CHAPTER

7

Patient Stabilization: Adjusting Ventilatory Support

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OUTLINE

OBJECTIVES

1. Describe items that should be assessed immediately following ventilator initiation.
2. List respiratory problems sometimes encountered following ventilator initiation.
3. Define the term *patient–ventilator interaction* and explain what is meant by patient–ventilator asynchrony.
4. Describe the adverse effects of patient–ventilator asynchrony.
5. Describe each of the types of trigger asynchrony and explain how to recognize and correct each.
6. Explain how to recognize and correct flow asynchrony.
7. Explain the importance of correctly adjusting rise time and expiratory sensitivity when using PSV.
8. Explain what is meant by the term *mode asynchrony* and explain how NAVA and PAV may improve patient–ventilator interaction.
9. Explain each of the factors that determine tissue oxygen delivery.
10. Describe appropriate clinical goals for most patients for P_{aO_2}, S_{aO_2}, and F_{IO_2}.
11. Describe methods to titrate F_{IO_2} down from 1.0 in ventilated patients.
12. Differentiate each of the following types of PEEP and explain how to apply each: minimum PEEP, compliance-titrated PEEP, optimal PEEP for oxygen delivery, PEEP–F_{IO_2} tables, static pressure–volume curves, and slow-flow pressure–volume curves.
13. Explain how to perform a decremental PEEP trial to include appropriate use of a lung recruitment maneuver.
14. Explain causes, recognition, and correction of autoPEEP.
15. Explain the purpose of prone positioning and describe its application.
16. Explain the purpose of lung recruitment maneuvers and describe the possible risks and benefits.
17. Describe bronchial hygiene techniques that may be beneficial in improving oxygenation.
18. Explain the relationships between tidal volume, dead space, respiratory rate, and alveolar ventilation.
19. Describe the relationship between alveolar ventilation, CO_2 production, and P_{aCO_2}.
20. Describe alterations in spontaneous breathing commonly seen in ICU patients.
21. Explain methods to alter ventilation and P_{aCO_2} during time-triggered controlled ventilation.
22. Describe factors that affect P_{aCO_2} when using each of the major modes of ventilation.
23. Explain the use of permissive hypercapnia.

24. Describe the purpose of intentional hyperventilation for patients with cerebral edema.
25. Explain the effects of $Paco_2$ on acid-base balance during mechanical ventilation.
26. Describe causes of metabolic acidosis and alkalosis and explain expected respiratory compensation.
27. List normal values for arterial blood gases and hemodynamic measures often monitored in the intensive care unit (ICU).
28. Describe major cardiac and cardiovascular abnormalities that will reduce oxygen delivery to the tissues.
29. Summarize hemodynamic changes associated with ARDS, volume overload, left ventricular failure, hypovolemic shock, septic shock, and cardiogenic shock.
30. Explain the importance of appropriate pain management and sedation protocols.
31. List possible indications for and hazards of neuromuscular blockade.

KEY TERMS

airway pressure-release ventilation (APRV)
assist-control pressure-control ventilation (PC A/C)
assist-control volume-control ventilation (VC A/C)
autotriggering
autoPEEP
barotrauma
baseline (bias) flow
bronchial hygiene
cycle asynchrony
decremental PEEP trial
diaphragmatic dysfunction
double cycling
double triggering
dynamic autoPEEP
electrical discharge from the diaphragm (EDI)
flail chest
flow asynchrony
flow trigger
inspiratory waveform
long cycling
lower inflection point (LIP)
minimum PEEP
missed triggering
mode asynchrony
neural–ventilatory coupling
neurally adjusted ventilatory assist (NAVA)
neuro-inspiratory time
neuromuscular blockade
obstructive lung disease
open lung ventilation
optimal PEEP
overdistention
patient–ventilator asynchrony
physiologic PEEP
pressure control–synchronized intermittent mandatory ventilation (PC-SIMV)
pressure-control ventilation (PCV)
pressure-regulated volume control (PRVC)
pressure-support ventilation (PSV)
pressure trigger
prone positioning
proportional assist ventilation (PAV)
recruitment maneuvers
reverse triggering
rise time
short cycling
static autoPEEP
terminal flow
titrate
trigger asynchrony
trigger delay
trigger sensitivity
trigger work
upper inflection point (UIP)

Introduction

Following establishment of an artificial airway and initiation of mechanical ventilation, the respiratory care clinician must assess the patient–ventilator system to assure appropriate ventilator function and patient–ventilator interaction. Support must provide adequate oxygenation and ventilation and reduce the work of breathing (WOB). Support must be adjusted to ensure patient comfort and safety and minimize harmful side effects. Support should also promote prompt patient liberation from the ventilator. Based on the clinician's initial assessment, adjustments in ventilatory support may be necessary to reach these goals.

A word about modes of ventilation: A sophisticated taxonomy has been developed to describe various modes of ventilation.[1,2] Manufacturers and clinicians, however, often use less rigorous and sometimes conflicting terminology. This chapter will focus on use of common clinical terminology to describe the most common modes of ventilation in use, specifically:

- **Assist-control volume-control ventilation** (VC A/C, aka patient- or time-triggered VC-CMV with set-point breath targeting)
- **Assist-control pressure-control ventilation** (PCV or PC A/C, aka patient- or time-triggered PC-CMV with set-point breath targeting)
- Pressure-support ventilation (PSV, aka PC-CSV)
- Volume control-synchronized intermittent mandatory ventilation (V-SIMV, aka VC-IMV with set-point breath targeting) and
- **Pressure control-synchronized intermittent mandatory ventilation** (P-SIMV, aka PC-IMV with set-point breath targeting).

A more formal taxonomy for description of ventilatory modes is described in Chapter 6. Using that taxonomy, VC indicates volume control, PC indicates pressure control, CMV indicates continuous mandatory ventilation, IMV indicates intermittent mandatory ventilation, and CSV indicates continuous spontaneous ventilation.[1,2]

Initiation of Mechanical Ventilation

Initiation of mechanical ventilation should be immediately followed by assessment of the patient and patient–ventilator system, including physical assessment of the patient, assessment of ventilator settings and patient–ventilator interaction, cardiovascular assessment, oximetry, and measurement of arterial blood gases. Ventilator adjustments are often needed to meet oxygenation and ventilation goals while maintaining optimal acid-base balance and minimizing harmful cardiovascular side effects. The ventilation provided must be safe and effective, minimize the WOB, and assure patient comfort. The initial assessment should

alert the respiratory care clinician to specific areas of concern. These may include signs of hypoxemia or inadequate ventilation, increased WOB, respiratory distress, and diaphragmatic fatigue. Findings associated with heart failure, volume overload, shock, blood loss, or sepsis should be addressed. Impaired central nervous system (CNS) or neurologic function, including depressed level of consciousness, heavy sedation, and signs of neuromuscular disease or paralysis, should be noted.

Respiratory problems sometimes encountered following ventilator initiation include inadvertent right mainstem intubation, misplaced endotracheal tube (e.g., esophageal intubation), cuff leak or malfunction, large air leak, inappropriate ventilator settings, and ventilator malfunction or disconnect. Other common problems include bronchospasm, mucosal edema, or secretions in a large airway. The clinician should be alert for the development or worsening of pulmonary edema, consolidation, pneumothorax, pleural effusion, or atelectasis. Based on this initial assessment, the respiratory care clinician should make appropriate ventilator adjustments to optimize oxygenation and ventilation, maintain acid-base homeostasis, reduce the WOB, minimize harmful cardiovascular side effects, and assure patient safety and comfort. **Box 7-1** summarizes the items that should be reviewed as part of the initial assessment of the patient following ventilator initiation.

