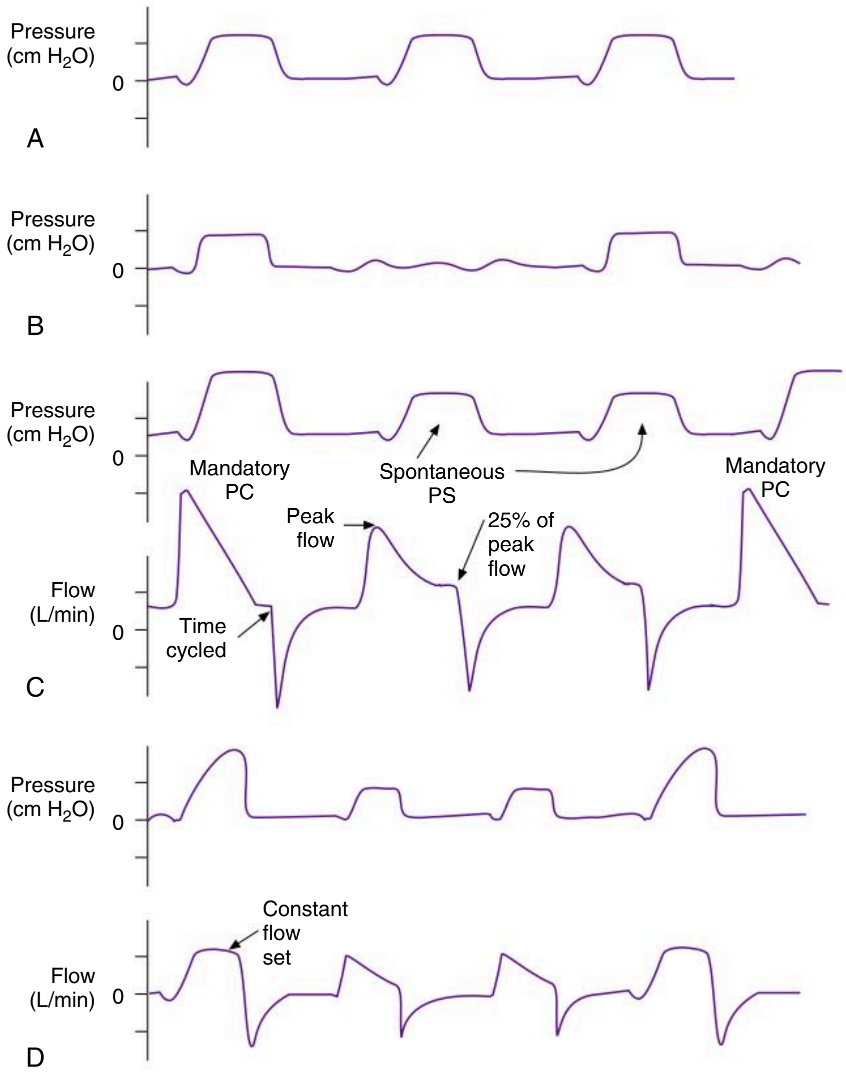


Fig. 5.5 (A) Pressure-controlled continuous mandatory ventilation (PC-CMV) mode; breaths are patient triggered. (B) Pressure-controlled ventilation using the spontaneous intermittent mechanical ventilation (PC-IMV) mode with spontaneous ventilation at zero baseline. (C) PC-IMV mode in which pressure support (PS) has been added for spontaneous breaths. The *top curve* shows pressure, and the *lower curve* shows flow. Note that peak flow and pressure are higher for mandatory pressure-controlled breaths and that flow returns to zero before end inspiration. In PS breaths, inspiration is flow cycled at 25% of peak flow. (D) VC-IMV mode with PS added for spontaneous breaths. Compare the upper and lower curves (pressure and flow, respectively) in (D) with those in (C).

pressure. Reaching the maximum pressure limit usually ends inspiration, as it does in volume ventilation, and prevents excessive system pressures. In some ventilators (e.g., Dräger Evita XL [Dräger Medical Inc., Telford, PA] and the Servo-i (Getinge, Göteborg, Sweden) the expiratory valves float. When excessive pressures build in the circuit (e.g., because of coughing), the valves open to release the excess pressure so that the ventilator does not reach the upper pressure limit, which in turn would end inspiration.

Before 1990, PC-CMV was indicated primarily for patients with ARDS because conventional VC-CMV with PEEP resulted in a high P_{alv} and failed to improve oxygenation.[34-37] Subsequent studies have indicated that PC-CMV with PEEP and VC-CMV with PEEP may be equally effective for ventilation in patients with ARDS.[38,39] However, PC-CMV has been shown to reduce the WOB in these patients more effectively than VC-CMV.[24] Some institutions use PC-CMV for other types of conditions in which guarding against increasing pressures is more important than guaranteeing a specific V_T.

Occasionally the inspiration time (T_I) is set longer than the expiration time (T_E) during PC-CMV. Although this approach is the opposite of the process that occurs during normal breathing, it has been shown that a longer T_I provides better oxygenation to some patients by increasing mean airway pressure (P_{aw}). This mode is referred to as *pressure-controlled inverse ratio ventilation (PC-IRV)* because T_I is greater than T_E. Sometimes the goal of PC-IRV is to prevent full exhalation and gas trapping (auto-PEEP) results. PC-IRV is generally used only for patients with stiff lungs who cannot be successfully administered ventilation with VC-CMV with PEEP or PC-CMV with PEEP. PC-IRV can be quite uncomfortable for the patient and therefore may require sedation or in some cases paralysis.

Intermittent Mandatory Ventilation

IMV involves periodic volume-targeted or pressure-targeted breaths that occur at set intervals (time triggering). During IMV, the patient can breathe spontaneously between mandatory (i.e., machine) breaths at any desired baseline pressure without receiving a mandatory breath.

The spontaneous baseline pressure between mandatory breaths can be set at ambient (zero gauge) pressures or above ambient pressure if PEEP/CPAP is desired (Fig. 5.6 and Key Point 5.3). During spontaneous breaths, the patient can breathe from either a continuous flow of gas or a demand valve. Most ventilators can also provide pressure support for spontaneous breaths during the spontaneous breathing period. Critical Care Concept 5.3 provides historical background about the evolution of IMV. The IMV mode is used when the goal is to have the patient breathe spontaneously without receiving a mandatory breath with every effort (i.e., partial ventilatory support). The patient assumes part of the WOB by actively breathing and not receiving complete support from the ventilator. It is thought that one of the main advantages of using IMV is that this mode allows for active participation by the patient in breath delivery, thus preserving a certain amount of respiratory muscle strength. In fact, the patient's WOB can actually increase with IMV because of a lack of coordination between mandatory and spontaneous breaths. The patient's efforts might not stop just because a mandatory breath is delivered.[40,41] Another potential advantage is that there are fewer cardiovascular side effects because parts of V_E occur at lower pressures.[41]

Key Point 5.3 Mandatory breaths are also called *machine breaths.*

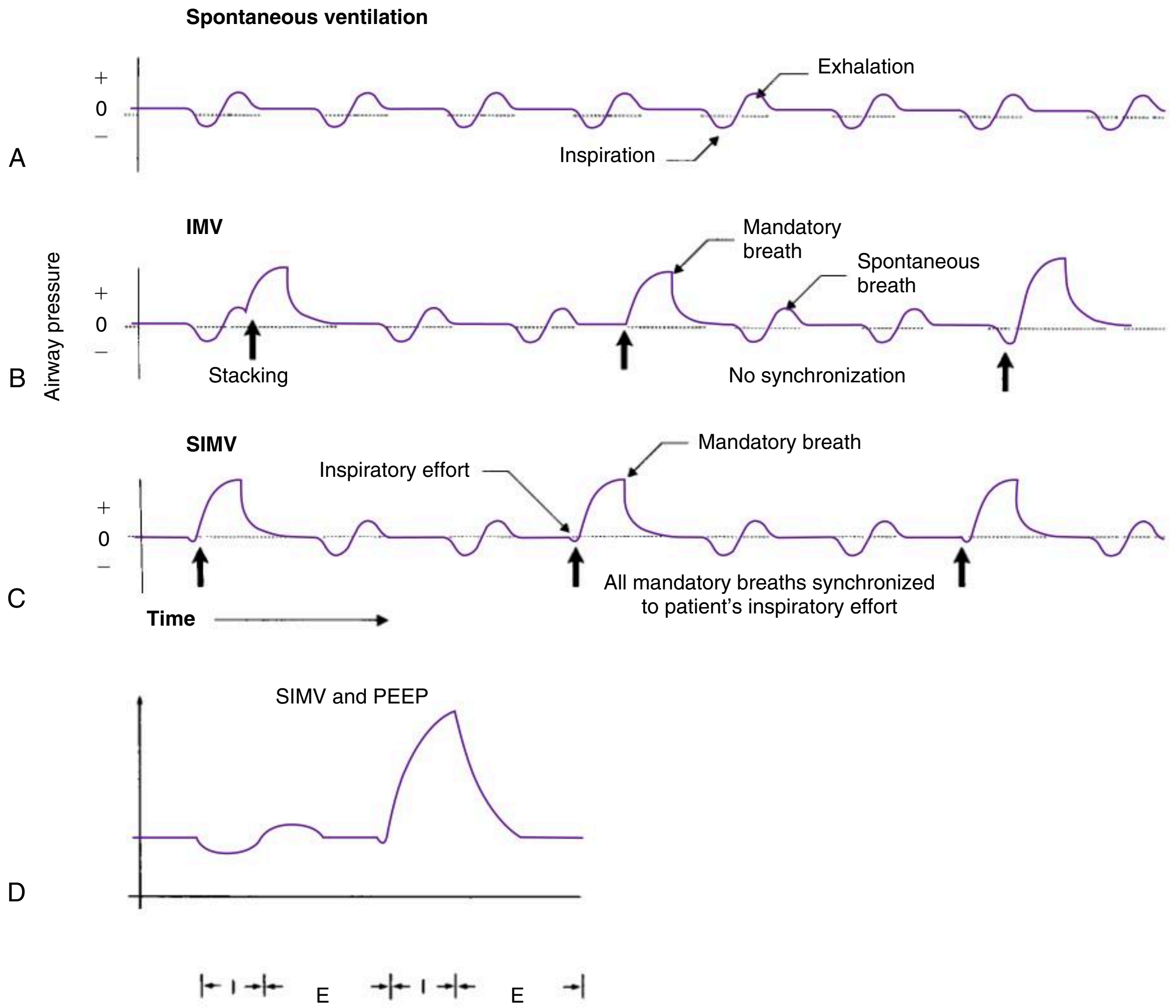


Fig. 5.6 Pressure waveforms showing essential differences in (A) spontaneous ventilation; (B) intermittent mandatory ventilation *(IMV)*; (C) synchronized intermittent mandatory ventilation *(SIMV)*; (D) IMV with positive end-expiratory pressure *(PEEP)*. Note that during intermittent mandatory ventilation, mandatory breaths *(vertical arrows)* and spontaneous breaths are not synchronized. (From Dupuis Y: *Ventilators: theory and clinical application,* ed 2, St. Louis, MO, 1992, Mosby.)

CRITICAL CARE CONCEPT 5.3

Successful use of intermittent mandatory ventilation (IMV) in the 1970s led to the development of a more refined mode of IMV called *synchronized IMV (SIMV)*. SIMV operates in the same way as IMV except that mandatory breaths are normally patient or time triggered rather than solely time triggered. Like IMV, the patient can breathe spontaneously through the ventilator circuit between mandatory breaths. At a predetermined interval (i.e., respiratory rate), which is set by the operator, the ventilator waits for the patient's next inspiratory effort. When the ventilator senses this effort, it assists the patient by synchronously delivering a mandatory breath (see Fig. 5.6). The clinician usually sets the volume target or pressure target, a maximum mandatory breath rate, and the sensitivity level. The ventilator then delivers the set volume or pressure breaths, which are patient or time triggered. After delivering the mandatory breath, the ventilator allows the patient to breathe spontaneously without receiving another machine breath until the next mandatory breath is due to occur.

As with IMV, spontaneous breaths that occur during SIMV can be pressure supported. The pressure target for pressure support breaths is commonly set lower than the peak pressure during a mandatory breath. For example, the mandatory breath may generate a peak pressure of 30 cm H_2O, and the pressure support spontaneous breath may be set at 15 cm H_2O. (Pressure support is discussed later in the chapter.)

Originally SIMV was designed to eliminate the problem of *breath stacking*. Breath stacking occurs with IMV when a machine-timed breath is accidentally delivered at the same time the patient spontaneously inhales. Consequently, the patient's lungs receive huge volumes of air, which can cause high pressure in the lungs and result in barotrauma or ruptured lung tissue. Clinicians can prevent this problem by setting an appropriate peak pressure limit. When large volumes reach the pressure limit, they are vented to the atmosphere or the machine ends inspiration. (NOTE: Although a number of current intensive care unit [ICU] ventilator manufacturers use the term *SIMV* to designate the synchronous nature of coordinating mandatory breaths with spontaneous breaths, the acronym IMV is used in this text because this technology is now considered a built-in feature in all contemporary ICU ventilators.)

Spontaneous breaths can be supported with PSV if the clinician wants to reduce the WOB for spontaneous breathing. Fig. 5.5C shows the pressure-time curve and flow-time curve for pressure-targeted IMV with pressure support for spontaneous breaths; these curves should be compared with those for volume-targeted IMV and pressure support in Fig. 5.5D.

IMV has been used to wean patients from mechanical ventilation. As the mandatory rate is lowered, the patient gradually assumes a greater part of the WOB. (NOTE: Many clinicians are moving away from this method of weaning from mechanical ventilation and choosing instead to use spontaneous breathing trials as criteria for discontinuation of mechanical ventilation. (See Chapter 20 for a more detailed discussion of discontinuation and weaning from mechanical ventilation.) Table 5.1 presents a comparison of the advantages, risks, and disadvantages of CMV and IMV.[40,42,43]

Spontaneous Modes

Three basic means of providing support for CSV during mechanical ventilation exist, as follows:

- Spontaneous breathing
- Continuous positive airway pressure (CPAP)
- Pressure support ventilation (PSV)

Spontaneous Breathing

With this mode, patients can breathe spontaneously through a ventilator circuit without receiving any mandatory breaths. This is sometimes called a T-piece method because it mimics having the patient's ET connected to a Briggs adapter (T piece) and a humidified oxygen source using large-bore tubing. The advantage of this approach is that the ventilator can be used to monitor the patient's breathing and activate an alarm if an undesirable circumstance arises. The disadvantage is that some ventilator systems require considerable patient effort to open inspiratory valves to receive gas flow, thus increasing WOB. Ventilator manufacturers have attempted to minimize this problem by incorporating rapidly responsive valves into their designs.

A spontaneous breathing trial (SBT) can be used to evaluate a patient's readiness to have ventilation discontinued. During the trial, ventilator support is reduced and the patient is allowed to breathe spontaneously for a brief period (15–30 minutes) while the person's vital signs, pulse oximetry, and physical appearance are monitored. A patient who can tolerate the procedure can typically tolerate longer periods of spontaneous breathing and is probably ready to be weaned from ventilation (see Chapter 20).

Continuous Positive Airway Pressure

Ventilators can also provide CPAP for spontaneously breathing patients. In this mode of ventilatory support, a continuous level of positive pressure is applied to the patient's airway throughout inspiration and expiration. In the acute care setting, CPAP may be helpful for improving oxygenation in patients with refractory hypoxemia and a low FRC, which can occur with acute lung injury. As with simple spontaneous breathing, the ventilator can provide a means of monitoring the patient. The advantages and disadvantages of ventilator-provided CPAP are similar to those for spontaneous breathing through a ventilator.

Pressure Support Ventilation

PSV is a special form of assisted ventilation.[44-49] The ventilator provides a constant pressure during inspiration once it senses that the patient has made an inspiratory effort (Fig. 5.7). It is important to recognize that the patient must have a consistent, reliable spontaneous respiratory pattern for PSV to be successful. The operator sets the inspiratory pressure, PEEP, flow cycle criteria, and sensitivity level. The patient establishes the rate, inspiratory flow, and T_I. V_T is determined by the pressure gradient (ΔP = Set pressure − EEP), lung characteristics (lung compliance [C_L] and R_{aw}), and patient effort. PSV is always an assist mode (patient triggered). The flow curve resembles a descending ramp, and the

TABLE 5.1 Advantages, Risks, and Disadvantages of Continuous Mandatory Ventilation and Intermittent Mandatory Ventilation

Mode	Advantages	Risks and Disadvantages
Volume-controlled or pressure-controlled continuous mandatory ventilation (VC-CMV or PC-CMV)	Set minimum minute ventilation (V_E) with volume-targeted breaths.	Respiratory alkalosis if the number of patient-triggered breaths is high. (V_E) may decrease with changes in compliance or airway resistance (R_{aw}) in PC-CMV.
	Guaranteed volume or pressure with each breath.	High mean airway pressure and related complications.
	May synchronize with patient efforts.	Patient–ventilator asynchrony if flow or sensitivity is set incorrectly.
	Patient may establish rate.	May not be well tolerated in awake patients who are not sedated; high rates can result in auto-PEEP.
	Can provide full support in patients who are not breathing spontaneously.	Muscle atrophy may result.
Volume-controlled or pressure-controlled intermittent mandatory ventilation (VC-IMV or PC-IMV)	May lower mean airway pressure compared with CMV.	IMV with pressure support ventilation (PSV) may increase mean airway pressure.
	Variable work of breathing for patient may maintain muscle strength and reduce muscle atrophy.	Can significantly increase work of breathing for spontaneous breaths; hypercarbia and muscle fatigue can occur if rate, flow, and sensitivity are set incorrectly.
	Can be used for weaning.	May increase weaning time.
	May reduce alkalosis associated with CMV.	Patients may have trouble adjusting to the set mandatory rate; acute hypoventilation can occur with low rates (<6 breaths/min mandatory).
	Full or partial support can be adjusted to meet patient's needs.	Spontaneous work of breathing may increase excessively as set mandatory rate is reduced.
	Sedation and paralysis are not required (unlike with CMV).	Patient–ventilator asynchrony may result if patient actively breathes during a mandatory breath when the set rate is low; rapid, shallow breathing may occur during spontaneous periods.

Data from Hudson LD, Hurlow RS, Craig KC, et al.: Does intermittent mandatory ventilation correct respiratory alkalosis in patients receiving assisted mechanical ventilation? *Am Rev Respir Dis* 1985;132:1071; Culpepper JA, Rinaldo JE, Rogers RM: Effect of mechanical ventilator mode on tendency towards respiratory alkalosis, *Am Rev Respir Dis* 132:1075, 1985; Kacmarek RM, McMahon K, Staneck K: Pressure support level required to overcome work of breathing imposed by endotracheal tubes at various peak inspiratory flowrates [abstract], *Respir Care* 33:933, 1988.

patient can vary the inspiratory flow on demand (see Fig. 5.7). A pressure support breath is patient triggered, pressure limited, and flow cycled. Remember that with flow cycling, the ventilator senses a decrease in flow and determines that inspiration is ending. The decrease in flow corresponds to a decrease in the pressure gradient between the mouth and lungs as the lungs fill (see Fig. 5.3). Sudden pressure changes can pressure cycle a pressure support breath, as can an excessive inspiratory time (which may occur with a leak in the circuit) (Box 5.5). The pressure-cycle and time-cycle capabilities are safety backup features; the manufacturer sets the exact pressure-cycle and time-cycle criteria (Fig. 5.8).

