Modes of mechanical ventilation

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INTRODUCTION

Numerous decisions need to be made once it is determined that a patient requires mechanical ventilation, including the mode of mechanical ventilation. The mode refers to the method of inspiratory support. Its selection is generally based on clinician familiarity and institutional preferences since there is a paucity of evidence indicating that the mode affects clinical outcome.

Common modes of mechanical ventilation are described in this topic review (table 1). Other aspects of initiating mechanical ventilation are discussed separately. (See "Overview of initiating invasive mechanical ventilation in adults in the intensive care unit".)

VOLUME-LIMITED VENTILATION

Volume-limited ventilation (also called volume-controlled or volume-cycled ventilation) requires the clinician to set the peak flow rate, flow pattern, tidal volume, respiratory rate, positive end-expiratory pressure (applied PEEP, also known as extrinsic PEEP), and fraction of inspired oxygen (FiO_2). Inspiration ends once the inspiratory time set has elapsed.

The inspiratory time and inspiratory to expiratory (I:E) ratio are determined by the peak inspiratory flow rate. Increasing the peak inspiratory flow rate will decrease inspiratory time, increase expiratory time, and decrease the I:E ratio.

Airway pressures (peak, plateau, and mean) depend on both the ventilator settings and patient-related variables (eg, compliance, airway resistance). High airway pressures may be a consequence of large tidal volumes, a high peak flow, poor compliance (eg, acute respiratory distress syndrome, minimal sedation), or increased airway resistance (figure 1 and waveform 1).

Modes — Volume-limited ventilation can be delivered via several modes, including controlled mechanical ventilation (CMV), assist control (AC), intermittent mandatory ventilation (IMV), and synchronized intermittent mandatory ventilation (SIMV) (table 1).

CMV — During CMV, the minute ventilation is determined entirely by the set respiratory rate and tidal volume. The patient does not initiate additional minute ventilation above that set on the ventilator. This may be due to pharmacologic paralysis, heavy sedation, coma, or lack of incentive to increase the minute ventilation because the set minute ventilation meets or exceeds physiologic need. CMV does not require any patient work.

AC — During AC, the clinician determines the minimal minute ventilation by setting the respiratory rate and tidal volume. The patient can increase the minute ventilation by triggering additional breaths. Each patient-initiated breath receives the set tidal volume from the ventilator.

Consider the following example. If the clinician sets the respiratory rate to 20 breaths per minute and the tidal volume to 500 mL, the lowest possible minute ventilation is 10 L per minute (20 breaths per minute times 500 mL per breath). If the patient triggers an additional 5 breaths beyond the preset 20 breaths, the ventilator will deliver 500 mL for each additional breath and the minute ventilation will be 12.5 L per minute (25 breaths per minute times 500 mL per breath).

Pressure regulated volume control (PRVC) is a form of volume control ventilation where tidal volume is set and the applied airway pressure changes to attain the target tidal volume. The initial applied inspiratory pressure is determined by the change in pressure required by the previous breath to attain the tidal volume. In both pressure controlled ventilation and PRVC inspiratory flow is variable and changes with patient effort and lung mechanics. Variable flow may be more comfortable to the patient. For any given tidal volume and lung compliance plateau pressure will be the same with AC and PRVC.

IMV — IMV is similar to AC in two ways: the clinician determines the minimal minute ventilation (by setting the respiratory rate and tidal volume) and the patient is able to increase the minute ventilation. However, IMV differs from AC in the way that the minute ventilation is increased. Specifically, patients increase the minute ventilation by spontaneous breathing, rather than patient-initiated ventilator breaths.

Consider the following example. If the clinician sets the respiratory rate to 10 breaths per minute and the tidal volume to 500 mL per breath, the lowest possible minute ventilation is 5

L per minute (10 breaths per minute times 500 mL per breath). If the patient initiates an additional 5 breaths beyond the preset 10 breaths, the tidal volume for each additional breath will be whatever size the patient is able to generate and the minute ventilation will be some amount greater than 5 L per minute. The precise minute ventilation depends on the size of the tidal volume for each spontaneous breath.

SIMV — SIMV is a variation of IMV, in which the ventilator breaths are synchronized with patient inspiratory effort [1,2]. SIMV (or IMV) can be used to titrate the level of ventilatory support over a wide range (figure 2) [3]. This is an advantage unique to these modes. Ventilatory support can range from full support (set respiratory rate is high enough that the patient does not overbreathe) to no ventilatory support (set respiratory rate is zero).

The level of support may need to be modified if hemodynamic consequences of positive pressure ventilation develop. In one study, cardiac output, mean blood pressure, pulmonary capillary wedge pressure, and oxygen consumption were all better when the level of support provided by SIMV was less than 50 percent [4]. (See "Physiologic and pathophysiologic consequences of mechanical ventilation", section on 'Hemodynamics'.)

Comparisons — SIMV and AC are the most frequently used forms of volume-limited mechanical ventilation [5]. Possible advantages of SIMV compared to AC include better patient-ventilator synchrony, better preservation of respiratory muscle function, lower mean airway pressures, and greater control over the level of support [6]. In addition, auto-PEEP may be less likely with SIMV. In contrast, AC may be better suited for critically ill patients who require a constant tidal volume or full or near-maximal ventilatory support.