BOX 7-1 Initial Assessment of the Patient

Following ventilator initiation, the patient should be assessed to ensure adequate oxygenation and ventilation while avoiding **patient–ventilator asynchrony**, increased WOB, or cardiovascular compromise. Assessment should include review of the following to include findings of concern:

- Physical findings and monitored information
  - General appearance: head and neck: normal or reduced level of consciousness (confusion, somnolent, or coma); signs of restlessness, anxiety, pain, discomfort, distress, or dyspnea; cyanotic lips and gums; pupils abnormally dilated or contracted; jugular venous distention
  - Extremities: warm and moist or pale, cold, clammy, edematous, or cyanotic
  - Respiratory rate and pattern: normal or abnormal, e.g., tachypnea, bradypnea, rapid shallow breathing, periods of apnea, ventilator–patient asynchrony
  - Heart rate, blood pressure, and presence of arrhythmia on cardiac monitor (normal or abnormal)
  - Pulse oximetry
  - Breath sounds: good bilateral aeration or absent, diminished, unilateral, or abnormal breath sounds
  - Chest exam: bilateral chest expansion vs. unilateral chest expansion, accessory muscle use, intercostal retractions, chest/abdomen asynchrony
    - Palpation for tracheal position, chest wall motion, presence of subcutaneous air
    - Percussion for resonance, dullness, or hyperresonance
  - Artificial airway
    - Placement, patency, and cuff inflation (pressure and volume)
    - Tube diameter and depth of insertion
  - Monitoring equipment
- Ventilator settings
  - Mode of ventilation
  - Ventilatory graphics display (pressure, flow, and volume waveforms)
  - Peak, plateau, and mean airway pressures
  - Exhaled volumes and rate (spontaneous and mandatory V_T, f, and $\dot{V}_E$)
  - Baseline pressure (PEEP/CPAP)
  - Trigger effort, trigger synchrony/asynchrony
  - Oxygen concentration
  - Inspiratory time, flow, and I:E ratio
  - Humidification and airway temperature
- Bedside equipment and supplies
  - Suctioning equipment and supplies
  - Manual resuscitator bag, oxygen supply, positive end-expiratory pressure (PEEP) valve, extra airways
  - Other equipment and supplies (e.g., chest tubes, urinary catheter collection bags).
  - Crash cart location.
  - Ancillary equipment (e.g., mechanical circulatory assistance devices, extracorporeal membrane oxygenation [ECMO], inhaled nitric oxide [NO])

Patient–Ventilator Interaction

With patient-triggered modes of ventilation (e.g., assist-control volume or pressure-control ventilation) and modes that incorporate spontaneous breathing (e.g., SIMV, pressure support) the patient and ventilator must interact. Patient–ventilator interaction refers to patient–ventilator synchrony, comfort, and WOB during ventilator-assisted breaths. This interaction may be good, resulting in adequate oxygenation and ventilation, while decreasing the WOB and promoting patient comfort. Poor patient–ventilator interaction can result in patient–ventilator asynchrony, which may increase the WOB, cause patient discomfort, and threaten effective oxygenation and ventilation.

Patients in ventilatory failure often experience diaphragmatic dysfunction, which may prolong the need for mechanical ventilation and lengthen ICU stay.[3] A sustained increase in ventilatory workload can lead to ventilatory muscle fatigue and structural injury. Once ventilatory muscle fatigue occurs, at least 24 hours is required for recovery. Ventilatory support should be adjusted to minimize the WOB and allow for ventilatory muscle rest. Absence of ventilatory activity as seen with controlled ventilation results in near-complete ventilatory rest. Controlled ventilation, however, may lead to ventilatory muscle weakness, deconditioning, and atrophy.[3] The development of **diaphragmatic dysfunction** while receiving mechanical ventilatory support may be correlated with the degree of support provided and the quality of the patient–ventilator interaction. Diaphragmatic dysfunction can develop within hours and worsen with the duration of mechanical ventilation.

Appropriate selection of ventilatory mode and associated ventilator settings can reduce the ventilatory work load without resulting in deconditioning and atrophy of the ventilatory muscles. Assist-control volume ventilation, assist-control pressure-control ventilation, synchronized intermittent mandatory ventilation (SIMV) with pressure support, and standalone pressure-support ventilation can reduce inspiratory work without eliminating respiratory muscle activity. Newer modes of ventilation (e.g., **proportional assist ventilation [PAV]**, **neurally adjusted ventilatory assist [NAVA]**) may be especially useful in enhancing patient–ventilator interaction.

Immediately following initiation of mechanical ventilation, the patient should be assessed for the presence of patient–ventilator asynchrony. Patient–ventilator asynchrony occurs when the timing of the ventilator does not coincide with the patient's respiratory center neurologic inspiratory/expiratory cycle. Patient–ventilator asynchrony may be detected via physical assessment and observation of the ventilator pressure, flow, and volume waveforms.

The degree of patient–ventilator asynchrony can vary from mild to very severe. The quality of the patient–ventilator interaction may also vary over time. For example, periods of sleep or sedation may improve patient–ventilator synchrony, while pain, anxiety, procedural interventions, and other clinician–patient interactions may worsen patient–ventilator asynchrony. It has been estimated that up to 25% of patients experience severe patient–ventilator asynchrony, while some have suggested that asynchrony occurs at some point in almost all patients receiving patient-triggered ventilatory support.[4,5] **Box 7-2** describes some of the adverse effects of patient–ventilator asynchrony.

BOX 7-2 Effects of Patient–Ventilator Asynchrony

Patient–ventilator asynchrony is associated with adverse effects, including:

- Increased WOB
  - Diaphragmatic fatigue
  - Structural damage to the diaphragm
- Hypoxemia due to decreased $\dot{V}/\dot{Q}$ or increased shunt
- Inadequate or ineffective ventilation
  - Hypoventilation (abnormally increased $PaCO_2$)
  - Hyperventilation (abnormally decreased $PaCO_2$)
  - Tachypnea, rapid shallow breathing (IMV/SIMV mode)
  - Slowed spontaneous breathing rate (sedation)
- Hemodynamic compromise
  - Tachycardia or bradycardia
  - Hypertension or hypotension
- Increased likelihood of complications
  - Increased peak inspiratory pressure (PIP)
  - Pneumothorax/tension pneumothorax, other forms of **barotrauma**
  - Increased mean airway pressure
    - Decreased venous return, decreased cardiac output
    - Increased likelihood of ventilator-associated lung injury (VALI)
- Prolonged duration of ventilation
  - Increased time to extubation
  - Increased need for tracheostomy
  - Increased time in the ICU
  - Increased hospital length of stay
  - Increased mortality

Types of patient–ventilator asynchrony include **trigger asynchrony**, **flow asynchrony**, **cycle asynchrony**, and **mode asynchrony**, as described below.