Additional settings in pressure support ventilation. With PSV, it is important that the ventilator deliver an appropriate flow at the beginning of inspiration. For example, flow delivery that is set too high can cause a pressure overshoot and inspiratory flow may end prematurely (i.e., pressure-cycled breath) (see Fig. 5.8). Conversely, a flow set too low may not meet the patient's need, leading to asynchrony.[49] There may also be a natural reflex that is a flow-related inspiratory termination reflex.[50,51] Stimulation of this reflex may shorten inspiration and result in brief, shallow inspiratory efforts. This is especially true for low-set pressures in pressure support. The significance of this reflex in clinical practice is not yet known.

Current ICU ventilators allow the operator to adjust the slope of the pressure and flow curves during inspiration (this is sometimes called *sculpturing* or *sloping the breath*). This feature has several names, including *rise time, flow acceleration percent, inspiratory rise time, inspiratory rise time percent,* and *slope adjustment.* The term *rise time* refers to the time required for the ventilator to rise to the set pressure at the beginning of inspiration. The clinician can use the ventilator graphics to help establish an appropriate inspiratory flow delivery (Fig. 5.9). If the patient is responsive, the practitioner can ask the person when flow delivery is most comfortable while adjusting this function.

As mentioned previously, inspiratory flow in PSV ends when the ventilator senses that the flow has dropped to a certain level (flow cycling). Current ventilators (e.g., Medtronics Puritan Bennett 840 [Medtronics Minimally Invasive Therapies, Minneapolis, MN] and the Dräger V500 [Dräger Medical, Inc., Telford, PA])

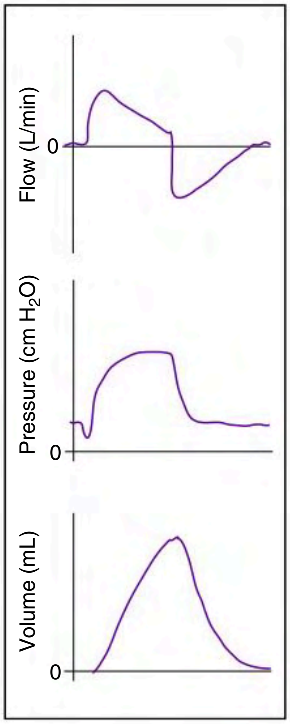


Fig. 5.7 Graph of a pressure support breath. The baseline pressure is above zero; therefore positive end-expiratory pressure (PEEP) has been set. Note the slight negative deflection in the pressure curve before it rises to the set value; this is caused by the patient's inspiratory effort, which triggers the flow from the ventilator. Inspiratory flow is graphed above zero, and expiratory flow is graphed below zero. The flow curve resembles a descending (decelerating) ramp.

have an adjustable flow cycle criterion, which can range from about 5% to about 80% of the measured peak inspiratory flow, depending on the specific ventilator. Manufacturers have given this feature names such as *inspiratory cycle percent, inspiratory flow termination,* and *expiratory flow sensitivity.* Patients with increased airway resistance (e.g., COPD) require a shorter T_I or higher flow cycle percentage, whereas patients with parenchymal lung disease (e.g., ARDS) require a longer T_I or lower flow cycle percent.[52,53] Software is available that allows the ventilator to adjust the flow cycle criterion automatically on a breath-to-breath basis, depending on the lung characteristics and the patient's active expiratory efforts.[54]

BILEVEL POSITIVE AIRWAY PRESSURE

Bilevel positive airway pressure (bilevel PAP), also called *biphasic positive airway pressure and bilevel pressure assist,* is another form of pressure ventilation often used in NIV. Bilevel intermittent positive airway pressure (bilevel IPAP) or airway pressure release ventilation (APRV) is different from classic bilevel PAP and is generally intended for patients with ARDS.[44]

The original BiPAP (Philips Respironics, Murrysville, PA) was introduced in the early 1990s. Machines that provide bilevel pressure assist generate a high gas flow through a microprocessor-controlled valve. The operator sets two pressure levels: an inspiratory and an expiratory positive airway pressure. Inspiration is typically patient triggered but can also be time triggered. It can be flow or time cycled. A full-face mask is the most popular technique for starting therapy, but a nasal mask or nasal pillows can be used. Leakage from the mouth often occurs with the nasal mask and nasal pillows, although chin straps sometimes help eliminate this

BOX 5.5 Time-Cycled and Pressure-Cycled Inspiration With Pressure Support Ventilation and Volume Support*

PSV inspiration ends if the inspiratory time (T_I) exceeds a preset value. This most often occurs with a leak in the circuit. For example, a deflated cuff causes a large leak. The flow through the circuit might never drop to the flow cycle criterion required by the ventilator. Therefore inspiratory flow, if not stopped, would continue indefinitely. For this reason, all ventilators that provide pressure support also have a maximum preset inspiratory time. Most ventilators use a fixed value, such as 1.5 to 2 seconds for adult patients and 0.5 seconds for infants, for the maximum inspiratory time. Other ventilators use different maximum time-cycle criteria.

PSV and VS breaths also end if the pressure in the circuit exceeds the preset pressure by a specific margin (the margin is preset by the manufacturer). For adult patients the margin is approximately 2 cm H_2O above the set pressure. For example, if the set pressure is 12 cm H_2O and the patient forcibly tries to exhale or coughs, the circuit pressure might rise to 14 cm H_2O. At this point inspiratory flow delivery ends for the pressure support breath.

The size of the patient (i.e., adult, child, infant) influences the specific time and pressure limits used. It is also important to mention that the specific times and pressure limits are different for every ventilator. The clinician must become familiar with each of these functions for the ventilator used.

PSV is used for the following three basic functions:

- To reduce WOB for spontaneously breathing patients breathing through a ventilator circuit.
- To reduce WOB in patients receiving continuous positive airway pressure or spontaneous intermittent mechanical ventilation. This is accomplished by setting the pressure level higher than that required to overcome system resistance.
- To provide full ventilatory support in the assist mode, in which each patient breath is a PS breath. The patient must have a dependable, intact respiratory center and a fairly stable lung condition because tidal volume can vary when used in this mode. This is sometimes referred to as maximum pressure support (PS_{max}).[17]

PSV can be used with an artificial airway or a mask to provide noninvasive ventilation.

PS, Pressure support; *PSV,* pressure support ventilation; *VS,* volume support; *WOB,* work of breathing.

*See the Review Questions at the end of the chapter for practice problems that provide examples of how these factors affect volume delivery during pressure ventilation.

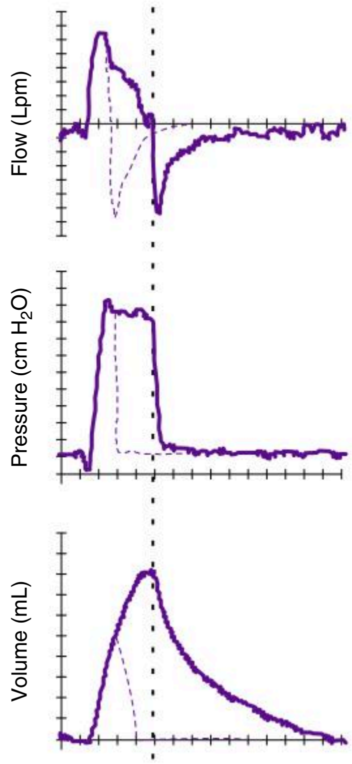


Fig. 5.8 Pressure support ventilation (PSV) graphs with a pressure overshoot at the beginning of inspiration. The *top curve* is flow (L/min), the *middle curve* is pressure (cm H_2O), and the *bottom curve* is volume (mL). The *solid line* of the curves represents PSV without premature termination of inspiration. The *dotted vertical line* through all the curves represents the end of inspiratory flow with normal pressure support breath delivery. The *dashed curve* represents premature cycling caused by pressure overshoot (i.e., a spike at the beginning of the pressure curve). With premature cycling, flow ends prematurely; therefore volume delivery is lower than normal. (Courtesy Ted Tabor, RRT, CBET, Paris, France. Redrawn for this text.)

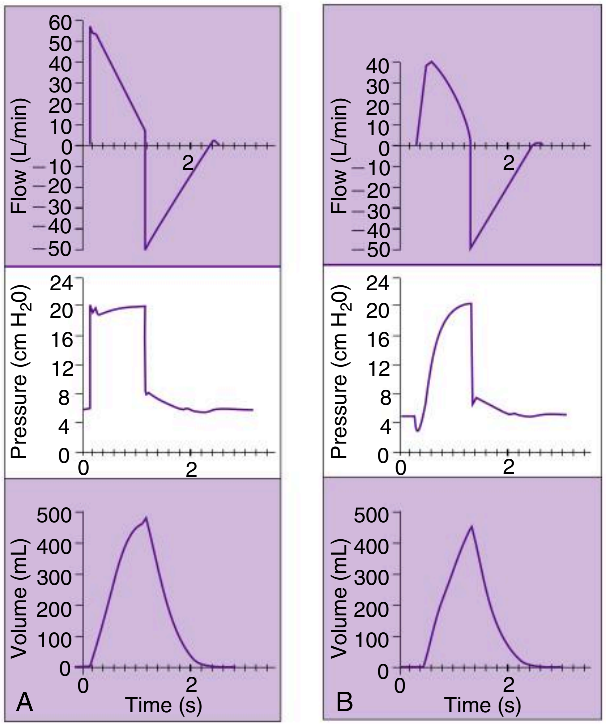


Fig. 5.9 Effect of rise time adjustment during pressure support ventilation (PSV). (A) Faster rise time. (B) Slow rise time. (From Hess DR, MacIntyre NR, Mishoe SC, et al: *Respiratory care principles and practice,* Philadelphia, PA, 2002, Saunders.)

problem. Some machines require a fixed-leak exhalation port and function best with nasal ventilation, which allows exhalation through the mouth. Most devices now compensate for leaks. Newer designs are even being used with artificial airways (see Chapter 19). Box 5.6 provides a list of names used by ventilator manufacturers to describe bilevel PAP for their device.

BOX 5.6 Manufacturer Names for Bilevel Positive Airway Pressure

- BiPAP (Philips Respironics)
- BiLevel (Covidien PB 840 ventilator)
- Bi-Vent (Maquet Servo-I ventilator)
- Duo PAP (Hamilton Medical C-1 ventilator)
- BIPAP (Dräger Savina ventilator)

ADDITIONAL MODES OF VENTILATION

Pressure Augmentation

Pressure augmentation (P_{Aug}) is a dual-control mode that provides pressure-limited ventilation with volume delivery targeted for every breath. Another term that has been used to describe this mode is *volume-assured pressure support (VAPS). VAPS* is the term used to describe P_{Aug} on the Bird 8400st (CareFusion, Yorba Linda, CA).

With P_{Aug} ventilation, the ventilator begins with a patient-triggered, pressure-targeted breath (e.g., a pressure support breath) but targets the volume preset by the operator and delivers that volume with every breath.[55] A key criterion for P_{Aug} is the ability to initiate breaths. These patients must also have a consistent respiratory frequency or be able to make consistent attempts at inspiratory triggering. P_{Aug} does not work if the patient has been sedated to the point at which the respiratory centers are not active; it is intended for conditions in which the respiratory drive waxes and wanes because of changes in level of alertness or moderate changes in sedation.

When using P_{Aug}, the operator selects a desired volume and minimum rate, a set pressure level above baseline, an inspiratory gas flow, and a sensitivity setting. When the patient triggers a breath, the ventilator delivers the set pressure level and monitors flow and volume. If volume is achieved before the inspiratory gas flow drops to the preset value, the breath cycles into expiration. Cycling occurs when the measured flow drops to 25% to 30% of the patient's peak inspiratory flow. The threshold value depends on the ventilator's flow cycle criterion. If volume is not achieved before flow drops to the set level, the ventilator maintains the flow at the set value until the volume is delivered (volume cycled). If the patient's inspiratory flow demand is high and pressure starts to fall below the set pressure level in this mode, the ventilator provides additional flow to the patient. In this sense, P_{Aug} targets a minimum volume, but the breath is not limited to that volume. Patients can receive more than the set volume if there is a high-flow demand.

Pressure-Regulated Volume Control

Pressure-regulated volume control (PRVC) is a volume-targeted, pressure-controlled breath that is available on most ventilators (e.g., Servo-i, CareFusion AVEA, Hamilton-G5, Covidien PB 840, Dräger Evita XL). Although PRVC was introduced on the Servo 300 in the 1990s and later has been used to describe this mode on the Servo-i and Servo-s (Getinge, Göteborg, Sweden) and the CareFusion AVEA (CareFusion, Inc., Yorba Linda, CA), it subsequently has been given different proprietary names on other ventilators (e.g., *AutoFlow* on the Dräger Evita Infinity [Dräger Medical Inc., Telford, PA], *VC+* on the Covidien PB 840 and 980 [Medtronics, Minneapolis, MN], *Adaptive Pressure Ventilation* on the Hamilton G5 and C3 ventilators [Hamilton Medical, Bonaduz, Switzerland]).

Pressure-regulated volume control delivers pressure breaths that are patient-triggered or time-triggered, volume-targeted, and time-cycled breaths. During breath delivery, the ventilator measures the V_T delivered and compares it with the targeted V_T, which is set by the operator. If the volume delivered is less than the set V_T, the ventilator increases pressure delivery progressively over several breaths until the set and the targeted V_T are about equal (Fig. 5.10). If the measured volume is too high, the pressure is reduced in an attempt to reach the targeted V_T. Generally, the ventilator does not allow the pressure to rise higher than 5 cm H_2O below the upper pressure limit setting. For example, if the upper pressure limit is 35 cm H_2O and the ventilator requires more than 30 cm H_2O to deliver a V_T of 500 mL, an alarm activates and the pressure delivery is limited to 30 cm H_2O. The clinician must determine why the higher pressure is required to deliver the set volume (e.g., the presence of secretions in the airway, bronchospasms, or changes in C_L). The clinician can then choose an appropriate course of action to address the higher pressure required. On the other hand, when a patient's lung condition improves, less pressure is required to achieve the set volume. The ventilator progressively lowers the pressure; however, it does not allow pressure to drop below the set baseline [PEEP].

Volume Support Ventilation

VSV is similar to PRVC. It is basically pressure support with a volume target and will have various names depending on the ventilator manufacturer. It is a pressure breath that is patient triggered, volume targeted, and flow cycled. There is no backup rate with VSV; however, there is generally a backup mode in the event that the patient becomes apneic on this purely spontaneous mode. As with PRVC, the ventilator adjusts the pressure, over several breaths, to achieve the set volume. If volume is too low, the pressure is increased. Conversely, the pressure is reduced if the volume is too high. VSV can be used for patients who are ready to be weaned from the ventilator and can breathe spontaneously (Fig. 5.11). Unlike PRVC, it is normally flow cycled when the flow drops to a set percentage of peak flow. It can also be time cycled (if T_I is extended for some reason) or pressure cycled (if the pressure rises too high) (see Box 5.5 and Chapter 6).

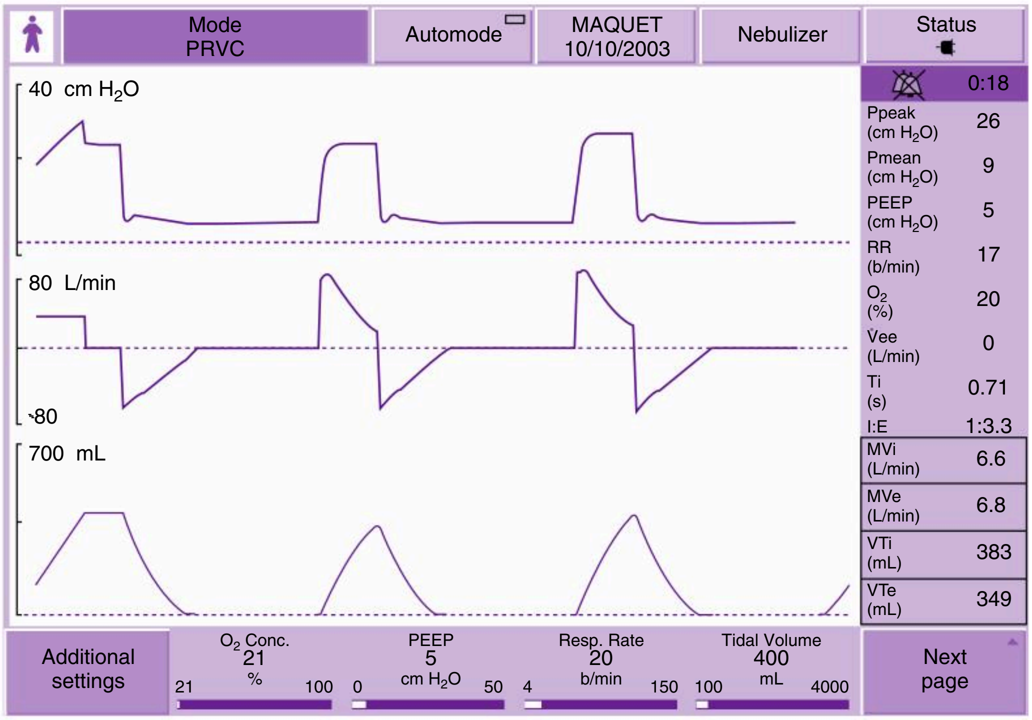


Fig. 5.10 A screen capture of pressure-regulated volume control (PRVC) in an adult patient on the Servo-i ventilator. The first breath *(left)* is a volume-targeted test breath with an inspiratory hold to measure plateau pressure. The second breath is a pressure-targeted breath with a pressure equal to the measured plateau pressure. Set tidal volume is 400 mL. Measured exhaled tidal volume is about 350 mL. Note how the pressure is increased by a few centimeters of H_2O on the third breath for the ventilator to achieve the set tidal volume.