PRESSURE-LIMITED VENTILATION

Pressure-limited ventilation (also called pressure-cycled ventilation) requires the clinician to set the inspiratory pressure level, inspiratory to expiratory (I:E) ratio, respiratory rate, positive end-expiratory pressure (applied PEEP), and fraction of inspired oxygen (FiO_2) [7,8]. Inspiration ends after delivery of the set inspiratory pressure.

The tidal volume is variable during pressure-limited ventilation. It is related to inspiratory pressure level, compliance, airway resistance, and tubing resistance. Specifically, tidal volumes will be larger when the set inspiratory pressure level is high or there is good compliance, little airway resistance, or little resistance from the ventilator tubing.

In contrast, the peak airway pressure is constant during pressure-limited ventilation. It is equal to the sum of the set inspiratory pressure level and the applied PEEP. As an example, a patient with a set inspiratory pressure level of 20 cm H_2O and an applied PEEP of 10 cm H_2O will have a peak airway pressure of 30 cm H_2O.

Pressure-limited ventilation can be delivered using the same modes of ventilation that deliver volume-limited ventilation (table 1):

- During pressure-limited controlled mechanical ventilation (CMV; also called pressure control ventilation), the minute ventilation is determined entirely by the set respiratory rate and inspiratory pressure level. The patient does not initiate additional minute ventilation above that set on the ventilator.
- During pressure-limited assist control (AC), the set respiratory rate and inspiratory pressure level determine the minimum minute ventilation. The patient is able to increase the minute ventilation by triggering additional ventilator-assisted, pressure-limited breaths.
- During pressure-limited intermittent mandatory ventilation (IMV) or synchronized intermittent mandatory ventilation (SIMV), the set respiratory rate and inspiratory pressure level determine the minimum minute ventilation. The patient is able to increase the minute ventilation by initiating spontaneous breaths.

VOLUME-LIMITED VERSUS PRESSURE-LIMITED

Pressure-limited ventilation was compared to volume-limited ventilation in a randomized trial and several observational studies [9-11]:

- There were no statistically significant differences in mortality, oxygenation, or work of breathing
- Favoring pressure-limited ventilation, it was associated with lower peak airway pressures, a more homogeneous gas distribution (less regional alveolar overdistension), improved patient-ventilator synchrony, and earlier liberation from mechanical ventilation than volume-limited ventilation
- Favoring volume-limited ventilation, only it can guarantee a constant tidal volume, ensuring a minimum minute ventilation

Most studies comparing pressure-limited and volume-limited ventilation used a square wave (constant flow) pattern for both modes. When volume-limited mechanical ventilation with a ramp wave (decelerating flow) pattern was compared to pressure-limited ventilation, lower peak airway pressures were no longer an advantage of pressure-limited ventilation [12].

PRESSURE SUPPORT

Pressure support ventilation (PSV) is a flow-limited mode of ventilation that delivers inspiratory pressure until the inspiratory flow decreases to a predetermined percentage of its peak value. This is usually 25 percent (figure 3) [13].

For PSV, the clinician sets the pressure support level (inspiratory pressure level), applied PEEP, and FiO_2. The patient must trigger each breath because there is no set respiratory rate. The tidal volume, respiratory rate, and minute ventilation are dependent on multiple factors, including the ventilator settings and patient-related variables (eg, compliance, sedation). In general, a high pressure support level results in large tidal volumes and a low respiratory rate.

The work of breathing is inversely proportional to the pressure support level, provided that inspiratory flow is sufficient to meet patient demand [13,14]. In other words, increasing the level of pressure support decreases the work of breathing. The work of breathing is also inversely proportional to the inspiratory flow rate. Increasing the inspiratory flow rate shortens the time until the maximal airway pressures are achieved, which decreases the work of breathing [15].

Potential uses — PSV seems particularly well suited for weaning from mechanical ventilation because it tends to be a comfortable mode, giving the patient greater control over the inspiratory flow rate and respiratory rate. However, clinical studies have failed to show that PSV improves weaning. (See "Methods of weaning from mechanical ventilation", section on 'Choosing a weaning method'.)

PSV is frequently combined with synchronized intermittent mandatory ventilation (SIMV). The ventilator delivers the set respiratory rate using SIMV, but patient-initiated breaths beyond the set respiratory rate are delivered using PSV. The purpose of adding PSV for patient-initiated breaths is to overcome the resistance of the endotracheal tube and ventilator circuit. The necessary level of pressure support is unknown and generally estimated. Resistance of the endotracheal tube is related to the tube diameter and inspiratory flow rate [16]. With small endotracheal tubes (eg, <7 mm), a pressure support level ≥10 cm H_2O may be needed to overcome the resistance [17,18]. Levels of pressure support higher than that required to overcome resistance will augment tidal volume.

Disadvantages — PSV is poorly suited to provide full or near-full ventilatory support. The following characteristics of PSV are disadvantages in that setting:

- Each breath must be initiated by the patient. Central apnea may occur if the respiratory drive is depressed due to sedatives, critical illness, or hypocapnia due to excessive ventilation [19].
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An adequate minute ventilation cannot be guaranteed because tidal volume and respiratory rate are variable.

- Ventilator asynchrony can occur when PSV is employed for full ventilatory support, potentially prolonging the duration of mechanical ventilation [20,21].