Trigger Asynchrony

Patient-triggered breaths may be pressure triggered or flow triggered. **Trigger sensitivity** should be adjusted so that **trigger work** is minimal without autocycling. For pressure triggering, the trigger is generally set at –0.5 to –1.5 cm H_2O below the baseline expiratory pressure, although some circuits may require **trigger sensitivity** be set at –2.0 cm H_2O to avoid autotriggering.[2,26] With flow triggering, the trigger sensitivity is generally set in the range of 1 to 2 L/min below the baseline or bias flow, although some systems may require flow triggers as high as 3 to 4 L/min below **baseline (bias) flow** to avoid autotriggering.[2,6] There are no clinically important differences between **pressure trigger** and **flow trigger** when using the current generation of critical care ventilators.[2,6] Trigger asynchrony occurs when the patient's inspiratory effort and the initiation of a ventilator-supported breath are poorly coordinated.

RC Insight

Trigger sensitivity should be adjusted so that trigger work is minimal without autocycling.

Trigger Work

Trigger work refers to that portion of the WOB performed by the patient to trigger the ventilator to the inspiratory phase. Inappropriate trigger sensitivity settings and **autoPEEP** can increase trigger work. For example, if pressure trigger sensitivity threshold is adjusted from –1.5 cm H_2O to –3.0 cm H_2O, the required patient effort (work) to trigger the ventilator will increase and the patient may not be able to generate this effort consistently.

AutoPEEP may also increase trigger work. For example, if the expiratory baseline pressure at the proximal airway is 0 cm H_2O, and the pressure trigger sensitivity is set at –2 cm H_2O, the patient must generate an inspiratory effort to decrease proximal airway pressure 2 cm H_2O to trigger the ventilator in the absence of autoPEEP. However, if the autoPEEP is +4 cm H_2O the patient would have to generate a pressure decrease from +4 cm H_2O to –2 cm H_2O in order to trigger the ventilator, a decrease of 6 cm H_2O significantly increasing trigger work. If patients are having trouble triggering the ventilator in the presence of autoPEEP, extrinsic PEEP may be applied to reduce trigger work, usually at 50% to 80% of the measured autoPEEP level.

Trigger asynchrony occurs when the patient's inspiratory effort becomes decoupled from the ventilator trigger. There are five types of trigger asynchrony: **missed triggering**, **trigger delay**, **double triggering**, **reverse triggering**, and **autotriggering**. Most forms of trigger asynchrony may occur in any mode that includes patient-triggered ventilation. Reverse triggering, however, occurs only with time-triggered "control mode" ventilation.

Missed Triggering

A patient inspiratory effort that does not trigger the ventilator is called missed triggering. This is typically detected by observing inspiratory muscle contraction that is not followed by a "machine" breath. The pressure–time curve observed on the ventilator's graphics display will indicate a dip in the baseline pressure caused by the patient's inspiratory effort that is not followed by a positive-pressure breath. **Figure 7-1** illustrates missed triggering.

Typically, missed triggering occurs intermittently. For example, two unsuccessful patient inspiratory efforts may be followed by a third effort that successfully triggers the ventilator to inspiration.[5] Missed triggering is most commonly caused by the presence of autoPEEP. AutoPEEP is caused by incomplete exhalation and most commonly occurs in patients with obstructive lung disease. AutoPEEP can be documented by observing the patient's expiratory flow curve; expiratory gas flow does not reach zero prior to the initiation of the next breath. Application of intrinsic PEEP (e.g., 50% to 80% of measured autoPEEP) to balance autoPEEP may correct missed triggering. One approach involves gradually increasing extrinsic PEEP by 1 to 2 cm H_2O and observing the effect on patient triggering. The appropriate extrinsic PEEP level to balance autoPEEP has been reached when each patient inspiratory effort results in effective ventilator triggering.[5] Following the application of extrinsic PEEP in this fashion, autoPEEP should be reevaluated to ensure it has not also increased. PEEP increases mean airway pressure and

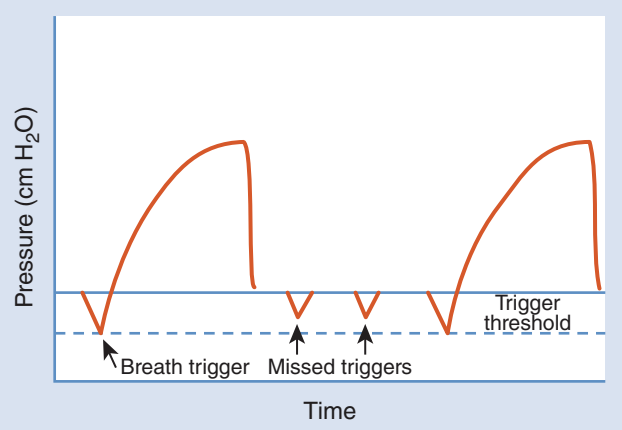

FIGURE 7-1 Missed Trigger Threshold.

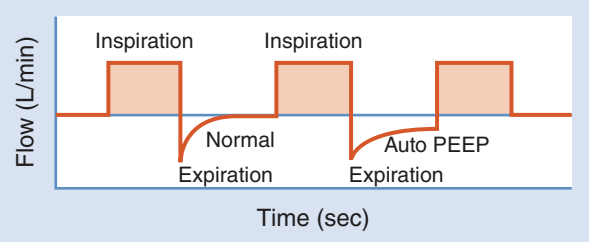

FIGURE 7-2 AutoPEEP.

may reduce venous return and cardiac output. Studies show that application of extrinsic PEEP in patients with **obstructive lung disease** can improve or occasionally worsen WOB. PEEP is contraindicated with untreated pneumothorax and should be used with caution in patients with hemodynamic compromise or elevated intracranial pressure (ICP).[5] **Figure 7-2** illustrates autoPEEP as seen on a flow–time curve during mechanical ventilation.

Other steps to reduce or eliminate autoPEEP include increasing expiratory time, decreasing tidal volume, use of larger diameter endotracheal tubes, bronchodilator administration, and secretion management. Inappropriate trigger sensitivity settings may also cause missed triggering. Inappropriate sensitivity settings should be corrected.

Trigger Delay

Trigger delay occurs when there is an increased time interval between the neurologic inspiratory signal from the patient's respiratory control center and the ventilator's initiation of breath. A trigger delay > 100 ms may increase the patient's perception of the delay and increase ventilatory drive.[5] Trigger delay can be best observed using an esophageal catheter with a multiple array electrode to detect the **electrical discharge from the diaphragm (Edi)**. The Edi signal is displayed graphically and provides a reflection of the respiratory center's neural output to the diaphragm. NAVA was developed to provide better **neural–ventilatory coupling** and to improve trigger and cycle synchrony.

Trigger delay is most commonly caused by inappropriate sensitivity settings, and adjustment of trigger sensitivity can often correct trigger delay. Trigger delay may also be caused by autoPEEP or ventilator malfunction. AutoPEEP should be measured; the application of extrinsic PEEP at 50% to 80% of the autoPEEP level may correct trigger delay. In the case of a ventilator malfunction, the ventilator should be replaced.