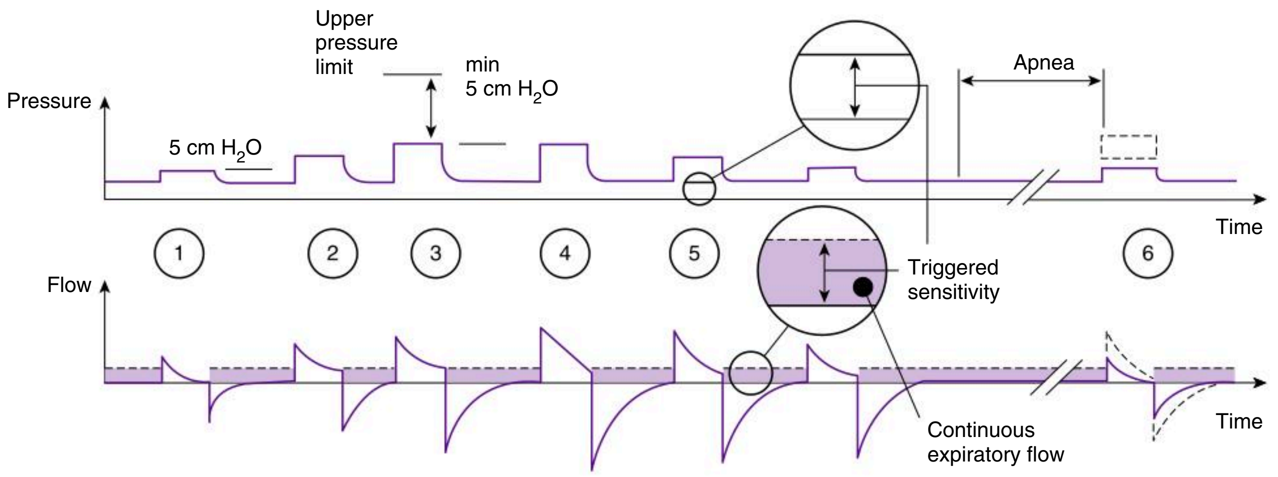


Fig. 5.11 *(1),* Volume support test breath (5 cm $H_2$0); *(2),* pressure is increased slowly until target volume is achieved; *(3),* maximum available pressure is 5 cm $H_2$0 below upper pressure limit; *(4),* tidal volume higher than set tidal volume delivered results in lower pressure; *(5),* patient can trigger breath; *(6),* if apnea alarm is detected, ventilator switches to pressure-regulated volume. (The 5 cm $H_2$0 test breath and breath delivery pattern are features of the original design; these have been modified in newer models of the Servo 300 and Servo-i.) (Courtesy Getinge, Göteborg, Sweden.)

Mandatory Minute Ventilation

MMV, also called *minimum minute ventilation* and *augmented minute ventilation,* has been used primarily for weaning patients from the ventilator. It allows the operator to set a minimum minute ventilation, which is usually 70% to 90% of a patient's current V_E. The ventilator provides whatever part of the minute ventilation the patient is unable to accomplish by increasing the breathing rate or preset pressure. The ventilator monitors the patient's spontaneous breathing and provides additional ventilatory support if the patient does not achieve the set V_E. If a patient increases the level of his or her spontaneous ventilation, the ventilator reduces its amount of support.

The clinician typically sets high rate and low V_T alarms to monitor significant changes in either of these parameters because either suggests an increased WOB. It is also important to monitor these parameters even if the patient can maintain the desired minute ventilation, because patients sometimes begin to breathe rapidly and take shallow breaths. This pattern increases dead space ventilation without effectively increasing alveolar ventilation (Table 5.2). MMV is rarely used in current practice in the United States.

Adaptive Support Ventilation

Adaptive support ventilation (ASV) was first described by Laubscher and colleagues in 1994 as a variation of mandatory minute ventilation.[56] ASV is a relatively new mode of ventilation that was introduced in the United States in 2006 in their Hamilton Galileo ventilator and subsequently included in the Hamilton C-6 ventilator (Hamilton Medical, Inc., Reno, NV). It has been described as a closed-loop ventilation and oxygenation mode of ventilation.

With ASV, the clinician sets the targeted minute ventilation (V_E based on the patient's ideal body weight and estimated dead space volume (i.e., 2.2 mL/kg of ideal body weight). The calculated minute ventilation represents the total minute ventilation normally required for the patient. The clinician can adjust the targeted ventilation based on the patient's needs (i.e., <100% of the targeted minute ventilation during weaning or >100% in cases in which ventilatory needs are increased, such as sepsis).[55]

The optimal breathing frequency that the ventilator delivers is determined by delivering a test breath to the patient, which is used to estimate the expiratory time constant for the patient's respiratory system. This expiratory time constant is used along with the estimated

TABLE 5.2 Constant Minute Ventilation With Changing Alveolar Ventilation[a]

Tidal Volume (mL)	Dead Space (mL)	Respiratory Rate (breaths/min)	Alveolar Ventilation (L/min)	Minute Ventilation (L/min)
800	150	10	6.5	8
667	150	12	6.2	8
533	150	15	5.75	8
400	150	20	5	8
250	150	32	3.2	8

[a]If a patient has a constant dead space of 150 mL, minute ventilation remains constant, whereas alveolar ventilation decreases, rate increases, and tidal volume falls.

dead space volume and the calculated minute ventilation to calculate the optimal breath frequency delivered by the ventilator. The optimal V_T then can be calculated by dividing the patient's calculated minute ventilation by the optimal breathing frequency.[56]

It has been suggested that ASV may be beneficial in weaning of critically ill patients from mechanical ventilation because it automatically selects the V_T and respiratory rate based on changes in the patient's lung mechanics. Additionally, this mode theoretically should require fewer ventilator settings by the respiratory therapist and improved patient-ventilator synchrony.[56]

Airway Pressure Release Ventilation

APRV, which is similar to bilevel PAP, was described by Stock in 1987 and became commercially available in the mid-1990s.[57] It is currently available in most ICU ventilators. APRV is designed to provide high and low airway pressure levels and allow spontaneous breathing at both levels when spontaneous effort is present.[58-60] Both pressure levels are time triggered and time cycled (Fig. 5.12). The terms P_{high} and P_{low} indicate the levels of pressure administered during APRV, and T_{high} and T_{low} are used to describe the time spent in high and low airway pressures. It is important to recognize that APRV differs from other forms of bilevel PAP ventilation in that APRV is characterized by longer high positive pressure level periods followed by a shorter low positive pressure level (i.e., near ambient pressure). APRV therefore allows the patient to spontaneously breathe during the high positive pressure level, which may help improve ventilation/perfusion (V). The shorter lower pressure level is designed to facilitate exhalation. Current-generation ICU ventilators also allow for patient triggering and patient cycling. The possible advantage of this modification may be its synchronization with patient breathing, which may reduce the need for sedation and paralysis.[61-64]

For the initial setup, an optimum high CPAP level is determined much as the optimum PEEP or an ideal $\overline{P}_{aw}$ is determined for improving oxygenation (see Chapter 13). The P_{high} level is interrupted intermittently to allow pressures to drop briefly (for about 1 second or less) to a P_{low} level near ambient pressure. Reducing the CPAP reduces the patient's FRC and allows exhalation and ventilation (i.e., exhalation of CO_2). Expiratory flow is generally not permitted to return to baseline (zero); therefore auto-PEEP is intentionally present, which helps maintain an open lung and prevents repeated collapse and reexpansion of alveoli. As soon as the release period is complete, the P_{high} level is restored. The optimum duration of the release time is a function of the time constant of the respiratory system.[61] The pressure curve generated during APRV resembles that of PC-IRV if the patient is not breathing spontaneously.

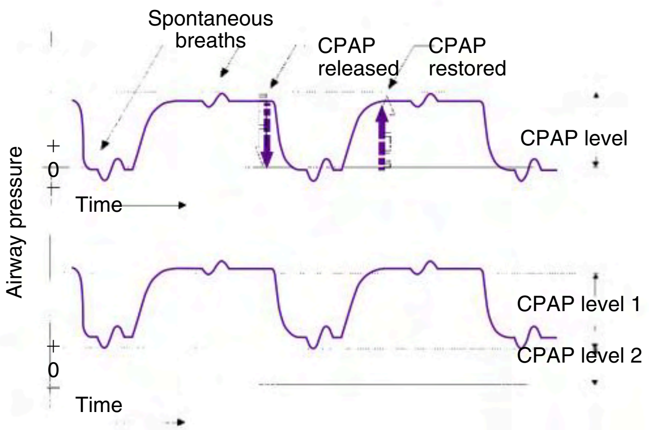


Fig. 5.12 Pressure waveforms for airway pressure release ventilation (APRV) in which alveolar ventilation is enhanced when pressure is released to zero *(upper graph)* and when release pressure is above zero *(lower graph).* Inspiratory/expiratory ratio for APRV is 2:1. *CPAP,* Continuous positive airway pressure. (From Dupuis Y: *Ventilators: theory and clinical application,* ed 2, St. Louis, MO, 1992, Mosby.)

Although originally intended for patients with stiff lungs, APRV has been shown to be as effective as conventional ventilation for providing ventilation and oxygenation for patients with mild pulmonary problems or with normal lung compliance.[60,63-66] Clinical studies have provided evidence that APRV can enhance alveolar recruitment and improve hemodynamic arterial oxygenation, reduce physiological dead space ventilation, and reduce peak airway pressures.[56,59,61,63-66]

Proportional Assist Ventilation

The PAV approach is a different approach to mechanical ventilation because pressure, flow, and volume delivery are proportional to the patient's spontaneous effort.[44,67,68] The amount of pressure the ventilator produces depends on two factors: (1) the amount of inspiratory flow and volume demanded by the patient's effort; and (2) the degree of amplification selected by the clinician (which determines the extent of ventilator response to patient effort). PAV is a positive feedback system.

Basically, the ventilator measures airway flow and pressure and compares patient demand with the gains (amplification) set by the operator. The amount of flow delivered to the patient is determined from this comparison. As the patient's inspiratory effort increases, the flow from the ventilator increases proportionally. This relationship is described by the equation in Box 5.7.

The clinician sets the gain of the volume amplifier to compensate for the abnormal elastance (f_1) of the patient and adjusts the gain of the flow amplifier to compensate for the abnormal resistance (f_2) of the patient.[19] The clinician must estimate these values beforehand. Setting the controls and measuring elastance and resistance can be difficult. Indeed, the pressure output from the ventilator can exceed the pressure needed to overcome the respiratory system impedance (C_L and R_{aw}) if the baseline measurements are inaccurate.[69]

BOX 5.7 Determining Proportional Assist

$$\overline{P}_{aw} = (f_1 \times \text{Volume}) + (f_2 \times \text{Flow})$$

where $\overline{P}_{aw}$ is the airway pressure; f_1 is the ventilator-supported elastic load (degree of volume assist); and f_2 is the ventilator-supported resistive load (degree of flow assist).

Ideally, PAV assists the patient's inspiratory effort on the basis of the patient's lung characteristics and amount of patient effort desired. PAV may prove to be a valuable alternative mode of ventilation. The advantage of PAV is its ability to track changes in patient effort, which can occur rapidly in acute respiratory failure. The disadvantages of PAV are that it provides only for assisted ventilation and cannot compensate for system leaks. Patients experiencing auto-PEEP may also find it more difficult to trigger the ventilator.

Neurally Adjusted Ventilatory Assist

Neurally adjusted ventilatory assist (NAVA) is a newer mode of ventilation that relies on the patient's neurological control of mechanical ventilation (i.e., triggering, breath delivery, and timing of the mechanical support provided).[70-72] It has been suggested that NAVA accomplishes the same goals as PAV but relies on the measurement of a diaphragmatic electromyelogram signal to control gas delivery.[72] This mode of ventilation is accomplished using a nasogastric tube with specialized sensors that obtain signals from the electrical activity of the diaphragm to control the timing and pressure of the ventilation delivered. In theory, this mode of ventilation is unaffected by circuit leaks, thus avoiding the potential for autocycling and hypocapnia in patients. As discussed in Chapter 22, NAVA has also been shown to provide better comfort and less need for sedation in neonates than PRVC. It is worth mentioning that this modality is invasive, and placement of the nasogastric tube must be evaluated to ensure proper function of this modality. Additional information about the application of NAVA in adult patients can be found in Chapter 23.

SUMMARY

- Once the need for mechanical ventilation has been established, the clinician must select the type of ventilator, breath type, and ventilator mode appropriate for the patient.
- Mechanical ventilators can function in a wide variety of settings and provide a variety of modes, features, monitors, and alarms.
- Three methods of providing noninvasive ventilatory support exist: NPV, CPAP, and NIV.
- CPAP has been shown to be an effective method to improve oxygenation in hospitalized patients and as an accepted method to treat obstructive sleep apnea.
- NIV has been successfully used to treat patients with respiratory failure caused by various neuromuscular disorders, chest wall deformities, COPD, central ventilatory control abnormalities, and acute cardiogenic pulmonary edema.
- Invasive positive pressure ventilation can involve full or partial ventilatory support. During full ventilator support, the ventilator provides all of the energy necessary to maintain effective alveolar ventilation. With partial ventilator support, the patient can assume a variable portion of the WOB.
- The breath type and pattern of breath delivery during mechanical ventilation constitute the mode of ventilation. The mode is determined by whether the breath is mandatory, IMV, or spontaneous; the targeted control variable; and the timing of breath delivery.
- The clinician determines the control variable that will be used to establish gas flow to the patient by choosing either volume or pressure ventilation.
- The primary advantage of volume-controlled ventilation is that it guarantees a specific volume delivery and minute ventilation, regardless of changes in lung compliance and resistance or patient effort.
- The main advantage of pressure-controlled ventilation is that it can be used as a lung-protective strategy because it reduces the risk for overdistention of the lungs by limiting the amount of positive pressure applied to the lung.
- The goal of IMV is to allow the patient to breathe spontaneously without receiving a mandatory breath with every effort (partial ventilatory support). The primary advantage of IMV is that this mode allows for active participation by the patient in breath delivery, thus minimizing the effects of respiratory muscle atrophy.
- PSV can be used with patients who have a dependable, intact respiratory center and a stable lung condition. It is used to reduce WOB in patients receiving CPAP or IMV.
- Pressure-regulated volume control, volume support, adaptive support ventilation, airway pressure release ventilation, and PAV provide several alternative methods of ventilation.
- Fig. 5.13 presents an example of a worksheet the reader can use to evaluate the types of ventilators and their settings. The worksheet also incorporates principles discussed in Chapter 4.

Worksheet: **Name** ______________________

Ventilator, Ventilator Mode, and Breath Delivery

Manufacturer ______________________ Model & No. ______________________

I. Power Source: Pneumatic Electric Microprocessor controlled Other ______________________

II. Circuit: Single Double

III. Drive Mechanism

Volume displacement design type ______________

Flow control valve type ______________

Other ______________ type ______________

Mode of Ventilation and Breath Description

1. VC-CMV; PC-CMV

Mandatory breath: volume ventilation or pressure ventilation

Triggering: time pressure flow

Limiting: volume pressure flow time

Cycling: volume pressure flow time

Inspiratory pause: (time) ______________ second(s)

Other: ______________

2. VC-IMV; PC-IMV

A. Mandatory breaths: volume ventilation or pressure ventilation

Triggering: time pressure flow

Limiting: volume pressure flow time

Cycling: volume pressure flow time

B. Spontaneous breaths

Zero baseline

Auto-PEEP (expiratory pause pressure) = ______________ cm H_2O

Positive baseline

SET PEEP (positive pressure baseline) = ______________ cm H_2O

Auto-PEEP (expiratory pause pressure) = ______________ cm H_2O

Total end-expiratory pressure = ______________ cm H_2O

PSV

Set pressure = ______________ cm H_2O

Flow cycling

or L/min cycling = ______________

3. Spontaneous Breathing Through a Ventilator

A. Zero baseline

Auto-PEEP (expiratory pause pressure) = ______________ cm H_2O

B. Positive pressure baseline

SET PEEP (positive pressure baseline) = ______________ cm H_2O

Auto-PEEP (expiratory pause pressure) = ______________ cm H_2O

Total end-expiratory pressure = ______________ cm H_2O

C. PSV set pressure = ______________ cm H_2O

Flow cycling

or L/min = ______________

4. Minimum Mandatory Ventilation

Volume ventilation Pressure ventilation Other

Set mandatory minute ventilation L/min

Other settings:

5. APRV

High CPAP level = ______________ cm H_2O

Low CPAP level = ______________ cm H_2O

Time one = ______________ sec

Time two = ______________ sec

Fig. 5.13 Worksheet for reviewing a ventilator's function, mode, and breath delivery.

6. Bilevel PAP
   IPAP = ______________ cm H_2O
   EPAP = ______________ cm H_2O
   Other settings: ____
7. PAV
   f1 (elastic load) = ______________
   f2 (resistive load) = ______________
   Volume = ______________
   Flow = ______________
8. Pressure Ventilation with Volume Guaranteed
   VAPS or pressure augment
   PRVC or ____ VC
   Other ______________
   Settings: desired volume ____________ pressure (set or limit) ____________
   flow (where appropriate) ____________ other ____________
9. Other: Description

Fig. 5.13, cont'd

REVIEW QUESTIONS *(See Appendix A for answers.)*

1. In which of the following situations would you try NIV?
   A. A patient in whom blood pressure is 65/35 mm Hg, heart rate is 150 beats/min, and respiratory frequency is 34 breaths/min
   B. A patient who nearly drowned who has copious amounts of white, frothy secretions
   C. A patient with COPD and right lower lobe pneumonia with respiratory acidosis and increased WOB
   D. A 5-year-old child who has aspirated a piece of chicken and is having trouble breathing

2. Which of the following would you use for a trauma victim with crushed chest injuries?
   A. Negative pressure ventilation
   B. Pressure-cycled ventilator
   C. VC-CMV
   D. Noninvasive ventilation

3. A patient with hiccups is receiving ventilation in the VC-CMV mode. Every time he hiccups, he triggers the ventilator. What would you recommend?
   A. Paralyze the patient and control ventilation
   B. Use PSV
   C. Use PC-CMV
   D. Use VC-IMV

4. A patient with severe tetanus needs ventilatory support. Which of the following modes would you recommend?
   A. Paralyze and sedate the patient; control ventilation using volume-controlled VC-CMV
   B. PC-CMV
   C. VC-IMV
   D. PSV with CPAP

5. In which of these four circumstances is it appropriate to select PSV?
   1. As a method of weaning
   2. To overcome the WOB through the ET and the circuit
   3. For patients using the IMV mode
   4. For long-term patient support
   A. 1, 2, and 3
   B. 2, 3, and 4
   C. 1, 3, and 4
   D. 1, 2, 3, and 4

6. A patient on PC-CMV has widely fluctuating changes in R_{aw} because of secretions and bronchospasm. The low tidal volume alarm is activated every few hours; the set pressure is 18 cm H_2O. The physician is concerned about consistency in ventilation. What would you recommend?
   A. Increase the set pressure
   B. Sedate the patient
   C. Switch to VC-CMV
   D. Switch to PSV

7. A patient with acute respiratory distress syndrome has a plateau pressure (P_{plat}) of 30 cm H_2O and a peak inspiratory pressure of 39 cm H_2O. V_T is 0.7 on VC-CMV. The decision is made to switch to PC-CMV (PCV) to keep pressures at a safe level. What pressure would you set and why?

8. A patient receiving VC-CMV is actively triggering every breath. The respiratory therapist notices that the patient is using accessory muscles (sternocleidomastoid muscles) during the entire inspiratory phase. The therapist also sees that the pressure-time curve has a negative deflection before inspiration and a concave appearance during inspiration. What is the apparent problem in this situation?