- PSV is associated with poorer sleep than AC. Specifically, there is greater sleep fragmentation, less stage 1 and 2 non-rapid eye movement (NREM) sleep, more wakefulness during the first part of the night, and less stage 3 and 4 NREM sleep during the second part of the night [22].

- Relatively high levels of pressure support (eg, >20 cm H_2O) are required during full ventilatory support to prevent alveolar collapse (which can lead to cyclic atelectasis and ventilator-associated lung injury) and to attain a stable breathing pattern [23,24]. Such high levels of pressure support are not as comfortable as moderate levels (eg, 10 to 15 cm H_2O) [25]. (See "Ventilator-induced lung injury".)

While PSV is poorly suited to provide full or nearly full ventilatory support in general, it is a particularly poor choice for patients who also have increased airway resistance (eg, COPD or asthma exacerbation). Minute ventilation is more likely to be insufficient when airway resistance is high, which may be related to decreased airflow causing inspiration to be terminated after a smaller than optimal tidal volume has been delivered [26,27]. In addition, PSV does little to decrease auto-positive end-expiratory pressure (auto-PEEP, also known as intrinsic PEEP), which can increase patient work and worsen respiratory muscle fatigue [28]. Choosing a higher percentage of the peak inspiratory flow as the trigger to end inspiration may improve auto-PEEP slightly [29].

Tube compensation — Many ventilators can be set to a mode called automatic tube compensation. This mode is a type of PSV that applies a sufficient level of positive pressure to overcome the work of breathing imposed by the endotracheal tube, which can vary from breath to breath. Automatic tube compensation is often used for a spontaneous breathing trial. Patients who undergo a spontaneous breathing trial with automatic tube compensation are more likely to successfully tolerate their trial than those who receive continuous positive airway pressure alone [30]. In addition, many ventilators have the option of combining automatic tube compensation with other modes, so that resistance of the endotracheal tube has no impact on ventilation.

CONTINUOUS POSITIVE AIRWAY PRESSURE

Continuous positive airway pressure (CPAP) refers to the delivery of a continuous level of positive airway pressure. It is functionally similar to PEEP. The ventilator does not cycle during CPAP, no additional pressure above the level of CPAP is provided, and patients must initiate all breaths.

CPAP is most commonly used in the management of sleep related breathing disorders, cardiogenic pulmonary edema, and obesity hypoventilation syndrome. (See "Initiation of positive airway pressure therapy for obstructive sleep apnea in adults" and "Noninvasive positive airway pressure therapy for the obesity hypoventilation syndrome" and "Noninvasive ventilation in acute respiratory failure in adults".)

BILEVEL POSITIVE AIRWAY PRESSURE

Bilevel positive airway pressure (BPAP) is a mode used during noninvasive positive pressure ventilation (NPPV). It delivers a preset inspiratory positive airway pressure (IPAP) and expiratory positive airway pressure (EPAP). The tidal volume correlates with the difference between the IPAP and the EPAP. As an example, the tidal volume is greater using an IPAP of 15 cm H_2O and an EPAP of 5 cm H_2O (difference of 10 cm H_2O), than an IPAP of 10 cm H_2O and an EPAP of 5 cm H_2O (difference of 5 cm H_2O). Most BPAP devices also permit a backup respiratory rate to be set.

The term "BiPAP" is often used incorrectly to refer to the BPAP mode. BiPAP is the name of a portable ventilator manufactured by Respironics Corporation; it is just one of many ventilators that can deliver BPAP. BPAP is discussed in more detail separately. (See "Noninvasive ventilation in acute respiratory failure in adults", section on 'Mode' and "Noninvasive positive airway pressure therapy for the obesity hypoventilation syndrome", section on 'Bilevel positive airway pressure'.)

AIRWAY PRESSURE RELEASE VENTILATION

During airway pressure release ventilation (APRV), a high continuous positive airway pressure (P high) is delivered for a long duration (T high) and then falls to a lower pressure (P low) for a shorter duration (T low) (figure 4 and figure 5).

The transition from P high to P low deflates the lungs and eliminates carbon dioxide. Conversely, the transition from P low to P high inflates the lungs. Alveolar recruitment is maximized by the high continuous positive airway pressure [31,32].

The difference between P high and P low is the driving pressure. Larger differences are associated with greater inflation and deflation, while smaller differences are associated with smaller inflation and deflation. The exact size of the tidal volume is related to both the driving pressure and the compliance.

T high and T low determine the frequency of inflations and deflations. As an example, a patient whose T high is set to 5.4 seconds and whose T low is set to 0.6 seconds has an inflation-deflation cycle lasting 6 seconds. This allows 10 inflations and deflations to be completed each minute. Most adherent believe adjusting the Flow-Time waveform should be done in order to optimize settings. Ideally, expiratory time is adjusted to cut off the expiratory flow during a release at about 75 percent of peak expiratory flow rate (PEFR).

Spontaneous breathing is possible at both P high and P low, although most spontaneous breathing occurs at P high because the time spent at P low is brief. This is a novel feature that distinguishes APRV from other types of inverse ratio ventilation (IRV).