Double Triggering

Patients may try to breathe in longer or deeper than the ventilator is set to provide. This occurs most often in the volume-control mode when the set tidal volume or inspiratory time is less than the patient's neurologic ventilatory control center demands. In these cases, the ventilator may cycle to the expiratory phase while the patient continues to make an inspiratory effort, resulting in double triggering. Double triggering may cause the patient to receive two consecutive tidal breaths from the ventilator before exhaling. Double triggering may be corrected by increasing the inspiratory time to match the patient's neuro-inspiratory time, increasing the tidal volume to better match the patient's demand or considering a different mode of ventilation (e.g., pressure support or assist-control PCV). If double triggering continues, sedation may be considered.

Reverse Triggering

Reverse triggering may occur during controlled ventilation in which a time-triggered ventilator breath stimulates the diaphragm, resulting in diaphragmatic contraction, which then triggers the next breath.[6] Reverse triggering has been observed in deeply sedated patients with acute respiratory distress syndrome (ARDS), and it may be promoted by sedation or sedation may make reverse triggering more apparent.

Autotriggering

Autotriggering occurs when the ventilator initiates inspiration without a corresponding patient effort due to inappropriate ventilator trigger sensitivity settings. Autotriggering most often occurs when trigger sensitivity thresholds are such that even minor fluctuations in ventilator circuit pressure and flow result in a breath trigger. With inappropriate sensitivity settings, autotriggering can occur due to ambient vibration (e.g., moving the breathing circuit), water in the circuit tubing, hyperdynamic cardiogenic contractions, system leaks, or endotracheal cuff leaks. Autotriggering can often be corrected by adjusting the ventilator trigger sensitivity setting, correcting any system leaks (e.g., replacing ventilator circuit), or draining water from the circuit.

Flow Asynchrony

Flow asynchrony occurs when the inspiratory gas flow from the ventilator is unable to match the patient's inspiratory flow demand. With a patient trigger, the patient initiates inspiration by contraction of the respiratory muscles. Although the ventilator responds by delivering gas flow to the patient, contraction of the respiratory muscles continues throughout the inspiratory phase. If the gas flow from the ventilator does not meet or exceed the patient's inspiratory flow demand, the WOB may increase substantially. With assist-control volume ventilation, this work may exceed that of spontaneous breathing.[7]

With assist-control volume ventilation, the clinician sets the tidal volume, inspiratory peak flowrate or

inspiratory time (I-time), and inspiratory flow waveform. Peak flow values ≥ 60 to 80 L/min are sometimes required to meet inspiratory demand in adult patients. Inspiratory time should match the patient's respiratory center neuro-inspiratory time; typical adult inspiratory times are 0.8 to 1.0 seconds. Flow asynchrony most commonly occurs during volume ventilation with inappropriately low peak flow settings or high inspiratory time settings. When ventilator settings are adjusted by increasing the peak flow (e.g., 60 to 80 L/min) and decreasing inspiratory time (e.g., 0.6 to 0.8 seconds) to match the patient's inspiratory flow demand and neuro-inspiratory time, the patient's WOB and flow asynchrony will decrease.

Most modern critical care ventilators allow the respiratory care clinician to select the **inspiratory flow waveform** during volume ventilation. In ventilators with clinician-selected peak flow controls, a down-ramp or decelerating flow waveform produces a high initial peak flow but increased inspiratory time (as compared to a square wave). In ventilators with a clinician-selected peak flow control, a square-wave or constant flow waveform results in a lower peak flow and decreased inspiratory time (as compared to a decreasing flow waveform). Increases in tidal volume increase inspiratory time, while decreases in tidal volume decrease inspiratory time in ventilators with a selectable peak flow control. During volume ventilation with ventilators incorporating a clinician-selected inspiratory time, the set tidal volume and I-time will determine peak flow. Most clinicians prefer a down-ramp or decreasing (aka decelerating) flow waveform because of the high initial peak flow, which then decreases throughout inspiration.

With **pressure-support ventilation (PSV)** or **pressure-control ventilation (PCV)**, modern critical care ventilators incorporate an inspiratory pressure **rise time** or pressure slope control. This control allows the clinician to adjust the rate at which flow increases from baseline to peak during pressure-supported or pressure-control breaths.[5] Rise time should be set to avoid a spike in inspiratory pressure at the beginning of the inspiratory phase, yet provide sufficient inspiratory gas flow to meet the patient's inspiratory demand. A rise time or pressure slope control is provided for pressure-limited breaths provided during PSV, PCV, pressure-control SIMV, volume support (VS), **pressure-regulated volume control (PRVC)** and **airway pressure-release ventilation (APRV)**.[5] **Figure 7-3** illustrates a fast rise time, slow rise time, and appropriate rise time with pressure-control ventilation.

With volume ventilation, if the patient's inspiratory effort increases, the work performed by the ventilator decreases and vice versa. With pressure-control ventilation, the work performed by the ventilator remains constant with changes in patients' inspiratory demand.

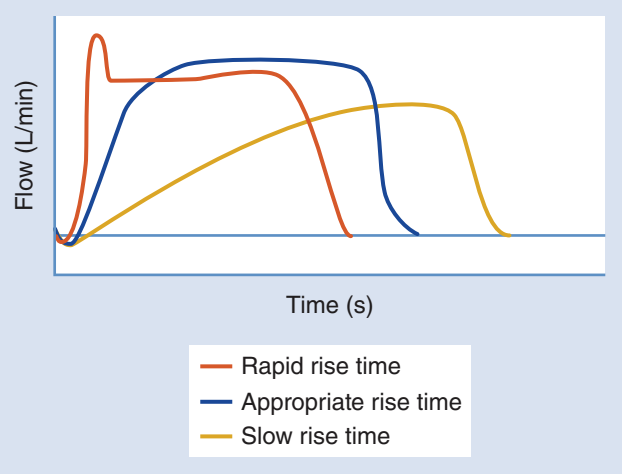

FIGURE 7-3 Pressure-Control Ventilation.

RC Insight

During volume ventilation peak flow should be adjusted to a value that meets or exceeds the patient's inspiratory flow demand.

Cycle Asynchrony

Cycle asynchrony occurs when the patient's respiratory center neurologic output and the ventilator do not match. Put another way, with cycle asynchrony there is poor coordination between the patient's desire to exhale and the ventilator's response.[5] Cycle asynchrony is most common during PCV, although it can occur in other modes.[8] If the ventilator's set inspiratory time exceeds the patient's neuro-inspiratory time, **long cycling** (delayed ventilator cycling) may occur. With delayed cycling, inspiratory times are excessive and the patient may attempt to actively exhale while the ventilator is still in the inspiratory phase, resulting in a spike in pressure at the end of the pressure-targeted breath.

If the ventilator's set inspiratory time is less than the patient's neuro-inspiratory time, **short cycling** (premature ventilator cycling) or **double cycling** may occur. With premature ventilator cycling, inspiratory times are too short. Double cycling typically occurs with volume ventilation when the ventilator's set inspiratory time and tidal volume are insufficient.