9. A patient has recovered from severe pneumonia that required 8 days of PC-CMV ventilation. The patient is now conscious and responsive. She is triggering every breath and has a strong cough. What should the therapist suggest to the physician?

10. A physician is concerned about the high pressures required to perform ventilation for a patient with terminal cancer and severe lung scarring. The lungs are stiff and fibrous. The physician is also concerned about maintaining a normal CO_2 value in this patient. What mode might be appropriate for this patient and why?

References

1. Klonin H, Bowman B, Peters M, et al.: Negative pressure ventilation via chest cuirass to decrease ventilator-associated complications in infants with acute respiratory failure: a case series, *Respir Care* 45:486–490, 2000.
2. Hassinger AB, Breuer RK, Nutty K, et al.: Negative-pressure ventilation in pediatric acute respiratory failure, *Respir Care* 62(12):1540–1549, 2017.
3. Pierson DJ: History and epidemiology of noninvasive ventilation in the acute-care setting, *Respir Care* 54:40–52, 2009.
4. Liesching T, Kwok H, Hill NS: Acute applications of noninvasive positive pressure ventilation, *Chest* 124:699–713, 2003.
5. Scala R, Pisani L: Noninvasive ventilation in acute respiratory failure: which recipe for success? *Eur Respir Rev* 27:180029, 2018.
6. Miro AM, Shirvaram U, Hertig E: Continuous positive airway pressure in COPD patients in acute respiratory failure, *Chest* 103:266–268, 1993.
7. MacIntyre NR: Physiologic effects of noninvasive ventilation, *Respir Care* 64(6):617–628, 2019.
8. Bello G, DePascale G, Antonelli M: Non-invasive ventilation, *Clin Chest Med* 37(4):701–710, 2016.
9. Rochwerg B, Brochard L, Elliott MW, et al.: Official ERS/ATS clinical practice guidelines: noninvasive ventilation for acute respiratory failure, *Eur Respir J* 50:1602426, 2017.
10. Patrick W, Webster K, Ludwig L, et al.: Noninvasive positive-pressure ventilation in acute respiratory distress without prior chronic respiratory failure, *Am J Respir Crit Care Med* 153:1005–1011, 1996.
11. Mehta S, Al-Hashim AH, Keenan SP: Noninvasive ventilation in patients with acute cardiogenic pulmonary edema, *Respir Care* 54:186–195, 2009.
12. Meduri GU, Fox RC, Abou-Shala N, et al.: Noninvasive mechanical ventilation via face mask in patients with acute respiratory failure who refused endotracheal intubation, *Crit Care Med* 22:1584–1590, 1996.
13. Hill NS, Spoletini G, Schumaker G, et al.: Noninvasive ventilatory support for acute hypercapnic respiratory failure, *Respir Care* 64(6):647–657, 2019.
14. Ambrosino N, Vagheggini: Noninvasive positive pressure ventilation in the acute care setting: where are we? *Eur Respir J* 31:874–886, 2008.
15. Peruzzi WT: Full and partial ventilatory support: the significance of ventilator mode [editorial], *Respir Care* 35:174, 1990.
16. Respiratory Distress Syndrome Network (ARDS network): Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome, *N Engl J Med* 342:1301–1308, 2000.
17. MacIntyre NR: Weaning from mechanical ventilatory support: volume-assisting intermittent breaths versus pressure-assisting every breath, *Respir Care* 33:121–125, 1988.
18. MacIntyre NR: Management of obstructive airway disease. In MacIntyre NR, Branson RD, editors: *Mechanical ventilation*, ed 2, Philadelphia, PA, 2009, Saunders, pp 297–305.
19. Op't Holt T: Introduction to ventilators. In Cairo JM, editor: *Mosby's respiratory care equipment*, ed 11, St. Louis, MO, 2022, Elsevier.
20. Chatburn RL, Volsko TA: Mechanical ventilators. In Kacmarek RM, Stoller JK, Heurer AJ, editors: *Egan's fundamentals of respiratory care*, ed 11, St. Louis, MO, 2017, Mosby.
21. Campbell RS, Davis BR: Pressure-controlled versus volume-controlled ventilation: does it matter? *Respir Care* 47:416–424, 2002.
22. Marini JJ, Rodriguez RM, Lamb V: The inspiratory workload of patient-initiated mechanical ventilation, *Am Rev Respir Dis* 134:902–909, 1986.
23. Marini JJ, Capps JS, Culver BH: The inspiratory work of breathing during assisted mechanical ventilation, *Chest* 87:612–618, 1985.
24. Kallet RH, Campbell AR, Alonso JA, et al.: The effects of pressure control versus volume control assisted ventilation on patient work of breathing in acute lung injury and acute respiratory distress syndrome, *Respir Care* 45:1085–1096, 2000.
25. Bein T, Grasso S, Moerer O, et al.: The standard of care of patients with ARDS: ventilatory settings and rescue therapies for refractory hypoxemia, *Intensive Care Med* 42:699–711, 2016.
26. De Vries H, Jonkman A, Shi ZH, et al.: Assessing breathing effort in mechanical ventilation: physiology and clinical implications, *Ann Transl Med* 6(19):387, 2018.
27. Downs JB: Ventilatory patterns and modes of ventilation in acute respiratory failure, *Respir Care* 28:586–591, 1983.
28. Hudson LD, Hurlow RS, Craig KC, et al.: Does intermittent mandatory ventilation correct respiratory alkalosis in patients receiving assisted mechanical ventilation? *Am Rev Respir Dis* 132:1071–1074, 1985.
29. Culpepper JA, Rinaldo JE, Rogers RM: Effect of mechanical ventilator mode on tendency towards respiratory alkalosis, *Am Rev Respir Dis* 132:1075–1077, 1985.
30. Kacmarek RM, Hess D: Pressure-controlled inverse-ratio ventilation: panacea or auto-PEEP? [editorial], *Respir Care* 35:945–948, 1990.
31. Kacmarek RM, McMahon K, Staneck K: Pressure support level required to overcome work of breathing imposed by endotracheal tubes at various peak inspiratory flowrates [abstract], *Respir Care* 33:933, 1988.
32. Banner MJ, Boysen PG, Lampotang S, et al.: End-tidal CO_2 affected by inspiratory time and flow waveform: time for a change, *Crit Care Med* 14:374–378, 1986.
33. Al-Saady N, Bennett ED: Decelerating inspiratory flow waveform improves lung mechanics and gas exchange in patients on intermittent positive-pressure ventilation, *Intensive Care Med* 11:68–75, 1985.
34. Hastings D, Sabo J: Pressure-controlled inverse ratio ventilation for adult respiratory distress syndrome [abstract], *Respir Care* 33:957, 1988.
35. Arnold JS, Summer JL, Tipton RD, et al.: Inverse ratio ventilation in hypoxic respiratory failure [abstract], *Chest* 96:150S, 1989.
36. Greaves TH, Gordon M, Cramolini M, et al.: Inverse ratio ventilation in a 5-year-old with severe post-traumatic adult respiratory distress syndrome, *Crit Care Med* 17:588–589, 1989.
37. Marini JJ: Pressure-targeted mechanical ventilation of acute lung injury, *Chest* 105(Suppl):109S–115S, 1994.
38. Lessard MR, Guerot E, Lorino H, et al.: Effects of pressure-controlled ventilation with different I:E ratios versus volume-controlled ventilation on respiratory mechanics, gas exchange, and hemodynamics in patients with adult respiratory distress syndrome, *Anesthesiology* 80:983–991, 1994.
39. Muñoz J, Guerrero JE, Escalante JL, et al.: Pressure-controlled ventilation versus controlled mechanical ventilation with decelerating inspiratory flow, *Crit Care Med* 21:1143–1148, 1993.
40. Marini JJ, Smith TC, Lamb VJ: External work output and force generation during synchronized intermittent mechanical ventilation: effect of machine assistance on breathing effort, *Am Rev Respir Dis* 138:1169–1179, 1988.
41. Kiiski R, Takala J, Kari A, et al.: Effect of tidal volume on gas exchange and oxygen transport in the adult respiratory distress syndrome, *Am Rev Respir Dis* 146:1131–1135, 1992.
42. Mecklenburgh JS, Latto IP, Al-Obaidi TA, et al.: Excessive work of breathing during intermittent mandatory ventilation, *Br J Anaesth* 58:1048–1054, 1986.
43. Papdakos PJ, Lachmann B: *Mechanical ventilation: clinical applications and pathophysiology*, Philadelphia, PA, 2007, Saunders.
44. Kuhlen R, Rossaint R: The role of spontaneous breathing during mechanical ventilation, *Respir Care* 47:296–303, 2002.
45. Ladeira MT, Vital FMR, Andriolo RB, et al.: Pressure support versus T-tube for weaning from mechanical ventilation in adults, *Cochrane Database Syst Rev* (5):CD006056, 2014.
46. Pellegrini JAS, Moraes RB, Maccari JG, et al.: Spontaneous breathing trials with T-piece or pressure support ventilation, *Respir Care* 61(12):1693–1703, 2016.
47. Thille AW, Coudroy R, Nay MA, et al.: Pressure support ventilation vs T-piece during spontaneous breathing trials before extubation among patients at high risk of extubation failure: a post-hoc analysis of clinical trial, *Chest* 158:1446–1455, 2020.
48. Subirá C, Hernández G, Vazquez A, et al.: Effect of pressure support vs T-piece ventilation strategies during spontaneous breathing trials on successful extubation among patients receiving mechanical ventilation, *JAMA* 321(22):2175–2182, 2019.
49. Croci M, Pelosi P, Chiumello D, et al.: Regulation of pressurization rate reduces inspiratory effort during pressure support ventilation: a bench study, *Respir Care* 41:880–884, 1996.
50. Fernandez R, Mendez M, Younes M: Effect of ventilator flow rate on respiratory timing in normal subjects, *Am J Respir Crit Care Med* 159:710–719, 1999.
51. Manning HL, Molinary EJ, Leiter JC: Effect of inspiratory flow rate on respiratory sensation and pattern of breathing, *Am J Respir Crit Care Med* 151:751–757, 1995.
52. Hess D, Branson R: Ventilators and weaning modes. Part II, *Respir Care Clin N Am* 6:407–435, 2000.

53. Parthasarathy S, Jubran A, Tobin MJ: Cycling of inspiratory and expiratory muscle groups with the ventilator in airflow limitation, *Am J Respir Crit Care Med* 158:1471–1478, 1998.
54. Parthasarathy S, Jubran A, Tobin MJ: Assessment of neural inspiratory time in ventilator-supported patients, *Am J Respir Crit Care Med* 162:546–552, 2000.
55. Mireles-Cabdovellia E, Diaz-Guzman E, Heresi GA, Chatburn RL: Alternative modes of mechanical ventilation: a review for the hospitalist, *Cleveland Clinic J Med* 76(7):417–430, 2009.
56. Laubscher TP, Frutiger A, Fanconi S, et al.: Automatic selection of tidal volume, respiratory frequency, and minute ventilation in intubated ICU patients as start-up procedures for closed–loop controlled ventilation, *Int J Clin Monit Comput* 11:19–30, 1994.
57. Stock MC, Downs JB, Frolicher DA: Airway pressure release ventilation, *Crit Care Med* 15:462–466, 1987.
58. Putensen C, Muzt NJ, Putensen-Himmer G, et al.: Spontaneous breathing during ventilator support improves ventilation-perfusion distribution in patients with respiratory distress syndrome, *Am J Respir Crit Care Med* 159:1241–1248, 1999.
59. Sydow M, Burchardi H, Ephraim E, et al.: Long-term effects of two different ventilatory modes on oxygenation in acute lung injury: comparison of airway pressure release ventilation and volume-controlled inverse ratio ventilation, *Am J Respir Crit Care Med* 149:1550–1556, 1994.
60. Daoud EH, Farag HL, Chatburn RL: Airway pressure release ventilation: what do we know? *Resp Care* 57(2):282–292, 2012.
61. Neumann P, Golisch W, Strohmeyer A, et al.: Influence of different release times on spontaneous breathing pattern during airway pressure release ventilation, *Intensive Care Med* 28:1742–1749, 2002.
62. Davis Jr K, Johnson DJ, Branson RD, et al.: Airway pressure release ventilation, *Arch Surg* 128:1348–1352, 1993.
63. Rouby JJ, Ben Amewr M, Jawish D, et al.: Continuous positive airway pressure (CPAP) vs intermittent mandatory pressure release ventilation (IMPRV) in patients with acute respiratory failure, *Intensive Care Med* 18:69–75, 1992.
64. Kaplan LJ, Bailey H, Formosa V: Airway pressure release ventilation increases cardiac performance in patients with acute lung injury/acute respiratory distress syndrome, *Crit Care* 5:221–226, 2001.
65. McCunn M, Habashi NM: Airway pressure release ventilation in the acute respiratory distress syndrome following traumatic injury, *Int Anesthesiol Clin* 40:89–102, 2002.
66. Habashi NM: Other approaches to open-lung ventilation: airway pressure release ventilation, *Crit Care Med* 33(Suppl):228–240, 2005.
67. Younes M: Proportional assist ventilation: a new approach to ventilatory support, *Am Rev Respir Dis* 145:114–120, 1992.
68. Younes M, Puddy A, Roberts D, et al.: Proportional assist ventilation: results of an initial clinical trial, *Am Rev Respir Dis* 145:121–129, 1992.
69. Branson R: Understanding and implementing advances in ventilator capabilities, *Curr Opin Crit Care* 10:23–32, 2004.
70. Sinderby C, Navalesi P, Beck J, et al.: Neural control of mechanical ventilation in respiratory failure, 5(12):1433–1436, 1999.
71. Sinderby C, Beck J: Neurally adjusted ventilatory assist (NAVA): An Update, 11:243–252, 2007.
72. Kacmarek RM: Proportional assist ventilation and neurally adjusted ventilatory assist, 56(2)140–152, 2011.

CHAPTER 6

Initial Ventilator Settings

OUTLINE

KEY TERMS

- Compressible volume
- Mechanical dead space
- Overinflation
- System compressibility
- Tubing compliance

LEARNING OBJECTIVES

On completion of this chapter, the reader will be able to do the following:

1. Calculate tubing compliance.
2. Determine volume loss caused by tubing compliance.
3. Calculate minute ventilation given a patient's respiratory rate and tidal volume.
4. Calculate total cycle time, inspiratory time, expiratory time, flow in liters per second, and inspiratory-to-expiratory ratios given the necessary patient data.
5. Select an appropriate flow rate and pattern.
6. Calculate initial minute ventilation, tidal volume, and rate for a patient placed on volume-controlled continuous mandatory ventilation based on the patient's sex, height, and ideal body weight.
7. Identify the source of the problem when an inspiratory pause cannot be measured.
8. Choose an appropriate initial mode of mechanical ventilation and determine the expired minute ventilation, tidal volume, respiratory frequency, and positive end-expiratory pressure settings on the basis of the patient's lung pathology, body temperature, metabolic rate, altitude, and acid-base balance.
9. Evaluate the response in peak inspiratory pressure and plateau pressure when the flow waveform is changed.
10. Recommend the selection and initial settings for the various modes of pressure ventilation, including bilevel positive airway pressure, pressure support ventilation, pressure-controlled ventilation, and Servo-controlled (dual modes) ventilation.
11. Identify a patient-ventilator problem when using pressure support ventilation from a pressure-time graph.
12. Measure plateau pressure using pressure-time and flow-time waveforms during pressure-controlled mechanical ventilation.
13. List the possible causes for a change in pressure during pressure-regulated volume control.
14. Identify the mode of ventilation on the basis of the trigger, target, and cycle criteria.

Mechanical ventilation has been shown to be an effective method of treating patients unable to achieve effective gas exchange. Selecting an appropriate tidal volume (V_T) and respiratory rate or frequency (f) to achieve a desired minute ventilation ($\dot{V}_E$) is important when initiating volume-controlled mechanical ventilation. This chapter examines how

$\dot{V}_E$ and related variables are set during the initiation of volume ventilation and then focuses on the settings required to initiate positive pressure ventilation.

DETERMINING INITIAL VENTILATOR SETTINGS DURING VOLUME-CONTROLLED VENTILATION

Initiating volume control ventilation for a patient requires an understanding of the interaction of several key variables, including $\dot{V}_E$ settings (V_T and f), inspiratory gas flow, flow waveform, inspiratory-to-expiratory (I/E) ratio, pressure limit, inflation hold (inspiratory pause), inspiratory pressure, and positive end-expiratory pressure (PEEP).

The design characteristics of mechanical ventilator control panels can vary. For example, many have V_T and rate settings, such as the Medtronics Puritan Bennett 840 and 980 ventilators (Medtronic Minimally Invasive Therapies), whereas other ventilators, such as the Servo-i (Getinge, Göteborg, Sweden), also allow the operator to set $\dot{V}_E$ and f. Some ventilator manufacturers provide time cycling and have controls for inspiratory time percentage, and still others control total cycle time (TCT).

It is important for clinicians charged with the responsibility of instituting mechanical ventilation to have a fundamental understanding of the various control variables available on intensive care unit (ICU) ventilators. Then, regardless of the ventilator involved, they will possess enough information to make an informed decision about how to proceed. The following discussion begins with the basics: $\dot{V}_E$, V_T, and f. A more detailed discussion of initial ventilator setting for patients with specific cardiopulmonary and neuromuscular disorders is provided in Chapter 7.

INITIAL SETTINGS DURING VOLUME-CONTROLLED VENTILATION

Setting Minute Ventilation

The primary goal of volume-controlled continuous mandatory ventilation (VC-CMV) is to achieve a $\dot{V}_E$ that matches the patient's metabolic needs. A typical healthy person at rest has a total oxygen consumption ($\dot{V}O_2$) of about 250 mL/min and a carbon dioxide production ($\dot{V}O_2$) of about 200 mL/min. As the patient's metabolic rate increases, ventilation must change to meet the need for increased O_2 uptake and CO_2 removal (Box 6.1).

Metabolic rate is directly related to body mass and surface area in humans. Measurements of heat production (i.e., direct calorimetry) provide a reliable method to quantify metabolic rate; however, direct calorimetry requires a considerable amount of space and time commitment and is typically reserved for research purposes. Indirect calorimetry, which uses measurements of inspired and expired O_2 and CO_2 to estimate energy expenditure, can be accomplished with significantly less time and effort. Indeed, advances in computer technology have made it relatively easy to perform indirect calorimetry in the clinical setting. (See Chapter 10 for more information about indirect calorimetry.)