Efficacy — APRV has not been shown to improve mortality. However, it may improve alternative important clinical outcomes compared to other modes of ventilation. In one trial, 30 patients being mechanically ventilated because of trauma were randomly assigned to receive APRV alone or pressure-limited ventilation for 72 hours followed by APRV [33]. The APRV alone group had a shorter duration of mechanical ventilation, a shorter ICU stay, and required less sedation and pharmacologic paralysis. Mortality did not differ between groups. In another trial of 148 patients with ARDS, APRV was associated with improved oxygenation and respiratory system compliance, decreased plateau pressure, more ventilator free days, and decreased ICU stay [34]. APRV in one randomized trial was associated with the generation of large tidal volumes, often exceeding 12 cc/kg of ideal body weight [35], although the optimal implementation of this modality remains the subject of debate [36].

Numerous observational studies suggest that APRV may decrease the peak airway pressure, improve alveolar recruitment, increase ventilation of the dependent lung zones and improve oxygenation [37-42]. However, such findings have not been universal. In one clinical trial, 58 patients being mechanically ventilated for acute lung injury were randomly assigned to receive either APRV or synchronized intermittent mandatory ventilation (SIMV) plus pressure support ventilation (PSV) [43]. There were no differences in physiologic or clinical outcomes.

APRV is well tolerated hemodynamically. In a trial of 12 patients who were being mechanically ventilated for acute respiratory distress syndrome (ARDS), the patients were switched from PC-IRV to APRV [44]. The initial P high was 75 percent of the peak airway pressure during PC-IRV. Following the change, there was significant improvement in the cardiac index and oxygen delivery, as well as a diminished need for vasopressors. Although much of the hemodynamic improvement in this trial was probably related to lower airway pressures during APRV compared to PC-IRV, spontaneous breathing also confers a hemodynamic advantage [45].

Indications — There are no universally accepted indications. Use of APRV and its related modes – intermittent mandatory airway pressure release ventilation and biphasic intermittent positive airway pressure (see 'Related modes' below) – has been best described in patients who have ARDS. In theory, APRV may recruit alveoli and improve oxygenation.

Contraindications — APRV and its related modes are infrequently used in patients with severe obstructive airways disease or a high ventilatory requirement because hyperinflation, high alveolar pressure, and pulmonary barotrauma may result. (See "Diagnosis, management, and prevention of pulmonary barotrauma during invasive mechanical ventilation in adults".)

Related modes — Intermittent mandatory airway pressure release ventilation (IMPRV) and biphasic intermittent positive airway pressure (herein called biphasic ventilation) are similar to APRV. Specifically, they allow spontaneous breathing and have cyclic inflations and deflations due to transitions between P high and P low.

- During IMPRV, the cyclic inflations and deflations are synchronized to occur after every few spontaneous breaths [46].
- The principal difference between biphasic ventilation and APRV is that T low is longer during biphasic ventilation, allowing more spontaneous breaths to occur at P low (figure 6) [47,48]. Another difference is that inverse ratio ventilation is more often performed using APRV than biphasic ventilation. Biphasic ventilation is also referred to as Bi-Vent, BiLevel, BiPhasic, and DuoPAP ventilation. It is different than bilevel positive airway pressure, a common type of noninvasive positive pressure ventilation. (See "Noninvasive ventilation in acute respiratory failure in adults".)

HIGH FREQUENCY VENTILATION

High frequency mechanical ventilation employs very high respiratory rates and small tidal volumes. It is described in detail separately. (See "High-frequency ventilation in adults".)

ADAPTIVE SUPPORT VENTILATION

Adaptive support ventilation (ASV) is a ventilatory mode in which respiratory mechanics dictate adjustments to the respiratory rate and inspiratory pressure that are necessary to achieve a desired minute ventilation:

- Patients who are unable to trigger the ventilator are given pressure-control breaths. (See 'Pressure-limited ventilation' above.)
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Patients who are able to trigger the ventilator are given pressure support for the triggered breaths, supplemented with pressure-control breaths as needed to achieve the desired respiratory rate. (See 'Pressure support' above and 'Pressure-limited ventilation' above.)

The basis for the adjustments is an equation that determines the respiratory rate that minimizes the work of inspiration at a given minute ventilation. This equation relies on an expiratory time constant, which can be obtained from the expiratory limb of the flow volume loop on a breath by breath basis [49,50]. Patients who have a long expiratory time constant (eg, chronic obstructive pulmonary disease [COPD]) receive a higher tidal volume and a lower respiratory rate when ventilated by ASV than patients with stiff lungs (eg, acute respiratory distress syndrome [ARDS]) or chest wall stiffness (eg, kyphoscoliosis, morbid obesity, neuromuscular disorder) who expire quickly [51,52]. The effect of ASV has not been demonstrated to be superior to other modes of mechanical ventilation on important clinical outcomes, although time to weaning initiation and weaning duration were shown to be somewhat shorter with ASV in one randomized trial [53].

NEURALLY ADJUSTED VENTILATORY ASSIST VENTILATION

Neurally adjusted ventilatory assist ventilation (NAVA) is an investigational ventilatory mode in which the electrical discharge from the diaphragm (ie, diaphragmatic excitation; EA_{di}) is used to trigger a mechanical breath [54]. When a deflection in the EA_{di} signal greater than the set threshold (typically 0.5 microvolts) is detected by a catheter embedded in a gastric tube, a mechanical breath is delivered. The degree of assist varies with the amplitude of the detected EA_{di} and an assist level set by the clinician such that there is breath-to-breath variation in the tidal volume. The set assist level is determined by a short empirical adjustment period where the assist level is increased to detect a comfortable and consistent tidal volume for the patient and an EA_{di} signal that remains flat.