During volume ventilation using ventilators with a clinician-selected inspiratory time control, cycle asynchrony can often be corrected by altering the set inspiratory time to match the patient's respiratory center **neuro-inspiratory time**. In ventilators with peak flow controls, inspiratory time is a function of the set tidal volume and peak flow; increasing peak flow reduces inspiratory time and vice versa. **Figure 7-4** illustrates a mismatch between the patient's inspiratory time and the ventilator's inspiratory time in which the patient begins

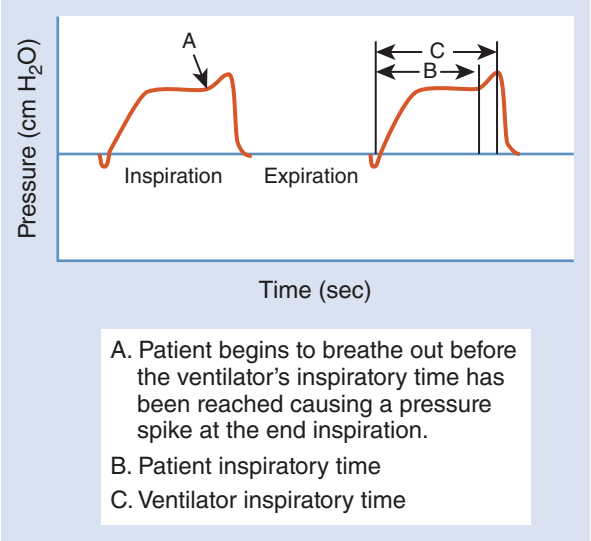

FIGURE 7-4 Cycling Asynchrony.

exhalation early resulting in a pressure spike at end inspiration in the pressure–time curve. Steps should be taken to match the patient's neuro-inspiratory time with the ventilator's inspiratory time. Inspiratory times (adults) are often set in the range of 0.8 to 1.0 seconds. Patients with high inspiratory demand may require shorter inspiratory times (e.g., 0.6 to 0.8 seconds).

With PSV, the ventilator cycles to expiration when the inspiratory flow decreases to a preset value (e.g., 10% to 25% of the inspiratory peak flow). This value works well for some patients; however, certain patients may attempt to terminate inspiration at a higher **terminal flow** (e.g., 50% of peak flow).[5] For example, a chronic obstructive pulmonary disease (COPD) patient with high levels of PSV may attempt to exhale before the machine has completed the inspiratory phase. When this occurs, the accessory muscles of expiration are employed to cycle the ventilator to the expiratory phase. Put another way, the ventilator remains in the inspiratory phase as the patient attempts to breathe out, resulting in cycle asynchrony and increased patient work. Careful observation of the pressure–time curve may reveal a spike in inspiratory pressure caused by the patient's active exhalation. This type of cycle asynchrony most commonly occurs in patients in distress and those with COPD.[5]

Modern critical care ventilators allow the clinician to adjust the PSV expiratory cycling criteria; this function may be used to correct cycle asynchrony. This function goes under various names for various ventilators, including *expiratory sensitivity* (Esens: PB 840, PB 980; range 1% to 80% peak flow); *expiratory trigger sensitivity* (ETS: Hamilton G5; range 5% to 70% peak flow); *end flow* (GE CareStation; range 5% to 80% peak flow), *expiratory termination* (Drager Evita V500; range 1% to 80% peak flow), and *inspiratory cycle off %* (Maquet Servo-i and Servo-u; range 1% to 80% peak flow). When using PSV, the respiratory care clinician should assess the patient to ensure that there is no increase in expiratory work due to cycle asynchrony and adjust the expiratory sensitivity as needed. **Figure 7-5** illustrates the effects of different flow termination criteria on the flow–time and pressure–time curves.

NAVA and PAV are designed to vary the level of support provided based on the patient's demand. NAVA uses electrical signals from the diaphragm to trigger and cycle inspiration and should minimize patient–ventilator asynchrony. The drawback to these two modes is that they will attempt to match the patient's ventilatory pattern, even if it is problematic. For example, patients with acute restrictive lung disease in respiratory failure (e.g., severe pneumonia, ARDS) often choose a rapid shallow breathing pattern.

Mode Asynchrony

Mode asynchrony occurs when the mode of ventilation selected is unable to match the patient's spontaneous ventilatory pattern.[5] Modes that increase the patient's control over of his or her own ventilatory pattern improve patient–ventilator interaction and reduce patient–ventilator asynchrony. For example, with PSV, each breath is patient triggered, pressure limited, and flow cycled. The patient initiates and terminates each breath and inspiratory flow varies with the patient's inspiratory effort; inspiratory pressure is constant, regardless of patient effort. With assist-control volume ventilation, the patient may trigger each breath; however, the inspiratory flow, flow waveform, inspiratory time, and tidal volume are determined by the clinician. While assist-control volume ventilation will deliver a consistent tidal volume breath to breath, pressures provided may decrease with increases in patient effort. Thus, PSV should improve patient–ventilator interactions and provide a more consistent level of support as compared to assist-control volume ventilation.

Proportional assist ventilation (PAV) and neurally adjusted ventilatory assist (NAVA) provide a proportional assist based on patients' inspiratory demand; as patient effort increases, ventilatory support increases, and vice versa. With PAV and NAVA, the patient triggers each breath and has control over his or her respiratory rate, inspiratory gas flow, tidal volume, inspiratory time, and expiratory time, which should improve patient–ventilator synchrony. The level of support provided by the ventilator varies with patient effort. NAVA uses a special esophageal catheter to detect the electrical discharge from the diaphragm as a reflection of the respiratory center's neural output to the diaphragm. As noted above, NAVA is specifically designed to achieve neural-ventilatory coupling to improve trigger and cycle synchrony.

As noted, breathing modes that increase patients control over their ventilatory pattern reduce the likelihood of patient–ventilator asynchrony. Modes providing patients the most control include NAVA and PAV