A more commonly used method to estimate metabolic rate and caloric intake involves using equations that were derived from laboratory studies performed in the early part of the 20th century.[1]

BOX 6.1 Determining Pressure, Tidal Volume, Respiratory Frequency, and Minute Ventilation to Establish Initial Ventilator Settings for Volume and Pressure Ventilation

Volume Control Ventilation

Minute Ventilation ($\dot{V}_E$)

Men $\dot{V}_E = 4 \times$ body surface area (BSA)
Women $\dot{V}_E = 3.5 \times$ BSA

Increase This by

5%/° F above 99° F or 10%/° C above 37° C
20% for metabolic acidosis
50% to 100% if resting energy expenditure is equally increased

Decrease This by

10%/° C between 35° C and 37° C

Tidal Volume (V_T)

Minimum of 4 mL/kg ideal body weight (IBW) (consider sigh or lung recruitment maneuver and high PEEP)*
Maximum of 8 mL/kg IBW (do not use sigh)†
Maintain transpulmonary pressure (P_L) <30 cm H_2O

Respiratory Frequency (f)

$f = f = \dot{V}_E/V_T$
Respiratory rate typically ranges from 12 to 18 breaths per minute

Pressure Ventilation

Pressure Support Ventilation (PSV)

To overcome system resistance in the spontaneous mode (PSV or continuous positive airway pressure [CPAP]) or in the intermittent mandatory ventilation (IMV) mode, set pressure at peak inspiratory pressure (PIP) − (P_{plat}), where P_{plat} is measured in a volume breath or at approximately 5 to 10 cm H_2O. To provide ventilatory support, set pressure to achieve a target V_T as described for VC-CMV.

Pressure-Controlled Ventilation (PC-CMV)

Set pressure to achieve V_T as described for VC-CMV. Set frequency to achieve the same $\dot{V}_E$. $f = \dot{V}_E/V_T$.

Set inspiratory percentage to achieve an inspiratory/expiratory (I/E) ratio of greater than or equal to 1:2.

*For patients being treated for ARDS, lower tidal volumes (e.g., 4 mL/kg) may be necessary to ensure that the P_{plat} <30 cm H_2O. See Chapter 13 for additional information regarding the use of lung recruitment maneuvers in lung protective strategies used for the treatment of ARDS.

†In patients with neuromuscular disorders or cerebral disorders, a V_T of >10 mL/kg might be required, but P_{plat} should still be maintained at 30 cm H_2O.

With these equations, metabolic rate is estimated on the basis of an individual's gender and body surface area (BSA).[1,2] BSA can be calculated using the DuBois BSA formula: $BSA = 0.007184 \times Ht^{0.725} \times W^{0.425}$, where BSA = body surface area in square meters, Ht = body height in centimeters, and W = body weight in kilograms. (It can also be determined using a nomogram such as the one shown in Fig. 6.1. Notice that this nomogram is based on the aforementioned DuBois BSA formula.)

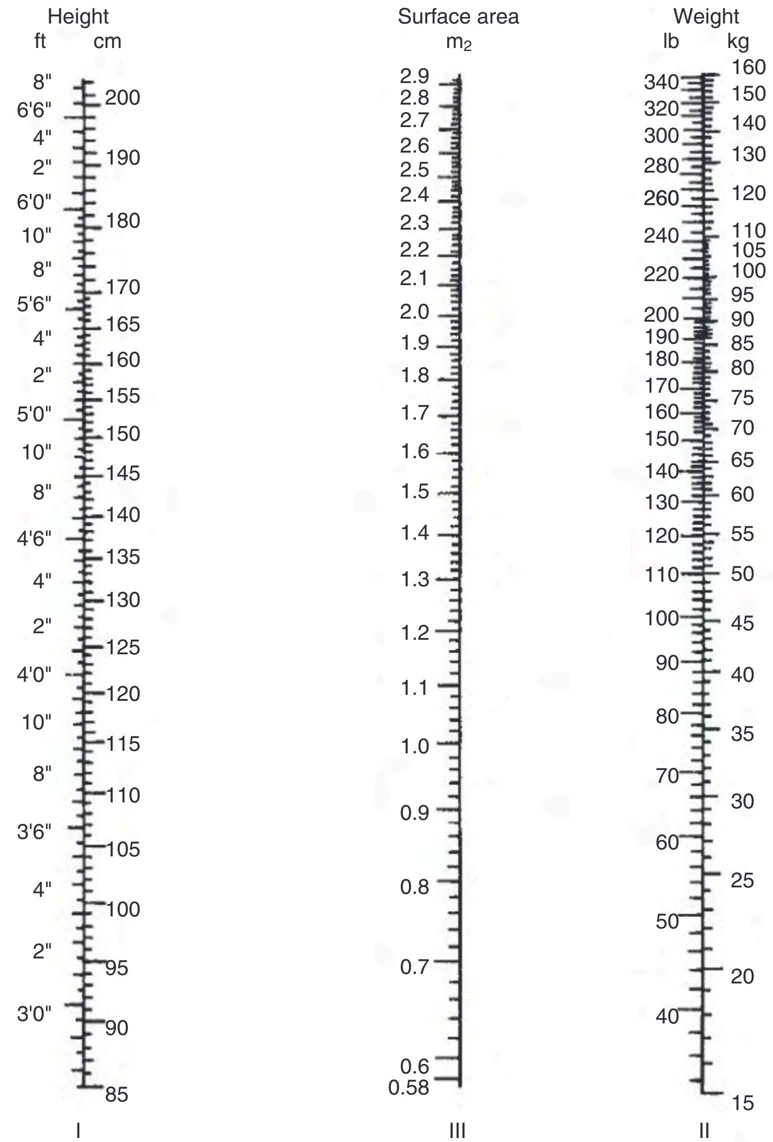


Fig. 6.1 Dubois body surface chart. To determine the body surface area (BSA), locate the height in inches or centimeters on scale I and weight in pounds or kilograms on scale II. Connect these two points with a straight line. Where the line intersects scale III determines BSA in square meters. (From Boothby WM, Sandiford RB: Nomographic charts for the calculation of the metabolic rate by the gasometry method, *Boston Med Surg J* 185:337, 1921.)

As shown in Box 6.1, $\dot{V}_E$ can also be estimated using a patient's BSA. $\dot{V}_E$ is approximately equal to four times the BSA in men and three and a half times the BSA in women. For example, the estimated $\dot{V}_E$ for an adult male patient with a BSA of 2.1 m^2 would be:

$$\dot{V}_E \text{ for a male} = 4 \times \text{BSA} = 4 \times 2.1\ \text{m}^2 = 8.4\frac{\text{L}}{\text{min}}$$

Notice that this calculation of $\dot{V}_E$ assumes that the individual is a typical healthy adult. The $\dot{V}_E$ must be adjusted for abnormal conditions, such as the presence of hypothermia or hyperthermia, a hypermetabolic state, and metabolic acidosis. Lung disorders that increase physiological dead space will also require an increase in $\dot{V}_E$.[2] For example, suppose that the patient already mentioned requires an initial $\dot{V}_E$ of 8.4 L/min but has a temperature of 39° C. $\dot{V}_E$ would have to be increased by 10% for each degree above 37° C: a total increase of 20% of 8.4 = 1.68; therefore the new $\dot{V}_E$ would be 8.4 + 1.68 = 10.08 L/min.

Settings for V_T and f should therefore be derived from the initial calculation of $\dot{V}_E$ (4 × BSA for men and 3.5 × BSA for women) and adjusted if the patient demonstrates a pathological condition like those mentioned previously. V_T can be determined by the method described in the discussion that follows. To determine breathing frequency (f), divide the $\dot{V}_E$ by the V_T ($\dot{V}_E/V_T = f$) (Case Study 6.1).

In many cases, physicians order settings for mechanical ventilation that include volume and rate and do not typically specify $\dot{V}_E$. The respiratory therapist must keep in mind that the ordered rate and volume must reflect the $\dot{V}_E$ needs of the patient.

Case Study 6.1

Minute Ventilation ($\dot{V}_E$) Needs

A physician orders a tidal volume (V_T) of 500 mL and a rate of 12 breaths/min for a 25-year-old woman with a body surface area of 2.0 m^2. The estimated $\dot{V}_E$ will be $3.5 \times 2.0 = 7.0$ L/min. What is the ordered $\dot{V}_E$ compared with the estimated $\dot{V}_E$ needed? If you were the respiratory therapist in this situation, how would you address the discrepancy between the physician's order and the actual $\dot{V}_E$ required?

CRITICAL CARE CONCEPT 6.1

Tidal Volume (V_T) and Ideal Body Weight (IBW)

What is the lowest and highest estimated V_T for a 5-ft, 6-in man (IBW = 65 kg)? What would the lowest and highest estimated V_T be for a 5-ft, 6-in woman?

***Key Point* 6.1** A person's tidal volume increases linearly with body weight up to that person's ideal body weight.

BOX 6.2 Calculating Ideal Body Weight (IBW) for Women and Men

$$Women: IBW(lb) = 105 + 5(H - 60),$$

where *H* is height in inches.

For example, the IBW of a 66-in-tall woman is 105 + 5(66 − 60) = 105 + 5(6) = 135 lb (61.4 kg). (To convert to kilograms, divide by 2.2.)

$$Men\ IBW(lb) = 106 + 6(H - 60).$$

For example, the IBW of a 66-in-tall man is 106 + 6(66 − 60) = 106 + 6(6) = 142 lb (64.5 kg).

Tidal Volume and Rate

The normal spontaneous V_T for a healthy adult is about 5 to 7 mL/kg with a spontaneous respiratory rate of 12 to 18 breaths/min. $\dot{V}_E$ is approximately 100 mL/kg of ideal body weight (IBW).[3] Box 6.2 provides formulas that can be used to calculate IBW.[3]

When determining V_T for ventilated patients, a range of 6 to 8 mL/kg of IBW is typically used for adults and 4 to 8 mL/kg IBW for infants and children.[4-6] Lower V_T rates (e.g., 4 mL/kg IBW) have been successfully used for ventilation of the lungs of adult patients with acute respiratory distress syndrome (ARDS). These lower V_T rates are described as lung protective ventilatory strategies that minimize the damaging effects associated with overdistention of the alveoli.[7]

It is important to understand that an adult's lungs do not get larger as he or she gains weight. For example, a male 5-ft, 6-in adult weighing 100 kg would require the same V_T as a male 5-ft, 6-in adult weighing 65 kg. Remember, however, that a heavier patient would have a higher metabolic rate and thus a higher $\dot{V}_E$. Critical Care Concept 6.1 provides an example of how to estimate tidal volumes based on IBW (Key Point 6.1). (It is interesting to note that the Radford nomogram [Fig. 6.2], which was used in the past by clinicians to estimate the set V_T, is based on a V_T range of about 5 to 7 mL/kg IBW.[8]) (Box 6.3 and Case Study 6.2.)

An alternative method for calculating initial V_T settings is to use predicted values for body weight rather than calculations of IBW. The predicted body weight of male patients can be calculated using the equation 50 + 0.91 (centimeters of height − 152.4). For female patients, the predicted body weight can be determined using the equation 45.5 + 0.91 (centimeters of height × 152.4).[7]

Recommended V_Ts for patients on ventilation vary depending on the lung pathologic conditions. For patients with normal lungs, such as patients with a drug overdose or patients with the postoperative effects of anesthesia, an initial V_T of 6 to 8 mL/kg IBW and a rate of 10 to 20 breaths/min is generally accepted.[3] For patients with chronic obstructive pulmonary disease (COPD) and asthma, in which airway obstruction and resistance are high, an initial V_T of 6 to 8 mL/kg IBW with a rate of 8 to 12 breaths/min is acceptable.[3,12-14] In patients with chronic or acute restrictive disease, such as pulmonary fibrosis or ARDS, an initial V_T of 4 to 6 mL/kg IBW with a rate of 15 to 25 breaths/min is indicated.[7] As suggested in restrictive disease, lower V_T and higher rates are used. However, high rates may not provide sufficient time for exhalation (short T_E) and air can be trapped in the lungs at the end of exhalation, resulting in intrinsic PEEP (auto-PEEP).[15] The V_T should be adjusted to maintain plateau pressure less than 30 cm H_2O and rates adjusted to minimize auto-PEEP.

A V_T of more than 9 to 10 mL/kg IBW is not recommended because of the risk for high pressures and accompanying overdistention and trauma to the lung, in addition to other complications. Low-volume settings (4–8 mL/kg IBW) are beneficial in restrictive disease and may help prevent high pressures and alveolar overdistention. It is worth mentioning that using volumes as low as 4 mL/kg may contribute to atelectasis. Using V_Ts this low may require a recruitment maneuver or sigh breaths to avoid atelectasis. Use of lower V_T may be especially important in patients receiving PEEP therapy to avoid high pressures and overdistention[16,17] (Key Point 6.2). Box 6.3 provides important background on how initial V_T settings were selected for this text.[3,7,9-14]

It is important to mention that use of lung protective ventilatory strategies also includes avoiding use of excessive transpulmonary pressures (P_L <30 cm H_2O),* as well as using driving pressures (i.e., P_{plat} − PEEP) of 15 cm H_2O or less. Additional information about the use of lung protective ventilatory strategies with various pathological conditions is presented in Chapters 7 and 13.

Tubing Compliance

The V_T set on the ventilator control panel represents the amount of gas sent to the ventilator circuit; however, not all of this volume

*Transpulmonary pressure is the difference between alveolar pressure and pleural pressure ($P_L = P_{alv} - P_{pl}$).

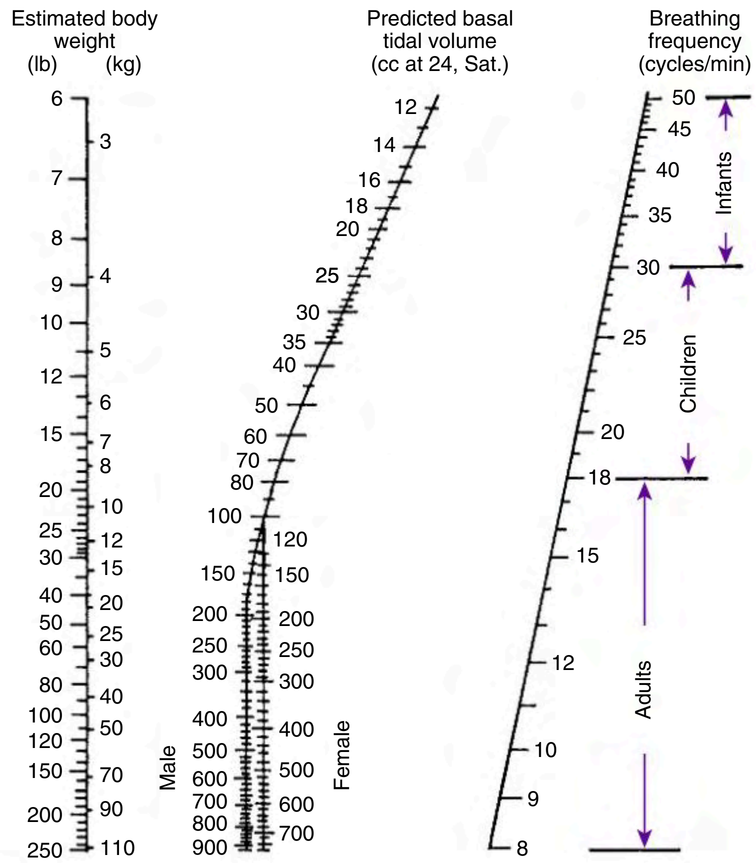


Fig. 6.2 Breathing nomogram (Radford's nomogram) for determining the predicted tidal volume (V_T) and breathing frequency. Corrections to be applied to predict basal (minimum) V_T. Daily activity (patient not in a coma): add 10%; fever: add 5% per degree Fahrenheit (F) above 99° F (rectal) or add 10% per degree centigrade (C) above 37° C (rectal); altitude: add 5% for every 2000 feet above sea level; artificial airway: subtract the volume equal to half the body weight in pounds or subtract 1 mL/kg of body weight; add equipment dead space volume; metabolic acidosis: add 20%. (From Radford EP, Ferris BG Jr, Driete BC: Clinical use of a nomogram to estimate proper ventilation during artificial respirations, *N Engl J Med* 21:877, 1954.)

reaches the patient. Some of the gas volume will not be delivered to the patient because of leaks and the effects of tubing compliance.

The **tubing compliance** (C_T), or **system compressibility,** reflects the volume (in milliliters) of gas compressed in the ventilator circuit for every centimeter of water pressure generated by the ventilator during the inspiratory phase: C_T = change in volume divided by change in pressure ($\Delta V/\Delta P$) in mL/cm H_2O.

As pressure builds in the ventilator circuit during inspiration, the circuit expands along with the patient's lungs; therefore the total volume that goes to the circuit never reaches the patient. As expiration begins, the volume of gas trapped under pressure in the patient circuit flows out the expiratory valve with the air that leaves the patient's lungs. This volume (exhaled volume from the ventilator tubing and the patient's lungs) is often referred to as the *exhaled* V_T.

The volume of gas in the circuit is referred to as the **compressible volume,** or the volume lost as a result of C_T. The compressible volume varies depending on the type of circuit used and is determined for each ventilator system before its use. Calculating compressible volume is especially important in infants, children, or petite patients because of the small V_T they require. A slight change in V_T may be insignificant for an adult, but it can be critical for an infant during mechanical ventilation. Thus practitioners routinely use small-bore, rigid circuits with infants because these types of circuits are less compliant. These ventilator circuits typically have low C_Ts and therefore have low compressible volumes. (NOTE: C_T for a patient's circuit changes slightly as the circuit warms, but this amount is usually not significant.)

Current ICU ventilators (e.g., Hamilton G5 [Hamilton Medical, Switzerland], Maquet Servo-i [Getinge, Göteborg, Sweden], Dräger 500 [Dräger Medical Inc., Telford, PA], Medtronics Puritan Bennett 980 [Medtronics Minimally Invasive Therapies], and CareFusion AVEA [CareFusion, Yorba Linda, CA]) have the capability of measuring and correcting for C_T. During start-up tests of the system, these ventilators calculate the compressibility of the ventilator circuit. The operator can choose to use this correction or simply ignore it. If correction for C_T is accepted, the ventilator measures the peak pressure during ventilation, calculates the volume lost to the patient circuit, and adds that volume to the set V_T. When the data are displayed on the ventilator, the exhaled V_T measured again corrects for C_T. For example, if the set V_T is 500 mL and the loss of volume is 50 mL, the ventilator actually delivers 550 mL, although it displays 500 mL as V_T inspired and 500 mL of V_T expired. The operator never actually "sees" the correction being made. It is important to recognize that ventilators perform this function in different ways. Therefore the clinician should understand how this function operates for the ventilator being used.

BOX 6.3 Tidal Volume (V_T) Settings

More than 50 years ago, Radford conducted an extensive study to determine normal V_T and rates in human subjects.[8] Radford's findings influenced early recommendations on setting tidal volumes during mechanical ventilation.[9,10] V_Ts derived from Radford's nomogram are low (range, 5–7 mL/kg). For example, a 190-lb, 6-ft man breathing at a rate of 10 breaths/min would have a V_T setting of 600 mL (7.4 mL/kg ideal body weight [IBW]) based on Radford's nomogram.

Early studies in anesthesia, however, showed that using low V_T very rapidly resulted in atelectasis, particularly in the lung bases. An often-cited study by Bendixon and colleagues, published in 1964, further demonstrated that a sustained high-pressure inspiration or "sigh" breath could help reverse atelectasis caused by breathing low V_T.[11] Interestingly, the actual V_T rates were not reported in this study. The study defined a sigh breath as a sustained high-pressure breath, not just as a single breath with a large V_T.