Neural-ventilator coupling (ie, time between a spontaneous breath and the delivery of a mechanical breath) is faster with NAVA than with conventional modes of mechanical ventilation. Thus, NAVA has the potential to improve patient-ventilator synchrony (eg, in patients with chronic obstructive pulmonary disease). However, although small uncontrolled trials have suggested improved patient-ventilator asynchrony with NAVA, none have shown improvement in clinically important outcomes, such as death or ventilator-free survival [55-57].

The success of NAVA depends upon an intact ventilatory drive (ie, patient has to be spontaneously breathing) and is not a plausible mode of ventilation in patients who have blunted or no respiratory drive (eg, hypoventilation due to heavy sedation or cervical spinal cord injury).

INVERSE RATIO VENTILATION

Inverse ratio ventilation (IRV) is not a mode of mechanical ventilation, but rather a strategy employed during volume-limited or pressure-limited mechanical ventilation. The inspiratory time exceeds the expiratory time during IRV (the inspiratory to expiratory [I:E] ratio is inversed), increasing the mean airway pressure and potentially improving oxygenation. A trial of IRV may be warranted when a patient is severely hypoxemic despite optimal positive end-expiratory pressure (PEEP) and fraction of inspired oxygen (FiO_2).

IRV has never been shown to improve important clinical outcomes, such as mortality, duration of mechanical ventilation, or duration of intensive care unit (ICU) stay. The preponderance of evidence suggests that IRV improves oxygenation, although the evidence is weak and characterized by low quality, conflicting studies [58-69]. The following studies are illustrative of the data that exist:

- In an observational study of 31 patients undergoing pressure control ventilation, initiation of IRV was followed by a significant increase in the mean airway pressure and the PaO_2 (from 69 to 80 mmHg), despite reduction of the PEEP [67].
- A crossover trial randomly assigned 16 patients with ARDS to received IRV or no IRV [59]. IRV increased the mean airway pressure, but the improvement in the PaO_2 did not reach statistical significance (93 versus 86 mmHg).

IRV generally requires heavy sedation or neuromuscular paralysis because the inverse I:E ratio is unnatural and uncomfortable. It is usually well tolerated hemodynamically [64,70].

Types — IRV can be performed during pressure-limited ventilation (PL-IRV) or volume-limited ventilation (VL-IRV). Neither is clearly superior to the other. In a multicenter, randomized trial that compared PL-IRV to VL-IRV in patients with ARDS, the type of IRV did not affect mortality [71].

Pressure-limited — During PL-IRV, IRV is initiated by increasing the I:E ratio until the inspiratory time exceeds the expiratory time. The primary advantage of PC-IRV is the ability to guarantee that a maximal plateau airway pressure will not be exceeded. This may limit the risk of pulmonary barotrauma or ventilator-associated lung injury. In addition, many clinicians believe that clinically significant auto-PEEP is less likely with PC-IRV than VC-IRV, although this is unproven [72]. (See "Ventilator-induced lung injury" and "Diagnosis, management, and prevention of pulmonary barotrauma during invasive mechanical ventilation in adults".)

Volume-limited — During volume-limited ventilation, IRV can be initiated using a ramp wave (decelerating flow) or a square wave (constant flow) flow pattern:

- With the ramp wave, the peak inspiratory flow rate is initially set at least four times higher than the minute ventilation and then slowly decreased until the inspiratory time exceeds the expiratory time

- With the square wave, an end-inspiratory pause is added (0.2 sec works well) and then slowly lengthened until the inspiratory time exceeds the expiratory time

Risks — The shorter expiratory time during IRV increases the risk of auto-PEEP and its adverse sequelae (eg, pulmonary barotrauma, hypotension) (figure 7) [67]. IRV also appears to increase the risk of pulmonary barotrauma independent of auto-PEEP. In a study of 14 patients undergoing mechanical ventilation with PC-IRV, the incidence of pneumothorax was 29 percent despite the lack of measurable auto-PEEP [73].

SUMMARY AND RECOMMENDATIONS

- The mode of mechanical ventilation refers to the method of inspiratory support. (See 'Introduction' above.)

- During volume-limited ventilation, inspiration ends after delivery of the set tidal volume. During pressure-limited ventilation, inspiration ends after delivery of the set inspiratory pressure. Each has unique advantages and disadvantages. (See 'Volume-limited ventilation' above and 'Pressure-limited ventilation' above and 'Volume-limited versus pressure-limited' above.)

- Pressure support ventilation (PSV) is neither volume-limited nor pressure-limited. Once a breath is triggered by the patient, inspiratory pressure is delivered until the inspiratory flow decreases to a predetermined percentage of its peak value. (See 'Pressure support' above.)

- Continuous positive airway pressure (CPAP) refers to the delivery of a continuous level of positive airway pressure. (See 'Continuous positive airway pressure' above.)