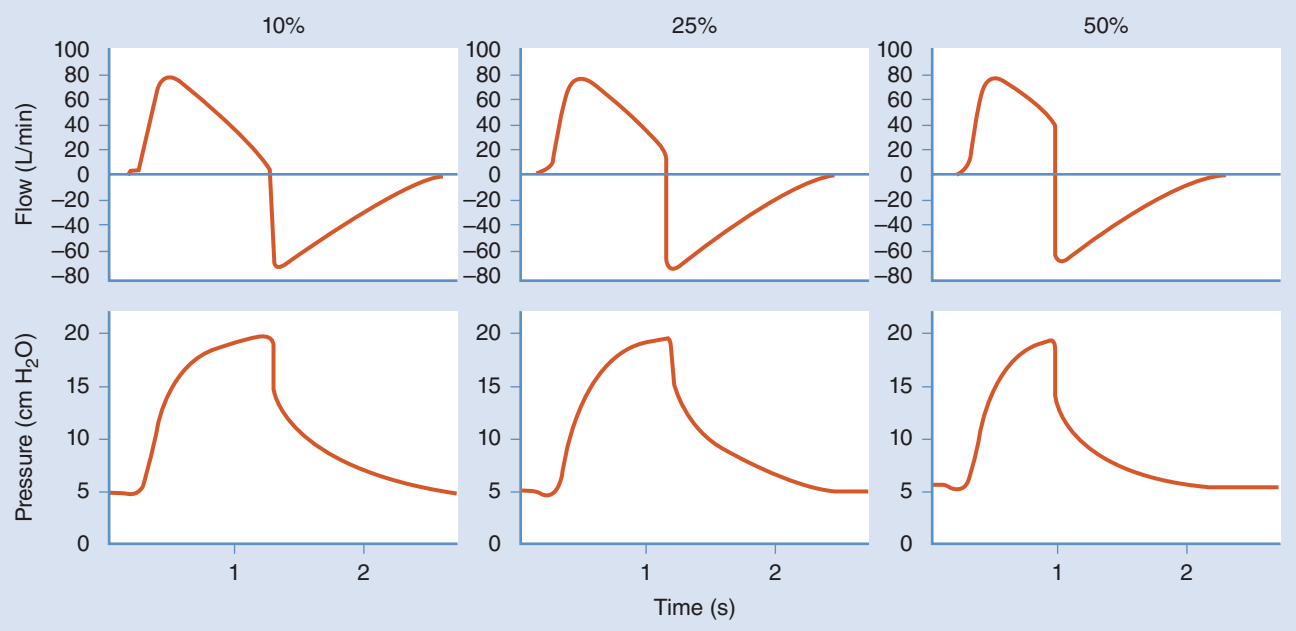

FIGURE 7-5 Effect of Changing the Flow Termination Criteria During Pressure-Support Ventilation. Note the effect on inspiratory time when a change in flow termination criteria as a percentage of peak flow is made.

followed by PSV. Assist-control PCV provides less patient control over their ventilatory pattern while assist-control volume ventilation provides patients with the least control. If mode asynchrony occurs, the respiratory care clinician may institute a different mode of ventilation that provides the patient better control of his or her ventilatory pattern.

In summary, following initiation of mechanical ventilatory support the patient should be immediately assessed for the quality of the patient–ventilator interaction by observing for trigger effort, accessory muscle use, patient–ventilator inspiratory time matching, respiratory rate, and signs of distress. Trigger work should be adjusted to minimize patient effort without autotriggering. The clinician should also carefully observe for the presence of patient efforts that do not result in a ventilator trigger or other triggering abnormalities. Inspiratory flow should meet or exceed the patient's ventilatory needs. Inadequate inspiratory flow will increase the WOB while excessive inspiratory flow may result in immediate and persistent tachypnea.

Mode of ventilation can also have a significant effect on the patient–ventilator interaction. Assist-control volume ventilation may result in an excessive trigger rate, hyperventilation, and patient–ventilator asynchrony in patients with increased respiratory drive. Inspiratory flows and times must match the patient's needs and neurologic respiratory cycle. With assist-control PCV, pressure must be adjusted to provide an adequate inspiratory volume and inspiratory time must be adjusted to match the patient's neuro-inspiratory time. SIMV can be problematic as it combines mandatory and spontaneous breaths. SIMV mandatory breaths should be adjusted to match the patient and spontaneous breaths should be pressure supported as the absence of pressure support may worsen ventilatory muscle dysfunction. PSV may improve patient–ventilator synchrony but does not guarantee tidal volume delivery. Newer adaptive modes combine the benefits of pressure control while assuring tidal volume delivery (e.g., pressure-regulated volume control [PRVC], volume support [VS]) while other newer modes (PAV, NAVA) vary the level of support provided based on the patient demand.

Oxygenation

Adequate tissue oxygenation requires adequate arterial oxygen content, sufficient cardiac output, and peripheral tissue perfusion. Arterial oxygen content (Cao_2) is dependent on arterial oxygen tension (Pao_2), arterial oxygen saturation (Sao_2), and hemoglobin level (Hb) where:

$$Cao_2 = 1.34 \times Sao_2 \times Hb + 0.003 \times Pao_2.$$

Tissue oxygen delivery ($\dot{D}O_2$) is dependent on the arterial oxygen content (Cao_2) and cardiac output ($\dot{Q}T$, total cardiac output) where:

$$\dot{D}O_2 = Cao_2 \times \dot{Q}T.$$

Cardiac output ($\dot{Q}T$, also noted as CO) is dependent on stroke volume (SV) and heart rate (HR) where:

$$\dot{Q}T = SV \times HR.$$

Normal values for each of these variables is listed in **Table 7-1**.

TABLE 7-1
Normal Values for Variables Affecting Tissue Oxygenation

Variable	Normal Breathing Room Air (range)	Clinical Goal	Comments
Pa_{O_2} (mmHg)	95 (80 to 100)	≥ 60 but ≤ 100	Pa_{O_2} varies with F_{IO_2} and lung function.
Sa_{O_2} (%)	97 (95 to 99)	≥ 90 but ≤ 99	Sa_{O_2} of 100% requires Pa_{O_2} > 150 to 200 mmHg.
Hb (g/dL)	15 (13.5 to 16.5 in men; 12 to 15 in women)	≥ 8	Tissue oxygenation may be compromised when Hb < 8 to 9 g/dL.
Ca_{O_2} (vol%)	19.8 (16 to 20)	≥ 16	Identify and correct causes of low Ca_{O_2}.
Cardiac output: $\dot{Q}_T$ (L/min)	5 (4 to 8)	Varies based on patient size	Review cardiac index (CI): CI = $\dot{Q}_T$ ÷ BSA.
Stroke volume: SV (mL)	70 (60 to100)	60 to 80	Identify and treat low SV.
Heart rate (HR)	80 to 100	80 to 100	Identify abnormalities and treat or correct.
Blood pressure (BP: mmHg) Mean arterial pressure (MAP)	120/80 (<140/90 and ≥ 90/60) 90 (80 to 100)	Within normal range; mean ≥ 65 if patient in shock	Identify abnormalities and treat or correct. Shock most commonly presents with hypotension.

Arterial oxygen saturation: Sa_{O_2}.
Arterial oxygen tension: Pa_{O_2}.
Body surface area (BSA): normal BSA is 18.5 to 24.9 m^2.
Cardiac index: CI; normal 3.5 +/– 0.7 L/min/m^2.
Cardiac output: $\dot{Q}_T$.
Oxygen content: Ca_{O_2}.
Oxygen delivery: $\dot{D}O_2 = Ca_{O_2} \times \dot{Q}_T$.

Tissue oxygenation is dependent on multiple factors including inspired oxygen concentration, alveolar ventilation, ventilation–perfusion relationships, diffusion across the alveolar–capillary membrane, arterial oxygen content, cardiac output, and peripheral perfusion. Problems in any of these areas should be identified and treated (if possible). The primary ventilator adjustments available to alter arterial oxygenation are inspired oxygen concentration (F_{IO_2}) and PEEP/CPAP. Other ventilatory techniques that may improve oxygenation in certain patients include **recruitment maneuvers**, **open lung ventilation**, and **prone positioning**. Basic respiratory care, including suctioning and airway care, **bronchial hygiene**, and bronchodilator and other inhaled medication administration, may be helpful. Less common techniques that may improve oxygenation in certain critically ill patients include inhaled nitric oxide (NO) and extracorporeal membrane oxygenation (ECMO).

F_{IO_2}

Ventilator initiation often includes providing 100% oxygen (F_{IO_2} = 1.0) as a safeguard against development of severe hypoxemia. F_{IO_2} should be rapidly **titrated** down (if possible) to avoid oxygen toxicity and related complications. These possible complications include absorption atelectasis, cellular injury, accentuation of hypercapnia, airway injury, parenchymal injury, and potentiation by bleomycin (Blenoxane).[8] Retinopathy of prematurity is a complication associated with Pa_{O_2} > 80 mmHg in premature infants. For most critically ill patients, the goal is to achieve adequate arterial oxygen levels (Pa_{O_2} ≥ 60 mmHg, Sa_{O_2} ≥ 90%) at a safe oxygen concentration (F_{IO_2} ≤ 0.50 to 0.60).

