate $Pao_2$ with an $F_{IO_2} \leq 0.60$. To begin, we suggest in initial PEEP of 5 to 8 cm $H_2O$. Other strategies to improve oxygenation include recruitment maneuvers, pressure-control inverse-ratio ventilation,

and prone positioning. Various open lung and PEEP strategies are discussed in Chapters 7 and 8. Slightly larger tidal volumes (e.g., 8 to 10 mL/kg) may be acceptable if $P_{plateau}$ remains ≤ 28 to 30 cm $H_2O$.[3]

### Neuromuscular Disease

Mechanical ventilatory support is sometimes required in patients with neuromuscular disease. NIV can often be effective in these patients and should be considered. Acutely ill patients, however, may require invasive mechanical ventilatory support.[35] Assist-control volume ventilation (aka VC-CMV) or volume SIMV (VC-IMV) to provide full ventilatory support generally is effective. Initially, tidal volume may be set at 8 mL/kg IBW with a respiratory rate of 12 to 16 breaths/min to achieve a desired minute ventilation (e.g., 100 mL/kg/min).[35] Initial inspiratory peak flow or inspiratory time may be set at 60 to 80 L/min (0.8 to 1.0 sec inspiratory time) with a down ramp flow waveform. Trigger sensitivity should be adjusted to ensure minimal trigger effort without autocycling. If IMV/SIMV is employed, pressure support starting at 5 cm $H_2O$ or automatic tube compensation should be used to overcome the $WOB_I$ associated with the artificial airway. Often, patients with neuromuscular disease, head trauma, or spinal cord injury have otherwise normal lungs. These patients may initially only require moderate concentrations of oxygen (e.g., 0.40 to 0.50). Initial $F_{IO_2}$ may be 1.0 if the patient is in distress or recent oximetry or blood gases suggest the need for a high initial oxygen concentration. Patients with neuromuscular disease and otherwise normal or near-normal lungs may benefit from the use of slightly larger tidal volumes (e.g., 8 to 10 mL/kg) to prevent the development of atelectasis. Some neuromuscular care units begin with tidal volumes in the range of 10 to 12 mL/kg IBW and quadriplegic patients with high spinal cord injury (C3 to C4) may achieve more rapid ventilator weaning with larger tidal volumes (> 20 mL/kg IBW).[40]

## Summary

Indications for mechanical ventilation include apnea, acute ventilatory failure, impending ventilatory failure, and severe oxygenation problems. Mechanical ventilatory support may be provided using noninvasive ventilation or invasive ventilation requiring endotracheal intubation or tracheostomy. Mechanical ventilation is usually initiated to provide full ventilatory support; partial ventilatory support modes may be appropriate in certain circumstances.

Conventional modes of ventilation include assist-control volume ventilation, also known as volume control-continuous mandatory ventilation (VC-CMV); assist-control pressure-control ventilation, also known as pressure control-continuous mandatory ventilation (PC-CMV) and intermittent mandatory ventilation (IMV/SIMV). There are also a large number of alternative modes that have been used to safely and effectively provide ventilatory support to critically ill patients. While these newer modes may have theoretic advantages, none has been shown to consistently improve patient outcomes as compared to more conventional approaches.

Ventilator initiation requires important choices, including whether to provide invasive or noninvasive ventilation, type of airway or ventilator interface, and whether to provide full or partial ventilatory support. The respiratory care clinician must also select the mode of ventilation and specific ventilator to be employed and the initial ventilator settings. These include initial pressures, volumes, and flows provided, as well as oxygen concentration, PEEP/CPAP, humidification, and ventilator alarms and limits. Careful patient observation and assessment must follow ventilator initiation and appropriate adjustments made. The goal is to ensure safe, comfortable support that achieves adequate tissue oxygenation, alveolar ventilation, and acid-base homeostasis while minimizing the WOB.