- Bilevel positive airway pressure (BPAP) is a mode used during noninvasive positive pressure ventilation. It delivers a preset inspiratory positive airway pressure (IPAP) and an expiratory positive airway pressure (EPAP). (See 'Bilevel positive airway pressure' above.)

- Airway pressure release ventilation (APRV) cycles between a high continuous positive airway pressure (P high) and a low continuous positive airway pressure (P low). Spontaneous breathing can occur during APRV. Variants include intermittent mandatory airway pressure release ventilation and biphasic intermittent positive airway pressure. (See 'Airway pressure release ventilation' above.)

- Inverse ratio ventilation (IRV) is not a mode of mechanical ventilation, but rather a strategy employed during volume-limited or pressure-limited mechanical ventilation. The inspiratory time exceeds the expiratory time during IRV (the I:E ratio is inversed), increasing the mean airway pressure and potentially improving oxygenation. (See 'Inverse ratio ventilation' above.)

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Topic 1651 Version 18.0

GRAPHICS

Modes of mechanical ventilation

Mode	Breath strategy (target)	Trigger		Cycle (breath termination)	Types of breaths		
		Ventilator	Patient		Mandatory	Assisted	Spontaneous
CMV	Volume-limited	Yes	No	Volume	Yes	No	No
	Pressure-limited	Yes	No	Time	Yes	No	No
AC	Volume-limited	Yes	Yes	Volume	Yes	Yes	No
	Pressure-limited	Yes	Yes	Time	Yes	Yes	No
IMV	Volume-limited	Yes	Yes	Volume	Yes	Yes*	Yes*
	Pressure-limited	Yes	Yes	Time	Yes	Yes*	Yes*
APRV		Yes	Yes	Time	Yes	Yes*	Yes*
PSV	Pressure-limited	No	Yes	Flow	No	Yes	No
CPAP		No	No	Flow	No	No	Yes
Tube compensation		No	Yes	Flow	No	No	Yes

Types of breaths:

Mandatory: Breaths are initiated by the ventilator and the ventilator performs the work of inspiration during those breaths

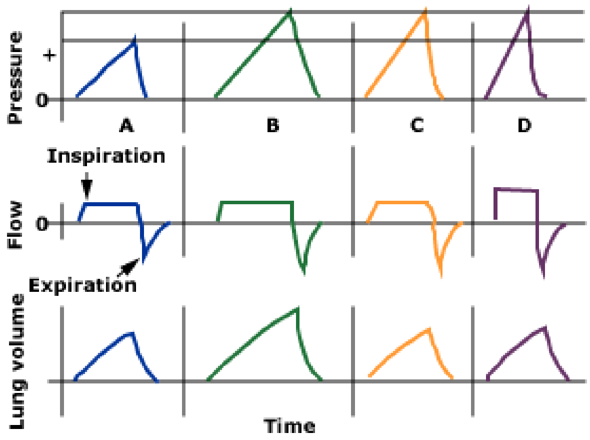
Assisted: Breaths are initiated by the patient, but the ventilator performs at least some of the work of inspiration for those patient initiated breaths

Spontaneous: Breaths are initiated by the patient and the patient performs the entire work of inspiration for those patient initiated breaths

CMV: controlled mechanical ventilation; AC: assist control; IMV: intermittent mandatory ventilation; PSV: pressure support ventilation; CPAP: continuous positive airway pressure; APRV: airway pressure release ventilation; BPAP: bilevel positive airway pressure.
* Note that there is overlap between the types of breaths that can be generated during various modes of ventilation. This overlap is dependent on the ventilator settings. As examples, APRV and IMV are capable of assisted breaths (pressure support added) or spontaneous breaths (no pressure support added). Both assisted and spontaneous breaths depend on the patient's ability to trigger the ventilator.

Graphic 77391 Version 5.0

Waveforms for volume-cycle ventilator

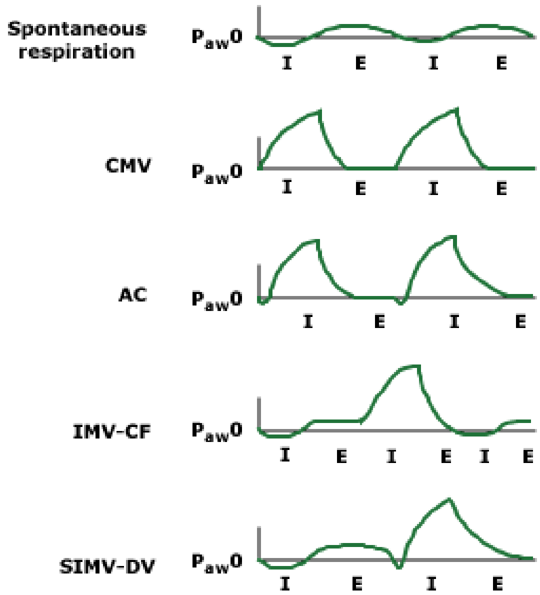


Pressure, flow, and volume waveforms for a volume-cycle ventilator using a constant flow generator (square wave) at baseline (A), and with increased delivered tidal volume (B), reduced lung compliance (C), and enhanced respiratory flow rate (D). An increase in peak airway pressure occurs in the last three settings.