Beginning in the 1970s and continuing until the 1990s it was common practice for clinicians to use high V_T settings (e.g., 10–15 mL/kg of IBW) for all patients. This practice may have resulted from the fear that using a low V_T would cause atelectasis. Unfortunately, clinicians at that time were unaware of the potential of lung injury and were more concerned with achieving an appropriate V_T and maintaining acceptable arterial carbon dioxide (P_aCO_2) and arterial oxygen (P_aO_2) values. Their focus, although intended for the good of the patient, was nevertheless wrong.

Preliminary laboratory studies conducted in the 1990s, however, showed that high volumes along with high pressures could cause significant damage to lung tissue (see Chapter 17). In 2000, a landmark multicenter clinical trial conducted involving more than 800 patients with acute lung injury and acute respiratory distress syndrome found conclusive evidence that using a V_T setting of 6 mL/kg based on the predicted IBW had a lower mortality rate for this patient population than a V_T of 12 mL/kg IBW.[7] A number of more recent clinical studies have been conducted to better define the most effective lung protective ventilatory strategies to use during mechanical ventilation. These clinical studies have corroborated previous findings and shown that there are significant benefits associated with using lower a V_T.[3-6]

Regardless of the method used for selecting the V_T for a patient, it is important for clinicians to be aware of the following four risks during the setup of V_T:

1. Overdistention of lung tissue
2. Repeated opening and closing (recruitment/derecruitment) of alveoli
3. Atelectasis formation
4. Inadequate V_T setting

Case Study 6.2

Minute Ventilation ($\dot{V}_E$), Tidal Volume (V_T), and Respiratory Rate

A 6-ft (72-in)-tall man weighs 190 lb and has a normal metabolic rate, temperature, and acid–base status. What is his body surface area and ideal body weight? What $\dot{V}_E$, V_T, and rate would be appropriate for this patient?

If a ventilator without this capability is being used, calculation of C_T can be determined during initial setup by doing the following procedure before connecting the patient to the ventilator:

1. Confirm there are no leaks in the circuit.
2. Set a low V_T (100–200 mL), set PEEP at 0 cm H_2O, and set inspiratory pause at 2 seconds.
3. Place the high-pressure limit on the highest possible setting (e.g., 120 cm H_2O) so that the breath does not pressure cycle.
4. Manually trigger the ventilator into inspiration while occluding the Y-connector.
5. Record the static or plateau pressure (P_{plat}).
6. Measure the volume at the exhalation valve using a respirometer.
7. Calculate C_T by dividing measured volume by measured static pressure.

Box 6.4 provides a practice problem for calculating volume lost to C_T.

Mechanical Dead Space Considerations

Another consideration when setting the V_T is the effects of mechanical dead space. **Mechanical dead space** (V_{Dmech}) is defined as the volume of gas rebreathed during ventilation. For example, to add flexibility to the patient-ventilator connection, clinicians sometimes add a 6-inch piece of corrugated tubing between the Y-connector and the tracheostomy tube connector. When the patient exhales, some of the exhaled gas will occupy the 6 inches of tubing. As the patient inhales during the next breath, the first part of the breath will contain end-expiratory gas from the previous breath, which has a lower O_2 level and a higher CO_2 level.

A number of devices can decrease or increase the amount of V_{Dmech} added to the breathing circuit. For example, the use of an endotracheal tube slightly reduces V_{Dmech} by about 1 mL/kg IBW because the tube bypasses the upper airway (mouth and nasal passages). In contrast, the addition of a Y-connector between the ventilator and patient may add about 75 mL of V_{Dmech}.

***Key Point* 6.2** When setting tidal volume (V_T) and rate, the goal is not to focus so much on the exact V_T and rate, but to focus on using settings that do not harm the patient. Maintaining plateau pressure lower than 30 cm H_2O is very important. In some cases it even may be necessary to let P_aCO_2 rise and pH fall outside the patient's normal values to avoid lung injury.[1]

BOX 6.4 Calculating Volume Lost to Tubing Compliance

A patient's estimated tidal volume (V_T) is 400 mL. Her peak pressure reading during inspiration is 30 cm H_2O and tubing compliance (C_T) is 2.9 mL/cm H_2O. What is the actual V_T delivery to the patient?

Volume lost = 2.9 mL/cm $H_2O \times$ 30 cm H_2O = 87 mL; actual volume received by the patient = 400 − 87 mL = 313 mL. To compensate, set V_T is increased to about 487 mL to deliver the desired 400 mL. As mentioned earlier, C_T is important when V_T settings are very low (<300 mL), such as when setting the V_T for infants and small children.

Interestingly, these two factors tend to balance each other. A heat-moisture exchanger (HME) inserted between the endotracheal tube and Y-connector adds V_{Dmech} to the circuit (20–90 mL). Fortunately, the low dead space volume associated with these devices (HME of 20 mL) is usually not of clinical significance for adult patients. (This is a small dead space volume in relation to an adult V_T and usually does not alter P_aCO_2. However, with a higher-volume HME [90 mL], P_aCO_2 may increase above previous values.)[13] The addition of mechanical dead space V_{Dmech} is a significant concern in patients on ventilation with lung protective ventilatory strategies (i.e., V_Ts of 4–6 mL/kg).

Relationship of Tidal Volume, Flow, Total Cycle Time, and Inspiratory-to-Expiratory Ratio

Each ventilator has specific settings to select for VC-CMV. As previously mentioned, the Medtronics PB 840 and 980 (Medtronics Minimally Invasive Therapies, Minneapolis, MN) allows the operator to set V_T, f, and flow, whereas the Maquet Servo-i allows the operator to set the rate and inspiratory time, or I/E ratio.

An understanding of the interrelation of inspiratory flow, inspiratory time (T_I), expiratory time, TCT, and I/E ratio will help the clinician provide effective ventilation to a patient regardless of the type of equipment being used. Box 6.5 includes the equations that describe a variety of these interrelations. Fortunately, most modern ventilators automatically perform these calculations and display them as measured and calculated values.

Calculating Total Cycle Time and Respiratory Rate

Some ventilators use T_I and T_E or TCT to determine the respiratory rate (or ventilator frequency). To determine these values, calculate the length of the respiratory cycle or the TCT (TCT = T_I + T_E) and determine the number of cycles that occur in 1 minute (see Box 6.5, I, II, and IV). For example, if the T_I is 2 seconds and the T_E is 4 seconds, then:

$$TCT = T_I + T_E = 2\ \text{seconds} + 4\ \text{seconds} = 6\ \text{seconds}$$

$$60\ \text{s}/TCT = f$$

$$60\ \text{s}/6\ \text{s} = 10\ \text{breaths/min}$$

Calculating Inspiratory-to-Expiratory Ratio

Some ventilators allow the clinician to set either a fixed T_I and rate or a fixed I/E.* For example, the Servo-i ventilator requires the respiratory therapist to set a T_I. If the rate is set at 10 breaths/min, the TCT is 6 seconds (60 s/[10 breaths] = 6 s/breath). If the T_I is set at 2 seconds, the expiratory time is 4 seconds (T_E will be TCT − T_I = 6 seconds − 2 seconds = 4 seconds). The resultant I/E ratio will therefore be 1:2 (T_I/T_E = 2 s/4 s = 2:4 or 1:2) (see Box 6.5, I through V).

The I/E ratio is typically expressed so that the T_I is equal to 1. For example, if the I/E ratio is 2:3, it is expressed as 1:1.5. Dividing the numerator and denominator by T_I reduces the expression to 1:X (see Box 6.5, V).

I/E ratios of 2:1 or 3:1 are called inverse I/E ratios. When I/E ratios are inversed (I greater than E), T_E takes on the value of 1. For example, if the T_I is 3 seconds and the T_E is 2 seconds, the I/E ratio is 3:2 or 1.5:1 (see Box 6.5, VI). (NOTE: In previous-generation

*Because ventilation software can be updated frequently, users should check their equipment updates to determine actual function.

BOX 6.5 Interrelation of Tidal Volume, Flow Rate, Inspiratory Time, Expiratory Time, Total Cycle Time, and Respiratory Rate

I. Total cycle time (TCT) equals inspiratory time (T_I) plus expiratory time:

$$TCT = T_I + T_E$$

II. Respiratory rate (f) equals 1 minute (60 seconds) divided by TCT.

$$f = \frac{1\text{min}}{TCT} = \frac{60\text{s}}{TCT(s)} = \text{breaths/min}$$

Calculate TCT from f.

$$TCT = 60\ \text{s}/f$$

III. Inspiratory-to-expiratory (I/E)ratio equals inspiratory time divided by expiratory time.

$$I/E = T_I/T_E$$

Remember: $TCT = T_I + T_E$ and $TCT - T_I = T_E$

IV. To calculate T_E from f and T_I:

$$f = 60\ \text{s}/TCT \text{ and } TCT = T_I + T_E$$
$$T_E = TCT - T_I$$

V. Reducing the I/E ratio to its simplest form:
Divide the numerator and denominator by T_I.

$$I/E = \frac{\frac{T_I}{T_I}}{\frac{T_E}{T_I}}$$

VI. Determine the I/E when inverse ratio ventilation is used:
I/E for inverse ventilation equals the division of both the numerator and the denominator by the expiratory time.

$$I/E = \frac{\frac{T_I}{T_E}}{\frac{T_E}{T_E}}$$

VII. Calculate T_I, T_E, and TCT from I/E and f.

$$TCT = T_I + T_E \text{ and } f = 60\ \text{s}/TCT$$
$$f = 60\ \text{s}/(T_I + T_E)$$
$$T_I + T_E = 60\ \text{s}/f$$

VIII. Calculate T_I from V_T and flow ($\dot{V}$)

$$T_I = V_T/V$$

IX. Calculate V_T from T_I and $\dot{V}$.

$$V_T = \dot{V} \times T_I$$

X. Calculate V from V_T and T_I.

$$\dot{V} = V_T/T_I$$

ventilators [e.g., Puritan Bennett 7200], the digital display of I/E was expressed as 1:X; thus inverse ratios will appear, e.g., as 1:0.5, rather than 2:1.)

Using inverse ratios can cause significant complications, such as increases in mean airway pressure (P_{aw}) and physiological dead space, decreases in venous return and cardiac output, and increased air trapping (auto-PEEP). For this reason, I/E ratios are usually set at 1:1.5 to 1:4 so that expiration is longer than inspiration, and the adverse effects of positive pressure are reduced. (NOTE: Inverse I/E ratios have been successfully used in some circumstances, such as to improve oxygenation in patients with ARDS.)

Inspiratory Time, Tidal Volume, and Flow

T_I can be determined if V_T and flow are known, and the flow pattern is a constant or square waveform. If V_T is 0.5 L and flow is 2 L/s, T_I equals 0.5 L/2 L/s, or 0.25 seconds. The flow control on adult ventilators is usually calibrated in liters per minute, so the value for flow needs to be converted to liters per second. For example, a flow of 30 L/min equals 30 L/60 s or 0.5 L/s.[†]

Conversely, V_T can be determined when T_I and flow are known and flow is constant: (V_T = flow × T_I). If T_I is 1 second and flow is 0.5 L/s, V_T = (1 second) × (0.5 L/s) = 0.5 L (see Box 6.5, VII and VIII).

Flow, Tidal Volume, and Inspiratory Time

Flow can be determined whether V_T and T_I are known. For example, if V_T is 500 mL and T_I is 1 second, the flow equals V_T/T_I, which is 500 mL/1 s, or 0.5 L/([1/60]th of a minute), or 30 L/min (multiply numerator and denominator by 60 to convert to minutes) (see Box 6.5, IX). These examples assume that flow is constant (Case Study 6.3 and Critical Care Concept 6.2).

Inspiratory Flow and Flow Patterns

During VC-CMV, the clinician may have the option to select a variety of ventilator flows and flow patterns. These selections are reviewed in this section.

Rate of Gas Flow

As previously discussed, the flow setting on a mechanical ventilator determines how fast the inspired gas will be delivered to the patient. During controlled mechanical ventilation (CMV), high flows shorten T_I and may result in higher peak pressures and poor gas distribution. Conversely, slower flows may reduce peak pressures, improve gas distribution, and increase P_{aw} at the expense of increasing T_I. Unfortunately, shorter T_E can lead to air trapping, and using a longer T_I may also cause cardiovascular side effects.[18] In reality, actual normal inspiratory times have never been measured, and much of clinical practice involved in setting appropriate T_I requires clinician observation of the patient's response to set values. These may require adjustments.

In general, the goal should be to use the shortest T_I possible. Achieving a short T_I usually is not difficult to attain in patients with normal lungs. As a beginning point, flow is normally set to deliver inspiration in about 1 second (range 0.8–1.2 seconds).[3,13] An I/E ratio of 1:2 or less (usually about 1:4) is also recommended. This can be achieved with an initial peak flow setting of about 60 L/min (range 40–80 L/min). It is important to remember that the flow must be set to meet a patient's inspiratory demand so that the spontaneously breathing patient is not trying to breathe in without the ventilator supplying adequate gas flow (see Fig. 5.4).[19]

When patient-triggered breaths are present during VC-CMV, the patient's respiratory rate may actually vary depending on flow and T_I setting. For example, if V_T is constant and the flow setting is increased, T_I will be shorter and the patient may begin to increase the rate at which he or she triggers the ventilator. Thus T_I can affect breath frequency when patient triggering is present.[20] The reason this occurs is not known at this time, but clinicians should be aware of this phenomenon.

A long T_I (requiring 3–4 time constants) has been shown to improve ventilation in nonhomogeneous lungs such as those seen in ARDS.[21] Fast flows (i.e., requiring fewer time constants to fill the lungs) may benefit patients with increased airway resistance (R_{aw}), as in COPD, providing longer T_E, which in turn will reduce or prevent the risk for air trapping (long T_E of 3–4 time constants). Tobin and colleagues reported that using flow rates up to 100 L/min can improve gas exchange in patients with COPD by providing a longer T_E.[22] It is important to recognize that flows that are set too high can result in uneven distribution of inspired air in the lung and also cause immediate and persistent tachypnea, in addition to increased peak inspiratory pressures[23] (Key Point 6.3).

Flow Patterns

Fig. 6.3 shows examples of flow patterns available on ICU ventilators. Selecting the most appropriate flow pattern and ventilator

> **Case Study 6.3**
>
> **Inspiratory/Expiratory Ratio (I/E) and Flow**
>
> You are asked to place a 63-year-old woman who is diagnosed with severe congestive heart failure on ventilation. She is 5-ft, 8-in tall and weighs 185 lb. She is orally intubated with a 7.5-mm endotracheal tube. Her arterial blood gases on a nonrebreathing mask are pH = 7.18, P_aCO_2 = 83 mm Hg, P_aO_2 = 98 mm Hg, HCO_3^- = 31 mEq/L. What recommendations would you make regarding her initial ventilator settings of V_T, f, I/E, and flow?

> **CRITICAL CARE CONCEPT 6.2**
>
> **Inspiratory Flow in a Time-Cycled Ventilator**
>
> A time-cycled ventilator is set with the following parameters: V_T = 500 mL (0.5 L), f = 12 breaths/min, and I/E = 1:4. If a constant flow waveform is used, what is the inspiratory gas flow?

> ***Key Point 6.3*** The clinician must carefully adjust the flow and flow pattern to suit the patient's ventilatory needs.

[†]Specifically, (30 L/1 min × 1 min/60 s) = (30 L/1 min × 1 min/60 s) = 0.5 L/s.

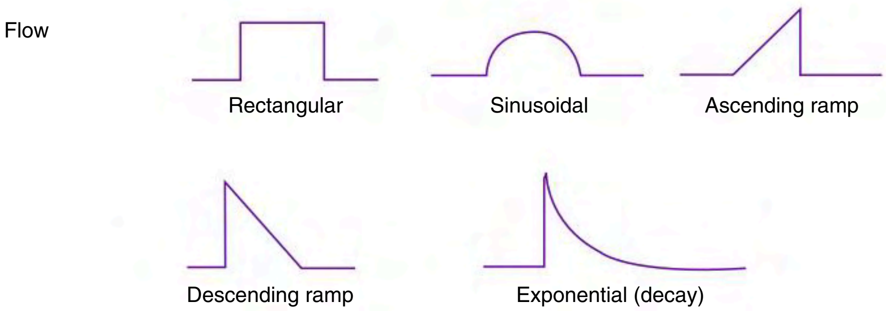


Fig. 6.3 Flow-time waveforms can take on a variety of forms. The most common are constant (square or rectangular) and descending ramp (decelerating ramp).

BOX 6.6 Tidal Volume (V_T), Rate, Inspiratory Time (T_I), and Flow on the LTV 1200

The CareFusion LTV 1200 ventilator has controls for V_T, rate, and a T_I setting. Flow is determined by the set V_T and T_I. (Flow $= V_T/T_I$.) Inspiratory flow is a descending ramp during volume-targeted mandatory breaths. The peak flow is determined by the ventilator so that V_T is delivered during the set T_I. Inspiration ends when flow decreases to 50% of peak or 10 L/min, whichever is highest.

Total cycle time (TCT) can be calculated using the following equation: TCT $= 60/f$. T_E becomes TCT minus T_I ($T_E = TCT - T_I$). Suppose, for example, that the inspiratory time is set at 1.0 seconds and the rate is set at 12. The TCT will equal 60/12 or 5 seconds. T_E equals 5 seconds $-$ 1 second, or 4 seconds, and the I/E is therefore 1:4.

rate depends on the patient's lung condition. For example, postoperative patients recovering from anesthesia may have modest flow demands, whereas a young adult with pneumonia and a strong hypoxemic drive would have a high flow demand. The most common flow patterns used clinically are the constant flow and descending (decelerating) flow waveforms.

Constant flow. Constant flow patterns are often used by clinicians because it is most familiar to them or it is the only flow pattern available on the ventilator in use. Constant flow patterns are also called rectangular and square waveforms. When initiating ventilation, a rectangular (constant) flow pattern is acceptable.[13] Generally a constant flow pattern provides the shortest T_I of all the available flow patterns with an equivalent peak flow rate setting.

Descending ramp. The amount of gas flow delivered at the beginning of the breath is probably the major determinant of patient effort and work of breathing (WOB). A descending (decelerating) flow waveform has a distinct advantage compared with other waveform patterns. With a descending pattern, flow is greatest at the beginning of inspiration, when patient flow demand is the highest. The descending waveform occurs naturally in pressure ventilation. Box 6.6 shows an example in which the ventilator automatically sets the flow at a descending ramp and calculates the flow rate based on V_T and T_I during VC-CMV.