## Key Points

- The primary function of a mechanical ventilator is to augment or replace normal ventilation.
- The four major indications for mechanical ventilation are apnea, acute ventilatory failure, impending ventilatory failure, and severe oxygenation problems.
- The major goals of mechanical ventilation are to provide adequate alveolar ventilation, ensure adequate tissue oxygenation, restore and maintain acid-base balance, and reduce the work of breathing.
- The tank ventilator or iron lung was developed by Drinker, McCann, and Shaw at Harvard University in 1928 and saw widespread use as the Emerson iron lung during the polio epidemics in the 1940s and 50s.
- Negative-pressure ventilators maintain the natural airway, which allows patients to talk and eat; however, it is challenging to access the patient for procedures, bathing, or turning and they are large, bulky, and difficult to maneuver.
- The most common trigger variables are time and patient effort (i.e., patient triggered).
- The common types of patient triggers are flow trigger and pressure trigger.
- Commonly used terms include *assist breath*, which is patient triggered, *control breath*, which is time triggered, and *assist-control*, which can be patient or time triggered.
- *Controlled ventilation* refers to time-triggered ventilation and requires apnea.
- Cycle variables include volume, pressure, flow, and time.
- With volume-control ventilation, a constant tidal volume is delivered; however, inspiratory pressure

varies with changes in the patient's compliance and resistance.
- With pressure-control ventilation, a constant inspiratory pressure is delivered; however, tidal volume varies with changes in the patient's compliance, resistance, and inspiratory effort.
- Pressure-support ventilation (PSV) is patient triggered, pressure limited, and flow cycled.
- Pressure-control ventilation (PCV) may be time or patient triggered and is pressure limited and time cycled.
- With continuous mandatory ventilation (CMV), every breath is a mandatory breath.
- With intermittent mandatory ventilation (IMV), mandatory breaths are interspersed with spontaneous breaths.
- With continuous spontaneous ventilation (CSV), the patient initiates and terminates each breath; however, inspiratory pressure augmentation may be provided (e.g., PSV or automatic tube compensation [ATC]).
- Noninvasive ventilation (NIV) may be indicated for patients with acute exacerbation of COPD with hypercapnic acidosis, cardiogenic pulmonary edema, and acute hypoxemic respiratory failure.
- NIV may also be useful to prevent postextubation respiratory failure and in the support of patients with chronic hypoventilation due to neuromuscular or chest wall disease.
- NIV should not be used in patients with cardiac or respiratory arrest, hemodynamic or cardiac instability, or severely impaired consciousness.
- Indications for endotracheal intubation include the inability to maintain a patent airway, inability to protect the airway against aspiration, failure to ventilate, failure to oxygenate, and anticipation of deterioration in the patient's condition that will lead to respiratory failure.
- Endotracheal intubation is the most common method to achieve invasive ventilatory support; however, tracheostomy should be considered in certain patients.
- Factors that should be considered when choosing a ventilator include clinical goals, the patient's needs, availability, reliability, ventilator features, alarms and monitoring capabilities, modes available, cost, and (most importantly) clinician's familiarity with the ventilator.
- The mode of ventilation can be described by the control variable, breath sequence, and targeting scheme employed.
- Common control variables are pressure control (PC) and volume control (VC) for the primary breath.
- With full ventilatory support, adequate alveolar ventilation is achieved even if the patient makes no spontaneous breathing efforts.
- Partial ventilatory support requires the patient to provide a portion of the work needed to maintain an acceptable $PaCO_2$.
- High airway pressures may result in barotrauma or VILI.
- The five major modes of ventilation are VC-CMV, PC-CMV, VC-IMV, PC-IMV, and PC-CSV. These modes may be supplemented with PEEP or CPAP.
- Advantages of VC-CMV include constant tidal volume delivery in the face of changes in compliance and resistance, provision of full ventilatory support, and reduced or eliminated work of breathing; however, unsafe airway pressures may result.
- Advantages of PC-CMV include a constant inspiratory pressure in the face of changes in compliance and resistance, allowing for maintenance of a safe $P_{plateau} \leq 28$ to 30 cm $H_2O$.
- IMV incorporates spontaneous breathing, which maintains ventilatory muscle activity and may help maintain ventilatory muscle strength and coordination.
- IMV may be used to provide full or partial ventilatory support; IMV may delay weaning as compared to spontaneous breathing trials (SBTs).
- Pressure-control inverse-ratio ventilation (PC-IRV) is a form of PC-CMV that may improve oxygenation in patients with acute, severe hypoxemia that is unresponsive to conventional ventilation.
- Automatic tube compensation (ATC) is designed to overcome the imposed work of breathing due to an endotracheal or tracheostomy tube during spontaneous breathing.
- CPAP may help maintain FRC and improve oxygenation in spontaneously breathing patients.
- Other modes of ventilation include adaptive pressure control, (APC), mandatory minute ventilation (MMV), adaptive support ventilation (ASV), airway pressure-release ventilation (APRV), proportional assist ventilation (PAV), automode, neutrally adjusted ventilatory assist (NAVA), and high-frequency ventilation.
- Adaptive pressure control (APC) automatically adjusts pressure-control or pressure-support levels to achieve the desired tidal volume.
- Pressure-regulated volume control (PRVC) and volume support (VS) are considered forms of APC.
- Mandatory minute ventilation (MVV) automatically adjusts the level of support provided to achieve a target minute ventilation.
- Adaptive support ventilation (ASV) automatically adjusts respiratory rate and inspiratory pressure to deliver the desired minute ventilation and minimize the work of breathing.
- Airway pressure-release ventilation (APRV) allows for two levels of CPAP that are time triggered and time cycled.
- Proportional assist ventilation (PAV) automatically adjusts the level of ventilatory support based on the patient's inspiratory effort, calculated work of breathing, and clinician-set percentage of support to be provided.