RC Insight

A clinical goal of Pa_{O_2} = 60 to 80 mmHg and Sa_{O_2} = 90% to 95% at F_{IO_2} ≤ 0.50 to 0.60 is appropriate for most patients.

Titration of F_{IO_2} is usually based on continuous pulse oximetry measurement (Sp_{O_2}), which should reflect Sa_{O_2} under most circumstances. Clinicians should be aware of factors that may cause Sp_{O_2} to be a poor surrogate for Sa_{O_2}. These include increased levels of abnormal hemoglobin (e.g., carboxyhemoglobin [CoHb], methemoglobin [MetHb], sulfhemoglobin),

high glycohemoglobin A1c in diabetics, and poor signal quality (e.g., low blood pressure, vasoconstriction, motion artifact, and probe position). Spo_2 values should be compared to measured Sao_2 via co-oximetry to verify that the values correlate; Spo2 values should correspond to Sao_2 values ± 2 to 3%.[9] **Table 7-2** compares Pao_2 to Spo_2 assuming a normal oxyhemoglobin dissociation curve to give a sense of the oxygen tensions (Pao_2) associated with specific pulse-oximetry values.

Fio_2 is titrated down from 1.0 in decrements of not more than 0.20 (20% O_2). Following each decrease the clinician should allow oxygen levels to stabilize for period of at least 10 minutes prior to the next decrease; COPD patients may take longer to stabilize. As the oxygen level approaches a more moderate value (e.g., 50% to 60%), alterations in Fio_2 should be in steps of 0.05 to 0.10 (5% to 10%) followed by assessment of Spo_2. When the desired Spo_2 is reached on a safe Fio_2, arterial blood gases should be drawn and analyzed. The goal is a Pao_2 of 60 to 80 mmHg and $Sao_2 \geq 90\%$ and/or $Spo_2 \geq 90\%$ to 92% on 40% to 60% O_2. In cases where adequate arterial oxygenation cannot be achieved at a safe Fio_2, PEEP or other techniques may be employed (see below). **Table 7-3** illustrates the titration of oxygen concentration down from an initial Fio_2 of 1.0 based on Pao_2 and Spo_2.

TABLE 7-2
Relationship Between Pao_2 and Sao_2*

Pao_2	Sao_2	Spo_2 (Sao_2 ± 2%)
100	98	100 to 96
95	97	99 to 95
90	96.9	98 to 95
85	96.4	98 to 94
80	95.7	98 to 94
75	94.9	97 to 93
70	93.8	96 to 92
65	92.4	94 to 90
60	90.6	93 to 87
55	88.2	90 to 86
50	85	87 to 83
45	80	82 to 78
40	75	77 to 73

Fio_2 in ventilated patients is often titrated based on continuous oximetry monitoring (Spo_2). Spo_2 values should be correlated with measured Sao_2 via co-oximetry. Normal Spo_2 accuracy is ± 2%. Accuracy declines when $Sao_2 < 90\%$ and is especially poor when $Sao_2 < 80\%$. The relationship between Sao_2 and Pao_2 displayed assumes a normal oxygen saturation curve and adjustments must be made based on changes in the patient's pH, $Paco_2$, body temperature, and 2 to 3 DPG.
Green = clinically acceptable values for most patients.
Yellow = moderate hypoxemia.
Red = moderate to severe hypoxemia.
Abbreviations: Pao_2, the partial pressure of oxygen in the arterial blood; $Paco_2$, partial pressure of carbon dioxide in the arterial blood; Sao_2, arterial oxyhemoglobin saturation; Spo_2, oxygen saturation as measured by pulse oximetry.
*Sao_2 values are estimates and will vary depending on the blood's chemical environment (pH, Pco_2, temperature, and 2 to 3 DPG).

In cases where initial blood gases are available, Fio_2 requirements to obtain a desired Pao_2 can be estimated using the following formula derived from the alveolar air equation and the assumption that the arterial (Pao_2) to alveolar (PAo_2) oxygen tension ratio (aka a/A ratio) remains relatively constant with recent changes in Fio_2:

$$\text{Required } Fio_2 = ([Pao_2 \text{ desired} \div \text{a/A ratio}] + Paco_2 \times 1.25] \times (1/[P_B - PH_2O])$$

Where a/A ratio is the initial measured Pao_2 divided by calculated initial alveolar oxygen tension (PAo_2); P_B and PH_2O are the barometric pressure and water vapor pressure, respectively.

A simpler, but less accurate estimate of the required Fio_2 to achieve a desired Pao_2 is:

$$\text{Required } Fio_2 = (\text{Initial } Fio_2 \div \text{Initial } Pao_2) \times \text{Desired } Pao_2.$$

Clinical Focus 7-1 illustrates use of these formulas for estimating Fio_2 based on Pao_2.

When titrating oxygen concentration, once the desired arterial oxygen level has been reached, monitoring should be continued. Oxygen levels are titrated up and down as needed with adjustments in Fio_2 of 0.05 to 0.10 (5% to 10%) to maintain Pao_2 in the range of 60 to 80 mmHg, Sao_2 90% to 97%, and/or $Spo_2 \geq 92\%$. The higher the Fio_2, the lower the concentration of nitrogen within the alveoli; therefore, some clinicians titrate the Sao_2 to 90% to 94% in all patients in order to minimize the risk of atelectasis. A lower oxygen saturation (e.g., Sao_2 88%) may be acceptable for patients requiring very high oxygen concentrations (e.g., $Fio_2 \geq 0.80$) for an extended time. O_2 concentration should be returned to 100% in emergencies and for performance of certain procedures (e.g., airway suctioning).

PEEP/CPAP

Mechanical ventilation often incorporates PEEP or CPAP to help restore or maintain lung volumes and prevent or treat atelectasis. PEEP/CPAP can be highly effective in improving oxygenation in patients with acute hypoxemic respiratory failure (e.g., ARDS, severe pneumonia, and pulmonary edema). Low levels of PEEP (e.g., 3 to 5 cm H_2O; called "**physiologic PEEP**") are thought to protect against the small decreases in

TABLE 7-3
F_{IO_2} Titration

Initial Pa_{O_2} (F_{IO_2} = 1.0)	Initial Sp_{O_2} (F_{IO_2} = 1.0)	Step 1 F_{IO_2} Decrease	Step 2 F_{IO_2} Decrease	Step 3 F_{IO_2} Decrease	Step 4 F_{IO_2} Decrease	Step 5
> 300	100%	↓20% → to 0.80 and assess Sp_{O_2}; if > 95% proceed to next step.	↓20% → to 0.60 and assess Sp_{O_2}; if > 95% proceed to next step.	↓10% → to 0.50 and assess Sp_{O_2}; if > 95% proceed to next step.	↓10% → to 0.40 and assess Sp_{O_2}; if ≥ 90% proceed to next step.	Obtain ABGs and reassess. Consider ↓5% → to 0.35 based on Sp_{O_2}.
200 to 300	100%	↓20% → to 0.80 and assess Sp_{O_2}; if > 95% proceed to next step.	↓20% → to 0.60 and assess Sp_{O_2}; if > 95% proceed to next step.	↓10% → to 0.50 and assess Sp_{O_2}; if > 95% proceed to next step.	↓10% → to 0.40 and assess Sp_{O_2}; if ≥ 90% proceed to next step.	Obtain ABGs and reassess.
150 to 199	99% to 100%	↓20% → to 0.80 and assess Sp_{O_2}; if > 95% proceed to next step.	↓20% → to 0.60 and assess Sp_{O_2}; if ≥ 90% proceed to next step.	Obtain ABGs and reassess.		
100 to 149	96% to 100%	↓20% → to 0.80; if ≥ 90% proceed to next step.	Obtain ABGs and reassess.			
< 100	< 96% to 100%	Consider increase in PEEP.				