Adapted from Spearman, CB, Egan, DF, Egan, J, Fundamentals of respiratory therapy, 4th ed, Mosby, St Louis, 1982.

Graphic 50556 Version 1.0

Airway pressures during various modes of ventilation

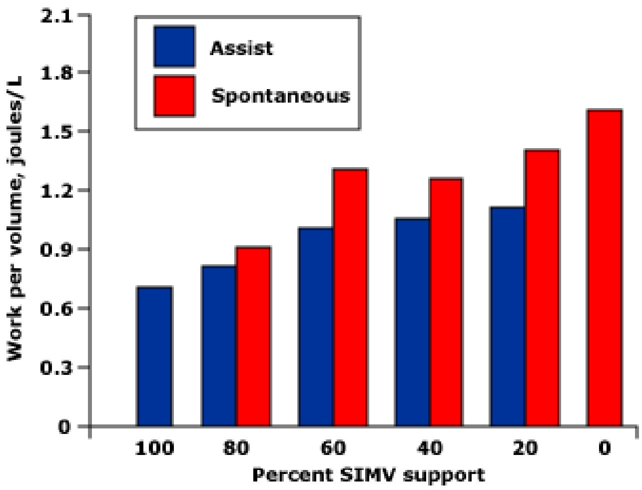


Airway pressures (Paw) during inspiration and expiration with controlled mechanical ventilation (CMV), assist-control (AC), intermittent mandatory ventilation delivered by a continuous flow circuit (IMV-CF), and synchronized intermittent mandatory ventilation delivered by demand valve circuit (SIMV-DV).

Data from Tobin, MJ, Dantzker, DR, In: Cardiopulmonary Critical Care, Dantzker, DR (Ed), Grune and Stratton, Orlando, 1986.

Graphic 75686 Version 2.0

Effect of decreased synchronized intermittent mandatory ventilation (SIMV) support in acute respiratory distress syndrome (ARDS)

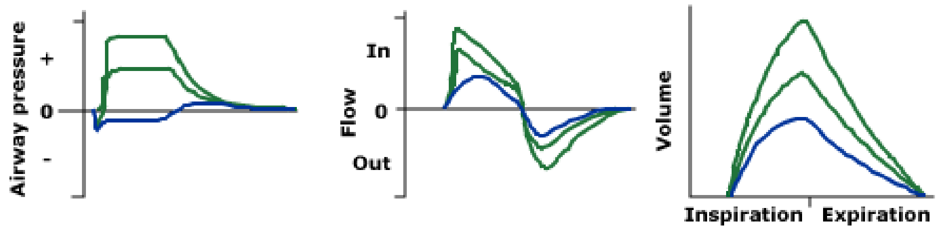


Effects of decreasing synchronized intermittent mandatory ventilation (SIMV) support on the work of breathing per liter of ventilation in patients with acute respiratory distress syndrome. Inspiratory work per unit volume (work per liter Wp/L) done by the patient is shown during assisted cycles (blue bars) and spontaneous cycles (red bars). As machine support was withdrawn, the patients performed an increasing amount of inspiratory work per liter of ventilation. The increased work was significantly greater at all levels of machine support less than or equal to 60 percent ($p \leq 0.01$). Spontaneous breaths required 25 percent more work per liter of ventilation than assisted breaths at these levels of machine support. The pressure-time index exceeded a fatiguing level of work at all levels of machine support less than 80 percent. It was suggested that, when using the SIMV mode, the back-up rate should result in at least 80 percent of the minute ventilation coming from the machine in order to prevent fatigue.

Redrawn from Marini JJ, Smith TC, Lamb V, Am Rev Respir Dis 1988; 138:1169.

Graphic 64325 Version 2.0

Pressure support ventilation

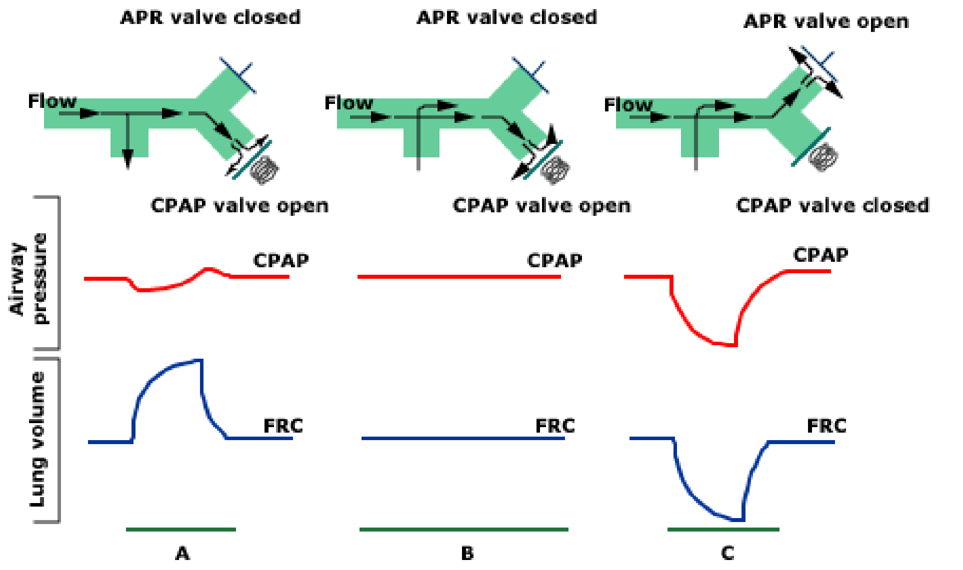


Changes in airway pressure, flow, and volume as measured in the distal endotracheal tube during unsupported and pressure-supported spontaneous breaths in intubated patients. The unsupported patient (blue lines) must first generate an initial negative pressure "spike" to open the ventilator demand valves and then must maintain a small amount of negative pressure during inspiration to produce flow through the ventilator circuitry. The addition of increasing levels of pressure support (green lines) provides plateaus of positive pressure that augment the spontaneous tidal volume in accordance with the patient's spontaneous respiratory flow demand and inspiratory time pattern.