Ascending ramp. The ascending ramp provides a progressive increase in flow. The ascending ramp is currently not used by most clinicians and is available only on a few older-generation ventilators. There are no compelling studies that support the use of the ascending flow ramp.[6]

Sine flow. The sine flow pattern produces a tapered flow at the end of the inspiratory phase. Although it has been suggested that this type of flow pattern may contribute to a more even distribution of gas in the lungs than the flow of the constant flow ventilator, it is not commonly used clinically, and additional clinical studies will be required to verify its efficacy.[24] P_{aw} and peak pressures are similar to those seen with the sine and square wave patterns, although peak pressures are higher with the sine wave than the square flow when airway resistance is increased, such as in acute asthma.[25]

Comparison of descending ramp and constant flow. Most clinical studies designed to investigate the effects of using various ventilator waveforms have compared the constant waveform with the descending (decelerating) ramp. As one changes from a constant to a descending ramp, peak pressure is lower and P_{aw} is higher.* Studies comparing the descending flow pattern with the constant flow pattern suggest that the descending flow pattern improves the distribution of gas in the lungs, reduces dead space, and increases oxygenation by increasing mean and plateau airway pressures.[3,13,21,25-27] It is important to remember that in situations in which plateau pressure (P_{plat}) is critical, changing to a descending ramp to reduce peak pressures may increase the P_{aw}.

Concerns about high peak inspiratory pressure and mean airway pressure. The clinician must decide when selecting a particular waveform whether P_{aw} is more important for the patient than are concerns of high peak inspiratory pressure (PIP). When R_{aw} and flows are high, peak pressures will be high if an ascending flow pattern is used. Much of this pressure is dissipated in overcoming the R_{aw} and may not reach the alveolar level.[25] Thus high peak pressures do not always increase the risk for damage to lung parenchyma. An example of a patient population in which this can occur involves patients with acute asthma experiencing severe bronchospasm, mucosal edema, and increased secretion production. It is important to recognize, however, that there is a risk that some of the high pressures may reach normal lung areas, which could be damaging in this group of patients.[14]

*T_I will also be longer unless the ventilator is time cycled.

TABLE 6.1 Example of a Time-Cycled Ventilator[a]

Flow Waveform	Peak Flow Value (L/min)	Percentage of Set Flow for Constant Flow Pattern
Constant	60	100
Descending ramp	78	133
Sine	94.2	157
Modified sine	78.9	133

[a]Using V_T = 1000 mL (1.0 L); T_I = 1 second.

Effects of changing flow pattern in time-cycled versus volume-cycled ventilators. For time-cycled machines (e.g., Hamilton Galileo G5 [Hamilton Medical, Switzerland], Servo-i, Dräger Evita Infinity V500 [Dräger, Inc., Telford, PA]), changing from constant flow to another flow pattern does not change the I/E ratio. However, it does change the peak flow required to deliver the volume in the time provided (T_I). With any ventilator, changing from one waveform to another can vary the peak flow delivery and distribution of flow. Table 6.1 shows an example of how peak flow varies between four different flow patterns in a time-cycled situation.

In volume-cycled ventilators, changing from a constant flow to a descending flow pattern does not change the peak flow selected. It does, however, change the T_I and I/E ratio (Fig. 6.4). Consequently, the clinician may have to change the peak flow setting to accomplish volume delivery at a better I/E ratio. Table 6.2 shows an example of what occurs with the Medtronics PB 840 ventilator, which cycles based on volume (i.e., flow/time).

With the Maquet Servo-i ventilator, there is no flow waveform selector or peak flow control. During VC-CMV the machine provides a constant (rectangular) waveform. The amount of flow delivered is based on the V_T selected and T_I. The flow also varies with patient demand regardless of the method of ventilation. When the patient's inspiratory needs exceed the flow provided and pressure begins to drop by 2 cm H_2O below the measured airway pressure, the ventilator provides additional flow to the patient. Therefore volume delivery is not the set value, but rather it is influenced by the patient's flow demands. The volume set by the operator becomes the minimum volume. Most current ICU ventilators also provide this feature.

In summary, clinicians must understand how ventilator function is affected when selecting peak flow and waveform pattern. It is reasonable to suggest that there is not one set prescribed pattern or rate of flow that is best for all patients. Rather, it is important to match the pattern and rate of gas flow to the patient's needs. Box 6.7 summarizes basic findings in flow waveform studies. The following points can provide some guidance when selecting a flow waveform:

- Flow pattern selection is not a critical issue in ventilation in patients with normal lung function; descending and constant flow patterns are effective.
- A descending flow pattern may be beneficial for patients with hypoxemia and low lung compliance (C_L) by maintaining low peak pressures and high P_{aw} and improving gas distribution.[27,28]

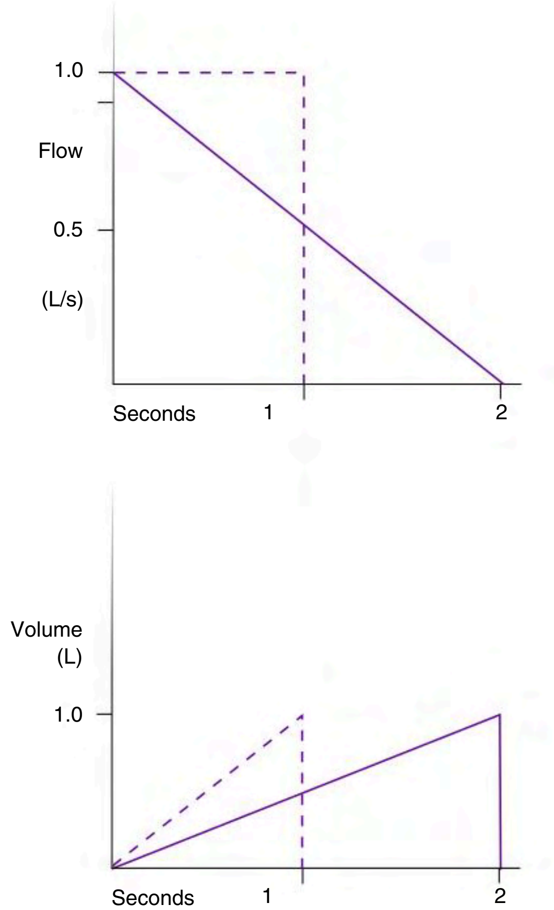


Fig. 6.4 Graphs showing flow and volume delivery during volume-controlled ventilation with a peak flow set at 1 L/s (60 L/min). Changing the flow waveform from constant *(dashed line)* to descending ramp *(solid line)* provides the same volume but increases inspiratory time. (NOTE: Ventilators do not usually allow flow to decrease to zero. It is used here only to simplify the concept.)

TABLE 6.2 Example of a Volume (Flow—Time) Cycled Ventilator: The Medtronics Puritan Bennett 980 Ventilator

Flow Waveform Selected	Determination of Inspiratory Time (T_I Flow Set at 60 L/min)
Constant	T_I = (V_T)/flow
Descending ramp	Begins at 60 L/min; ends at 5 L/min
If flow is set too low or volume too high to be achieved, and the inspiratory-to-expiratory (I/E) ratio becomes greater than 1:1, the ventilator will give a visual warning and a message to "decrease the rate." The alarm becomes audible when the I/E is 3:1 (displayed as "1:0.3").	

V_T is constant. Peak flow does not exceed its set value.

BOX 6.7 Summary of Findings From Flow Waveform Studies

When initiating mechanical ventilation, most clinicians will choose to start with a descending (decelerating) ramp or a constant (rectangular) waveform for the following reasons:

- The mean airway pressure is higher with descending flow waveforms.
- The peak inspiratory pressure is higher with ascending flow waveforms and lower with descending flow waveforms.
- Descending waveforms improve gas distribution.
- Descending waveforms improve arterial oxygenation.

- A constant (rectangular) flow pattern produces a lower P_{aw} compared with a descending flow pattern and may be useful in ventilation in patients with severe hypotension and cardiac instability.[25]
- For patients with high R_{aw}, a descending pattern is more likely to deliver a set V_T at a lower pressure and provide for better distribution of air through the lung than a constant flow.[26-29]

SETTING THE MINUTE VENTILATION: SPECIAL CONSIDERATIONS

Practical considerations for setting a desired $\dot{V}_E$ have been discussed, but a few precautions should be considered before implementing these procedures. Although an optimum inspiratory flow and flow pattern may exist for every patient, there is no prescribed formula that can be applied to ensure the best possible results for all patients.[29,30] The variability in results related to setting these parameters is influenced by the condition of the patient's lungs and conductive airways and the patient's changing metabolic needs.

Consider a situation in which a patient's P_aO_2 falls, his P_aCO_2 rises, and his $\dot{V}_E$ increases. Several reasons could account for this type of situation, including the presence of auto-PEEP, poor ventilation/perfusion ($\dot{V}/\dot{Q}$) matching in the nonhomogeneous lung, and changes in venous return. Resolution of this situation may require changing gas flow and/or pattern, V_T, f, or I/E ratio. Using a mode of ventilation that allows some spontaneous breathing may also benefit the patient in this type of situation by allowing the spontaneously breathing patient to have some control over ventilation. There is no "bottom line" and no easy prescription. Management of the patient on mechanical ventilation is both an art and a science requiring the use of sound judgment.

Key Point 6.4 Plateau pressure can be accurately measured only if the patient is not actively breathing so that a stable pressure reading can be obtained.

INSPIRATORY PAUSE DURING VOLUME VENTILATION

The inspiratory pause or inflation hold (also called *end-inspiratory pause*) is a maneuver that can be performed by preventing the expiratory valve from opening for a short time at the end of inspiration, when the inspiratory valve is also closed. Most ICU ventilators have an inspiratory pause button or control. As mentioned in Chapter 1, the inspiratory pause maneuver is used to obtain measurements of plateau pressure (P_{plat}), which allows estimation of the alveolar pressure (P_{alv}) for the calculation of static compliance (Key Point 6.4).

Inspiratory pauses can also be selected for use with each mandatory breath to improve the distribution of air throughout the lungs regardless of the type of flow pattern used. It has been proposed that an inspiratory pause provides a longer inspiratory time, which in turn provides improved $\dot{V}/\dot{Q}$ matching and reduces dead space to tidal volume ratios (V_D/V_T ratios).[31,32] Inspiratory pause with each breath is not commonly used in clinical practice because it may significantly increase P_{aw} and the risk of impeding venous return and cardiac output. This is particularly true when treating patients whose condition is hemodynamically unstable (i.e., hypovolemic or hypotensive).[33]

Clinical Scenario: Ventilatory Support Post Myocardial Infarction

After admission to a hospital for myocardial infarction, a 55-year-old man is intubated and placed on ventilatory support. The patient's IBW is 70 kg and BSA is 1.5 m^2. The physician requests the VC-CMV mode. What $\dot{V}_E$, V_T, rate, flow, and flow pattern would be appropriate? A $\dot{V}_E$ of $4 \times 1.5 = 6.0$ L/min is an appropriate starting point. A V_T of 6 mL/kg would equal 420 mL for this patient. A minimum rate setting would be the $\dot{V}_E$ divided by the V_T or 6.0 L/0.42 L = 14.2 or 14 breaths/min. Because no changes in body metabolism such as a fever are evident, we assume these initial settings would be appropriate. No chronic pulmonary disease was mentioned, so we assume a moderate rate setting would be adequate. A flow of 40 L/min or 40 L/60 s or 0.67 L/s using a descending flow pattern would provide sufficient time for exhalation to occur. What is the T_I in this case? Because the V_T is 0.42 L, $T_I = V_T$/flow or $T_I = 0.42$ L/(0.67 L/s) = 0.63 second. The TCT is 60 s/(14 breaths/min) = 4.3 s/breath. T_E = TCT − T_I = 4.3 seconds − 0.63 second = 3.67 seconds. T_I is 0.63 second and T_E is 3.67 seconds, which is an adequate time for exhalation. Note that this is a fairly short T_I for an adult patient and may need to be increased.

Clinical Scenario: Ventilator Required?

A 45-year-old man receiving VC-CMV ventilation has a V_T of 800 mL and a set rate of 8 breaths/min. The actual total rate is 15 breaths/min because the patient is triggering additional breaths. Flow is set at 40 L/min using a constant flow waveform. Inspiratory pressure actually stays in the negative range (below baseline) during most of inspiration and finally peaks at 60 cm H_2O. The respiratory therapist is unable to obtain an inspiratory pause maneuver to determine P_{plat} because the patient is actively breathing.

Using the actual rate (15 breaths/min), determine T_I. TCT is 60 s/(15 breaths/min) = 4 s/breath. Flow is 40 L/min or 40 L/60 s = 0.67 L/s. $T_I = V_T$/flow or 0.8 L/(0.67 L/s) = 1.19 second. $T_E = TCT - T_I$ = 4 seconds − 1.19 second = 2.81 seconds. The I/E ratio is about 1:3, which should be an adequate amount of time for exhalation.

The C_T is 3 mL/cm H_2O and was determined when the ventilator was set up. How much volume is lost to tubing compliance? The peak pressure is 60 cm H_2O, so the lost volume is $C_T \times$ PIP = 3 mL/cm $H_2O \times$ 60 cm H_2O = 180 mL. Of the 800 mL V_T, 180 mL is lost in the circuit and is not delivered to the patient. What is the volume of gas delivered to the patient? 800 mL − 180 = 620 mL is delivered to the patient. How can the respiratory therapist correct for this loss of volume delivery to the patient? The respiratory therapist can either set the ventilator to automatically compensate for C_T, if it has that feature, or manually adjust the set volume. For example, adding about 200 mL to the set volume would help compensate this loss. It is important to remember that making these adjustments will increase the set V_T and also increase the patient's PIP.

In this example, the patient's problem occurs during inspiration. Why does the pressure waveform demonstrate a negative deflection during inspiration? Perhaps the flow is not adequate to meet the patient's demand. The respiratory therapist readjusted the flow to 100 L/min, but this change did not improve the situation, and the therapist reports that occasionally "he seems to trigger two tidal volumes during one inspiratory effort." What would you suggest?

There are several possible solutions. Switching to PC-CMV and adjusting the pressure to achieve the original V_T or even a slightly higher volume might be appropriate. Pressure ventilation modes are more likely to deliver a flow that meets the patient demands because the ventilator can provide all the flow needed to maintain the set pressure. Another option would be to place the patient on continuous positive airway pressure (CPAP) for a trial of spontaneous breathing and see what flow and volume the patient can achieve on his own. (This patient actually achieved a spontaneous volume of 1.2 L.) Other possible solutions are to increase the ventilator rate or V_T to meet patient need or switch to pressure support ventilation (PSV) and possibly VC-IMV or pressure-controlled intermittent mandatory ventilation (PC-IMV) and use PSV for spontaneous breaths. The original ventilator settings did not provide adequate flow or volume to meet the patient ventilatory demands. (NOTE: With spontaneous V_T this high, one wonders if the patient needs the ventilator.)

DETERMINING INITIAL VENTILATOR SETTINGS DURING PRESSURE VENTILATION

As previously defined, pressure-targeted ventilation provides a set pressure to the patient during breath delivery, whereas V_T can vary from breath to breath (see Chapter 5). There are several methods to provide a pressure breath that should be considered. This discussion begins with baseline pressure and then includes PSV, pressure-controlled ventilation, bilevel positive airway pressure, and dual-control modes (pressure-regulated volume control [PRVC] and volume support [VS]). Each of these modes has specific controls that are set by the operator (Table 6.3). Less frequently used pressure-targeted modes, such as pressure control inverse ratio ventilation, are discussed in Chapter 13, and airway pressure release ventilation is reviewed in Chapter 23.

Volume-targeted ventilation has the advantage of guaranteeing volume delivery; however, it has the disadvantage of increasing PIP as C_L decreases or R_{aw} increases. **Overinflation** is also a risk. Pressure-targeted breaths have the advantages of providing flow on demand and potentially limiting pressures to avoid overinflation. With pressure-targeted breath delivery, rapid initial flows may cause frictional forces (shearing) between adjacent alveoli with differing lung inflation characteristics (time constants). In addition, V_T varies as lung characteristics change. Currently, there are no definitive studies that have demonstrated a clear advantage of one method over the other.[34]

TABLE 6.3 Required Setting Selection and Variables During Pressure Ventilation

Name	Trigger	Cycle
Pressure support ventilation	Patient	Flow
Pressure-controlled continuous mandatory ventilation	Time/patient	Time
Bilevel positive airway pressure	Time/patient	Flow
Pressure-regulated volume control	Time/patient	Time
Volume support	Patient	Flow

SETTING BASELINE PRESSURE: PHYSIOLOGICAL POSITIVE END-EXPIRATORY PRESSURE

Functional residual capacity (FRC) frequently decreases when a patient is intubated or placed in a supine position.[35,36] In most situations it is appropriate to use minimum levels of PEEP (3–5 cm H_2O) to help preserve a patient's normal FRC.* Because only a modest amount of pressure is applied with this minimum level of PEEP, it is not considered a problem in terms of causing

*Sometimes called *compensating PEEP.*

complications. In fact, not using a low level of PEEP may result in atelectasis. Use of low levels of PEEP may also be beneficial in patients with COPD who would normally pursed-lip breathe but cannot do so with an artificial airway in place (Box 6.8).

Determining Tidal Volume Delivery in Pressure Ventilation

In any pressure-targeted breath the difference in pressure (ΔP) between baseline (PEEP + auto-PEEP) and PIP determines what is set to establish V_T delivery. Volume delivery will also be affected by the patient's lung characteristics and any patient effort present.

There are two ways to set the pressure in pressure-targeted breaths to provide the desired V_T. One way is to deliver a volume-targeted breath to the patient at the desired V_T and measure plateau and baseline pressures. Using the same baseline pressure, the breath can be switched to pressure-targeted breath using a set pressure equal to the P_{plat}. The resulting V_T will be approximately equal to the V_T during the volume breath, as long

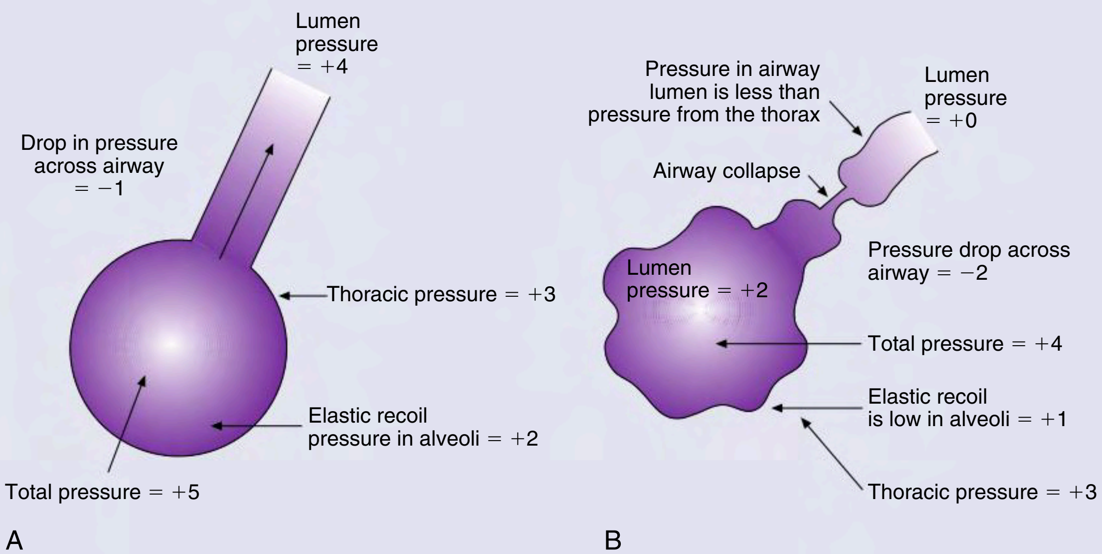
BOX 6.8 Factors Affecting Expiratory Gas Flow

During normal expiration, gas flow from a lung unit (acinus) is the result of the elastic recoil of the alveolus (+2 cm H_2O) plus the force (pressure) from recoil of the chest wall (+3 cm H_2O) acting on the alveolar gas volume to produce a pressure gradient between the alveoli and the mouth (see figure below, part A). Notice that the total pressure (+5 cm H_2O) at the alveolar level is greater than that at the mouth, so the air moves out of the lung.