- Automode is a form of IMV that incorporates a targeting scheme for both primary and secondary breaths based on the modes selected.
- Neurally adjusted ventilatory assist (NAVA) uses the electrical discharge from the diaphragm to trigger and cycle ventilator breaths.
- High-frequency ventilation uses small tidal volumes and very high respiratory rates; possible indications include ARDS, bronchopleural fistula, and air leaks.
- There are currently four major types of HFV: high-frequency positive-pressure ventilation (HFPPV), high-frequency percussive ventilation (HFPV), high-frequency jet ventilation (HFJV), and high-frequency oscillatory ventilation (HFOV).
- Assist-control volume ventilation, also known as VC-CMV, is a good initial mode choice for most patients.
- An acceptable alternative to assist-control volume ventilation is assist-control pressure-control ventilation (also known as PC-CMV); this mode requires careful attention to the delivered tidal volume.
- Pressure-support ventilation (PSV) can be used as the primary mode of ventilation when patients have a consistent, stable, spontaneous ventilatory pattern.
- SIMV is a serviceable option for initial ventilator setup, although it is used less commonly.
- Initial tidal volume (adults) may be set in the range of $V_T$ 6 to 8 mL/kg IBW with the rate of 12 to 16 breaths/min; smaller tidal volumes and faster rates may be required for some ARDS patients.
- Tidal volume should be adjusted to ensure that $P_{plateau} \leq 28$ to 30 cm $H_2O$ with a peak inspiratory pressure (PIP) $< 40$ cm $H_2O$.
- Intermittent sigh breaths have been used in the past to prevent development of atelectasis; routine use of PEEP may eliminate the need for an intermittent sigh.
- Patient-triggered breaths may be negative pressure or flow triggered; trigger sensitivity should be set to minimize trigger work while avoiding autotriggering.
- Most modern ventilators allow for the adjustment of rise time and expiratory sensitivity during PSV.
- An inspiratory pause allows for the measurement of the plateau pressure ($P_{plateau}$) and calculation of compliance and resistance.
- I:E ratio should be 1:2 or lower for most patients.
- In general, the safest option for initial oxygen concentration is 100%.
- PEEP/CPAP may improve and maintain lung volumes and improve oxygenation in patients with acute restrictive pulmonary disease.
- Initial PEEP/CPAP of 5 cm $H_2O$ is appropriate for most patients.
- Ventilator alarms and limits are to ensure patient safety and should be adjusted to alert ICU personnel that the patient–ventilator system should be assessed.
- Heated humidification should be provided at 35°C ± 2°C; heat and moisture exchangers (HME) may be appropriate for some patients.
- A careful assessment should be done immediately following ventilator initiation and appropriate ventilator adjustments should be made to ensure patient safety, comfort and effective gas exchange.

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