Redrawn from Respir Care 1987; 32:447.

Graphic 67019 Version 1.0

Airway pressure release ventilation (APRV)

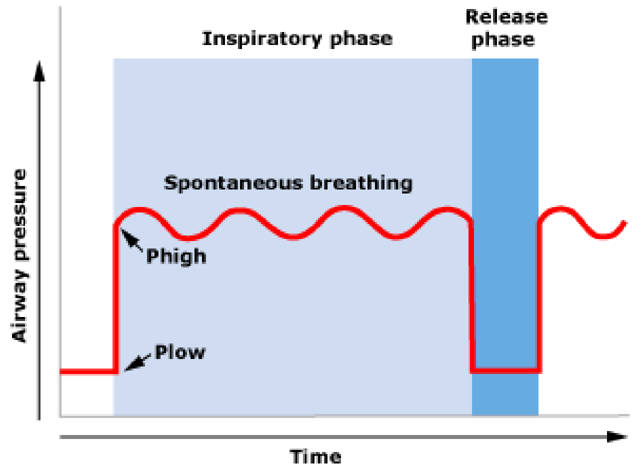


A: Continuous flow positive airway pressure (CPAP). B: During exhalation with CPAP, the CPAP valve opens and the airway pressure release (APR) valve closes. C: During airway pressure release from the preset CPAP level to ambient pressure, the CPAP valve closes and the APR valve opens. After closure of the APR valve, functional residual capacity (FRC) is re-established.

Adapted from Downs JB, Stock MC, Crit Care Med 1987; 15:459.

Graphic 50395 Version 2.0

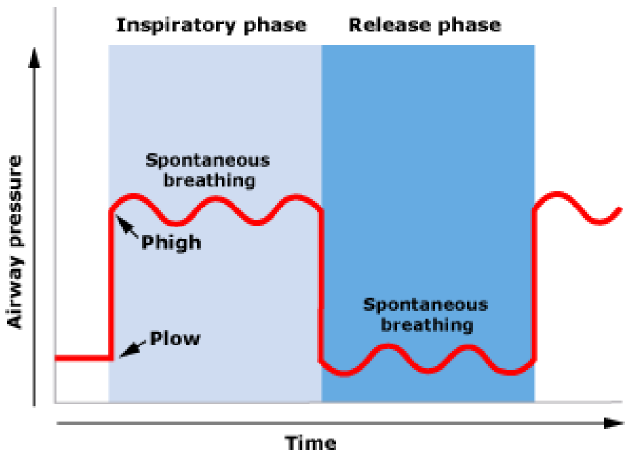
Airway pressure release ventilation (APRV)



Data from: Seymour, CW, Frazer M, Reilly, PM, Fuchs, BD. Airway pressure release and biphasic intermittent positive airway pressure ventilation: are they ready for prime time? J Trauma 2007; 62:1298.

Graphic 71401 Version 1.0

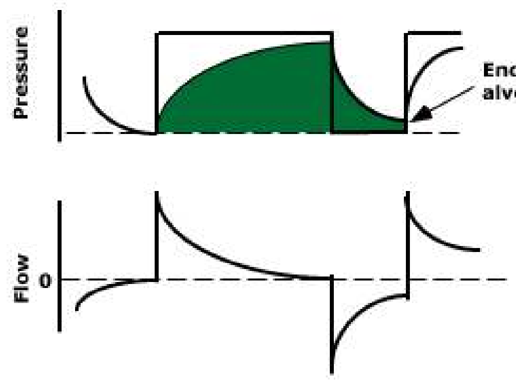
Biphasic intermittent positive airway pressure ventilation



Data from: Seymour, CW, Frazer M, Reilly, PM, Fuchs, BD. Airway pressure release and biphasic intermittent positive airway pressure ventilation: are they ready for prime time? J Trauma 2007; 62:1298.

Graphic 73129 Version 1.0

Pressure controlled inverse ratio ventilation



Depiction of flow and airway pressure characteristics during a pressure limited breath provided by pressure-controlled inverse ratio ventilation (PC-IRV). End-expiratory alveolar pressure is positive at the end of the shortened expiratory period. Airflow has not ceased, and auto-PEEP has developed. A pressure limited breath without inverse ratio ventilation has similar pressure and flow characteristics except that flow has ceased at the end of expiration, and there is no auto-PEEP present.

Redrawn from Marcy, TW, Marini, JJ, Chest 1991; 100:494.

Graphic 55132 Version 1.0

Contributor Disclosures

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