As the exhaled air moves across the conductive airways, some of the driving pressure is lost to airway resistance, R_{aw} (−1 cm H_2O). In normal lungs, this pressure loss is small because the intrathoracic forces exert pressure on both the alveoli and the conductive airway. In a patient with normal airways, the resilience of the airway combined with the gas pressure in the airway lumen prevents airway collapse in most regions of the lung during most phases of the respiratory cycle. The pressure in the alveolus minus the pressure drop across the airway equals the pressure in the airway lumen (+5 cm H_2O − 1 cm H_2O = +4 cm H_2O intraluminal).*

The pressure gradient changes in patients with weakened airways caused by loss of supportive connective tissue. (Loss of lung elasticity occurs with aging and in patients with pulmonary emphysema.) Part B of the figure shows an example of an alveolus with lower than normal lung elastic recoil forces (+1 cm H_2O). The intrathoracic forces (+3 cm H_2O) will not be affected, but the total force providing gas flow out of the lungs is lower (+4 cm H_2O). When gas flows through an airway where R_{aw} is increased, the pressure drop is greater than in normal airways (−2 cm H_2O). As a result, the intraluminal pressure is lower (+4 cm H_2O − 2 cm H_2O = +2 cm H_2O). Because chest wall elastic recoil pressures are greater than intraluminal pressures in the small airways weakened by loss of elastic recoil forces, these small airways tend to collapse from dynamic compression. Pursed-lip breathing is an effective maneuver that helps prevent airway collapse by resisting expiration, thus raising pressures across the entire length of the airway.

For patients with chronic obstructive pulmonary disease (COPD), it is not possible to pursed-lip breathe with an artificial airway in place and air trapping (auto-positive end-expiratory pressure [auto-PEEP]) is common. Early-generation ventilators offered an expiratory retard control, which slowed the rate of exhalation by applying resistance to the expired gas flow. Older expiratory and PEEP valves actually increased resistance to exhalation whether resistance was desired or not. Newer microprocessor ventilators do not provide an expiratory retard option, and resistance through current expiratory valves is very low. Some practitioners consider that using low levels of PEEP (≤5 cm H_2O) offers a means to provide a similar effect.



(A) Alveolar, thoracic, and airway dynamics during exhalation in a patient with normal lungs (units in centimeters H_2O pressure). (B) Alveolar, thoracic, and airway dynamics during exhalation in a patient with COPD (units in centimeters H_2O pressure).

*The numerical values used here are for the sake of simplicity and are only approximations of actual values.

Case Study 6.4

Tidal Volume (TV) During Pressure Control Continuous Mandatory Ventilation (PC-CMV)

A patient is set on 12 cm H_2O of pressure during PC-CMV. If the measured V_T is 350 mL and the desired V_T is 550 mL, how would you adjust the pressure to achieve the desired V_T?

as inspiratory time is set appropriately. Then the pressure can be adjusted as needed to obtain the desired volume delivery. The V_T should then be continually monitored.

A second method to initiate pressure ventilation is to start at a low pressure (10–15 cm H_2O) and check the V_T before readjusting the pressure to attain the desired volume. (Box 5.4 includes a list of factors that affect volume delivery during pressure-targeted breaths.) Case Study 6.4 offers an exercise to illustrate this concept.

Initial Settings for Pressure Support Ventilation

PSV is typically initiated after the patient has been on full ventilatory support and is being changed to partial support to begin the process of discontinuing ventilation. PSV is used to support spontaneous breaths in a patient with an artificial airway when IMV or spontaneous/CPAP modes are used. The pressure is set at a level sufficient to prevent respiratory muscle fatigue associated with an increased inspiratory workload.

Some clinicians recommend calculating the level of pressure support based on an estimation of total ventilatory system resistance determined while the patient is receiving VC-CMV. The resistance of the patient and the ventilator circuit during VC-CMV with constant flow can be estimated with the equation $R_{aw} = (PIP - P_{plat})/\text{flow}$.[36-39] It is probably easier and effective to set the initial PSV level to equal the transairway pressure ($PIP - P_{plat}$) after establishing these values with VC-CMV. The level of PSV can be adjusted once it has been initiated to an adequate level. Sometimes simply asking the patient if he or she feels it is easy to breathe and if he or she is getting enough air can help when adjusting initial PSV. (NOTE: Another way to determine whether an adequate amount of pressure support is being provided involves observing the patient's use of the accessory respiratory muscles [e.g., sternocleidomastoid muscle] during inspiration. Increased use of the accessory muscles of inspiration may indicate that the level of PSV is inadequate.)

The goal of adjusting PSV is threefold:

1. To help increase V_T (4–8 mL/kg)
2. To decrease respiratory rate (to fewer than 30 breaths/min)
3. To decrease the WOB associated with breathing through an artificial airway

For patients with lung disease, levels of 8 to 14 cm H_2O are typically used to compensate for additional work associated with breathing through a tube and ventilator system. For patients without lung disease, about 5 cm H_2O should be adequate to compensate for the additional WOB.

When patients, particularly infants, are receiving CPAP through a ventilator, it is recommended that pressure support is added if a high level of CPAP (10 cm H_2O) is being used. CPAP by itself may increase WOB, and adding pressure support reduces this workload.[40]

As previously discussed in this chapter, V_T selection varies depending on the patient's lung condition. Low-volume and high-frequency alarms must be set appropriately because a number of factors can change the V_T and $\dot{V}_E$. If a backup ventilation mode is available on the ventilator, it is also appropriate to set the backup ventilation parameters for the patient, particularly if PSV is being used by itself.

When patients with COPD are placed on ventilation with PSV, it may be prudent to use graphic displays of pressure and flow versus time to monitor their status. These patients often have active short inspirations. In addition, if the patient begins to exhale actively during flow delivery from the ventilator, the flow may not drop to the necessary cycling value. Consequently, the ventilator breath may not end as normally expected, resulting in a sudden rise in the pressure curve at the end of the breath[41] (Fig. 6.5). The breath may actually pressure cycle. This situation can also occur in other patients when a low-flow criterion for ending inspiration is used. This can also induce expiratory muscle activity.[42] The problem can be avoided by using a ventilator with adjustable flow-cycling characteristics for patients demonstrating expiratory muscle activity. A cycle criterion of 40% of peak flow is an appropriate starting point for a patient with COPD. (NOTE: Using a low-flow cycling value [10%] may be appropriate for patients with restrictive disorders [Case Study 6.5].)

Initial Settings for Pressure Control Ventilation

Rate, inspiratory time, and I/E ratio are set in PC-CMV as they are with VC-CMV. The pressure gradient (PIP − PEEP, including auto-PEEP) is adjusted to establish volume delivery on the basis of patient lung characteristics and effort. Initial pressure is set at the P_{plat} value determined during VC-CMV and must be adjusted as needed to achieve V_T. If P_{plat} is not available, the peak pressure from VC-CMV minus 5 cm H_2O (PIP − 5 cm H_2O) can be used as a starting point.[43,44]

If volume readings are not available, an initial pressure of 10 to 15 cm H_2O with simultaneous volume measurement and

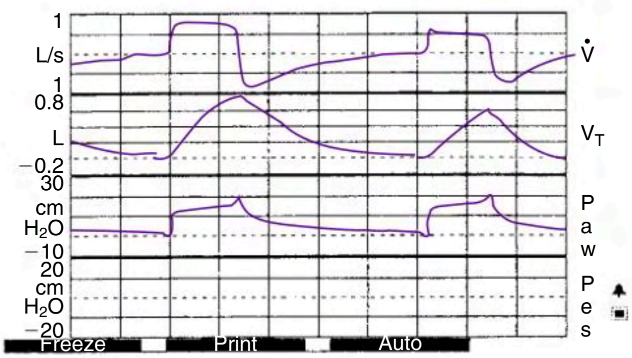


Fig. 6.5 Pressure and flow waveforms depicting a PC-CMV with pressure-supported breath. Note that the inspiratory flow does not descend to the 5 L/min terminal flow. Pressure rises slightly at the end of inspiration, showing an active exhalation by the patient before the flow cycle criterion is met. V_T, tidal volume. (From Campbell RS, Branson RD: Ventilatory support for the 90s: pressure support ventilation, *Respir Care* 38:526–537, 1993.)

Case Study 6.5

Inspiratory Flow Termination in Pressure Support Ventilation (PSV)

Problem 1

During PSV, a patient's peak flow is 50 L/min. At what flow level will inspiration end if the ventilator has a 25% flow cycle criterion?

Problem 2

A patient on PSV has an endotracheal tube cuff that is not inflated, preventing the ventilator from reaching the flow cycle criterion to end inspiration. What will terminate inspiration?

Problem 3

At the end of inspiration, a patient on PSV actively exhales before the ventilator detects the drop in flow required to cycle the breath. How will this affect the pressure/time waveform of the ventilator?

adjustment is appropriate. The pressure limit must be set because in some ventilators, pressure can be higher than the set pressure control level if the patient actively coughs. Low V_T and high f alarms are also necessary.

An important advantage of PC-CMV is that P_{alv} usually will not exceed the applied pressure. Setting a PIP of less than 30 cm H_2O can therefore help avoid alveolar overinflation. Because it is not possible to measure P_{alv} in all situations, PIP is maintained less than this set pressure. The patient's P_{alv} can be estimated by observing the flow curve. If the flow drops to zero before inspiration ends, the applied pressure is reaching the alveolar level by the end of inspiration (see Fig. 5.2). If inspiration ends before the flow reaches zero, P_{alv} is less than applied pressure but is not measurable. In this case, T_I may need to be adjusted (increased) depending on patient need and V_T delivery.

Normally PC-CMV provides a descending ramp waveform. As with PSV, current-generation ventilators (e.g., the CareFusion AVEA) are able to adjust the inspiratory rise time, which is the amount of the T_I required for the ventilator to reach the set pressure at the beginning of inspiration. The practitioner can adjust the rise to meet patient needs as with PSV (Fig. 5.9). It is advisable to use graphic monitoring to help make adjustments in pressure, T_I, and flow taper. If T_I is too long and the patient starts to actively exhale, a slight rise will occur at the end of the breath on the pressure curve.

Compared with similar settings on VC-CMV, PC-CMV has been shown to improve oxygenation and gas exchange, increase P_{aw}, and facilitate lung healing. PC-CMV also reduces the PIP, amount of applied PEEP, V_E, respiratory work, need for sedation, and duration of mechanical ventilation.[44-48] Pressure-targeted ventilation is safe and well tolerated as an initial mode of ventilation in patients with acute hypoxemic respiratory failure and may result in greater patient comfort.[43,48]

Initial Settings for Bilevel Positive Airway Pressure Ventilation

Bilevel positive airway pressure (or BiPAP) can be used for intubated patients or nonintubated patients, although it is most often used as noninvasive positive pressure ventilation (NIV). Initial settings include an inspiratory positive airway pressure (IPAP) of about 5 to 10 cm H_2O. The level of IPAP is increased in increments of 3 to 5 cm H_2O until a rate of 25 breaths/min or lower is achieved and the V_T is 4 to 8 mL/kg or more, depending on the patient's pathological processes. Expiratory positive airway pressure (EPAP) or PEEP is initiated at 2 to 5 cm H_2O and increased in increments of 3 to 5 cm H_2O. The initial F_{IO_2} is set to ensure adequate oxygenation. It is important to recognize that initiating NIV may require a considerable amount of time to achieve patient compliance.

For patients with COPD experiencing air trapping (auto-PEEP), EPAP is typically set at 80% to 90% of the level of auto-PEEP, which is usually about 3 to 10 cm H_2O. Observing the patient's use of accessory muscles (e.g., sternocleidomastoid muscles) during inspiration can assist in the titration of EPAP when auto-PEEP is present. For patients with hypoxemic respiratory failure, a PEEP/CPAP level greater than 5 cm H_2O is often required. (NOTE: The application of PEEP to help a patient trigger the ventilator is also used in other modes of ventilation besides NIV.) If no improvement is seen after about 2 hours of treatment, this mode of ventilation is probably not benefiting the patient and a more aggressive intervention may be necessary. Additional information on noninvasive ventilation can be found in Chapter 19.

Initial Settings for Pressure Ventilation Modes With Volume Targeting

Pressure ventilation with volume targeting, which is also called adaptive pressure control (APC) ventilation, provides the benefits of pressure breaths along with targeting a set volume. The following is a brief description of the two modes in which volume is targeted for each breath: pressure-regulated volume control (PRVC) and volume control plus (VC+).

Initial Settings of Pressure-Regulated Volume Control

PRVC is a mode of ventilation that provides closed-loop pressure breaths and targets the pressure to achieve the set volume. PRVC is a pressure-limited, time-cycled mode that uses the set V_T as a feedback control.[49] PRVC was originally available only with the Servo 300 ventilator, but it has now been incorporated into a number of other ventilators. Table 6.4 lists various names used by ventilator manufacturers to describe PRVC on their respective devices.

With PRVC, the operator sets a V_T to be delivered that is appropriate for the patient. The baseline pressure and the maximum pressure limit are also set. The ventilator delivers one or more test breaths. For example, the Servo-i produces a test breath, which is a volume-targeted breath with an inspiratory pause. The test breaths allow the ventilator to calculate static compliance and R_{aw} of the patient and system to determine the pressure required to achieve the set V_T. The first pressure level delivered in PRVC

TABLE 6.4 Names for Pressure-Regulated Volume Control (PRVC) and Volume Support on Different Ventilators

Ventilator Name	PRVC Name
Hamilton G5	Adaptive pressure ventilation
CareFusion AVEA	PRVC
Dräger V500	Autoflow
Servo-i	PRVC
Medtronics 870 and 980	VC+
Ventilator Name	**VS Name**
Servo-i	VS
Dräger V500	SPN-CPAP/VS
Medtronics Puritan Bennett 840 and 980	VS

equals the plateau pressure measured during the test breath. The ventilator progressively adjusts the pressure level until the set V_T is achieved. The operator can evaluate volume and pressure graphics to ensure these parameters are set appropriately (see Fig. 5.10). (NOTE: The exact maximum level of pressure delivery may differ among ventilators, but the ventilator relies on the upper pressure limit to determine how high to go when increasing pressure delivery to deliver the set V_T.)

It is important to set the upper pressure limit for two reasons:

1. It provides the upper limit for the ventilator to use in adjusting the pressure breath. (Pressure will not exceed a fixed amount, usually 5 cm H_2O below the upper pressure limit.)
2. If the patient coughs or forcibly exhales during the inspiratory phase, the ventilator will not permit pressure to exceed the upper pressure limit.

Current-generation ventilators with floating exhalation valves can actually release pressure during a forceful cough. This helps maintain the inspiratory pressure without prematurely ending inspiration as a result of pressure cycling when circuit pressures reach the upper pressure limit.

The following example illustrates how the ventilator adjusts pressure during PRVC. Suppose that the tidal volume is set at 600 mL, the baseline pressure is +5 cm H_2O of PEEP, and an upper pressure limit of 35 cm H_2O is set. Imagine that the patient begins ventilation with the PRVC mode using a pressure of 20 cm H_2O to achieve the 600-mL volume target. Then suppose the patient suddenly develops a pneumothorax. This would reduce the patient's compliance, thus requiring a higher pressure to deliver the desired V_T of 600 mL. (The ventilator reaches 30 cm H_2O but is unable to deliver the 600 mL.) Circuit pressure is now within 5 cm H_2O of the upper pressure limit, and the ventilator's alarm will activate. This will be an audible alarm and perhaps a digital message that might say, "Pressure limited, please evaluate." The clinician must evaluate the patient and determine whether ventilator changes are required (Case Study 6.6).

Initial Settings of Volume Support

Volume support is a purely spontaneous mode (see Fig. 5.11). In addition to setting the ventilator sensitivity, the operator sets the V_T and upper pressure limit. The selection of V_T is based on the same criteria used in VC-CMV. The advantage of VS is that spontaneously breathing patients can establish their own respiratory rate and V_T. (NOTE: In volume support, the set V_T is the minimum V_T. A patient can obtain a higher V_T if desired.) As lung characteristics improve, less pressure is required from the ventilator to deliver the volume, which automatically reduces pressure delivery. At the same time, if the patient becomes apneic, volume support modes provide a "safety net," usually as a backup mode that can provide a set rate and volume. Table 6.4 lists various names used by ventilator manufacturers to describe the volume support mode on their respective devices.

Case Study 6.6

Pressure-Regulated Volume Control (PRVC)

A patient on PRVC has a set volume of 550 mL. The upper pressure limit is set to 30 cm H_2O. Initially, 19 cm H_2O is required to deliver the volume. The pressure is now at 13 cm H_2O. What should the therapist do in this situation?

SUMMARY

- The primary goal of VC-CMV is to achieve a $\dot{V}_E$ that matches the patient's metabolic needs and ensures adequate gas exchange.
- Initiation of VC-CMV requires several considerations, including $\dot{V}_E$ settings (V_T and f), inspiratory gas flow, flow waveform, I/E ratio, pressure limit, inflation hold (inspiratory pause), and inspiratory and expiratory pressure (PEEP).
- Settings for V_T and f should reflect a $\dot{V}_E$ that is derived from the initial calculation based on patient gender, BSA, and pathology.
- Regardless of the method used for selecting the V_T for a patient, it is important for clinicians to be aware of potential risks of causing lung injury, such as overdistention of lung tissue and atelectasis.
- The tubing compliance, or system compressibility, reflects the volume of gas compressed in the ventilator circuit during the inspiratory phase.
- A number of devices can decrease or increase the amount of V_{Dmech} added to the breathing circuit.
- An understanding of the interrelation between inspiratory flow, inspiratory time (T_I), expiratory time (T_E), TCT, and I/E ratio is necessary for the clinician to provide effective ventilation to a patient.
- During VC-CMV where patient-triggered breaths are present, the patient's respiratory rate may actually vary, depending on flow and T_I setting.
- The most common flow patterns used during mechanical ventilation are constant and descending ramp patterns.
- Clinicians must be familiar with how the ventilator functions when selecting peak flow and waveform pattern.
- A constant flow pattern generally provides the shortest T_I of all the available flow patterns with an equivalent peak flow rate setting. Descending flow pattern may improve the distribution