Patients often receive 100% O_2 upon initiation of mechanical ventilation. F_{IO_2} is then rapidly titrated down based on oximetry (Sp_{O_2}) and patient observation. If an initial arterial blood gas (ABG) study demonstrates initial Pa_{O_2} values ≥ 150 mmHg while receiving 100% O_2, F_{IO_2} generally can be titrated down in increments of 0.20 for the first several steps followed by patient assessment and continued monitoring of Sp_{O_2}.

The clinician should wait 10 to 30 minutes after each decrease in F_{IO_2} to allow oxygenation values to stabilize before making any additional decreases. If the patient appears to be in distress or Sp_{O_2} falls to < 90% to 92% F_{IO_2} should be immediately returned to its previous value (or 100%) and the patient reassessed.

If initial ABGs on 100% O_2 are not available, although Sp_{O_2} is 100%, it is reasonable to **cautiously** assume that this corresponds to a Pa_{O_2} > 150 mmHg and make appropriate adjustments based on patient observation and continued Sp_{O_2} monitoring. It is generally acceptable to continue to decrease F_{IO_2} if Sp_{O_2} remains > 95%. **If at any point Sp_{O_2} falls to < 90%, immediately return to the previous F_{IO_2} (or 100% O_2) and reassess the patient.**

CLINICAL FOCUS 7-1 Oxygen Titration

Invasive mechanical ventilation is instituted for a patient in acute respiratory failure with the following settings:

Mode: assist-control volume ventilation (V-AC aka patient- or time-triggered VC-CMV)

Tidal volume: 8 mL/kg IBW

Set rate: 14 breaths/minute

F_{IO_2}: 1.0

PEEP: + 5 cm H_2O

Arterial blood gases are obtained shortly after initiation of mechanical ventilatory support:

pH: 7.36

Pa_{CO_2}: 35 mmHg

Pa_{O_2}: 182 mmHg

Sa_{O_2}: 100%

The respiratory care clinician is asked to titrate the F_{IO_2} down from 1.0 to a safe level.

Question 1. Estimate the F_{IO_2} needed to obtain a Pa_{O_2} of 100 mmHg with an Sa_{O_2} of 0.97 (97%)

The F_{IO_2} to obtain a desired Pa_{O_2} is:

$$\text{Required } F_{IO_2} = (\text{Initial } F_{IO_2} \div \text{Initial } Pa_{O_2}) \times \text{Desired } Pa_{O_2}.$$

Based on the initial oxygen concentration and initial and desired Pa_{O_2} this becomes:

$$\text{Required } F_{IO_2} = (1.0 \div 182 \text{ mmHg}) \times 100 \text{ mmHg} = 0.55 \text{ or } 55\%.$$

Question 2. Suggest an approach to decreasing this patient's F_{IO_2} based on the calculation performed above.

Based on the data provided, if the F_{IO_2} is reduced to 0.55 (55%), the patient's Pa_{O_2} should decrease to about 100 mmHg. However, initial F_{IO_2} decreases from 1.0 should be limited to a maximum of 0.20 (20%) per step followed by patient assessment and Sp_{O_2}

measurement. This patient's F_{IO_2} was decreased incrementally in a stepwise fashion, allowing 10 to 15 minutes for stabilization after each decrement in F_{IO_2}:

Initial F_{IO_2}: 1.0	Initial Pa_{O_2}: 182 mmHg	Initial Sp_{O_2}: 100%
Step 1: decrease F_{IO_2} to 0.80.		Resultant Sp_{O_2}: 99%
Step 2: decrease F_{IO_2} to 0.60.		Resultant Sp_{O_2}: 98%
Step 3: decrease F_{IO_2} to 0.55.	**Resultant Pa_{O_2}: 95 mmHg**	Resultant Sp_{O_2}: 97%

This patient's F_{IO_2} has been safely and successfully decreased from 1.0 to 0.55, resulting in a satisfactory Pa_{O_2} and oxygen saturation. The patient's F_{IO_2} can now be further decreased an additional 0.10 (10%) to 0.45, which should result in an acceptable Pa_{O_2} of about 78 mmHg with an Sp_{O_2} of about 95%. The goal is $F_{IO_2} \leq 0.50$ to 0.60 with $Pa_{O_2} \geq 60$ mmHg and/or $Sp_{O_2} \geq 92\%$.

functional residual capacity (FRC) that may occur following endotracheal intubation due to loss of normal glottic function. Small amounts of applied PEEP can also compensate for patient-trigger difficulties caused by autoPEEP. PEEP has also been used in the presence of **flail chest** to stabilize the chest wall.

Initial ventilator settings for most patients include the application of 5 to 8 cm H_2O PEEP. PEEP prevents end-alveolar collapse and may reduce the incidence of ventilator-associated pneumonia (VAP) and ventilator-associated lung injury (VALI).[10]

PEEP can cause pulmonary barotrauma or VALI by increasing alveolar pressures and causing alveolar **overdistention**.[11] PEEP increases mean airway pressure, which may reduce venous return and compromise cardiac output and blood pressure. PEEP should be used cautiously in patients with hypotension or hypovolemia. Increased intrathoracic pressures due to PEEP may reduce cerebral venous outflow; PEEP should be used with care in patients with elevated intracranial pressures (ICP). Patients with obstructive lung disease (e.g., COPD, acute asthma) may have an already elevated FRC. Except in cases to balance autoPEEP to enable ventilator triggering, PEEP should be used with caution in these patients. Other relative contraindications to PEEP include unilateral or focal lung disease, pulmonary embolism, and bronchopleural fistula.[10] PEEP may have unintended consequences in patients undergoing prone ventilation (e.g., regional lung over distention).[10] PEEP may also increase $P_{plateau}$, and care must be used to maintain $P_{plateau} < 30$ cm H_2O. Untreated tension pneumothorax is an absolute contraindication to PEEP.

Methods

Many approaches to the application of PEEP have been advanced to include minimum PEEP, **optimal PEEP** for oxygen delivery, and compliance-titrated PEEP. The ARDSNet protocol suggests use of PEEP tables, which many clinicians find effective and easy to use. Others have advocated PEEP titration using pressure–volume curves as part of a lung-protective strategy. Extrinsic or applied PEEP is also sometimes used to balance auto-PEEP in certain circumstances. Each of these methods is described below.

Minimum PEEP

PEEP can be effective in improving oxygenation in patients with hypoxemic respiratory failure. **Minimum PEEP** is simply the least PEEP needed to achieve adequate arterial oxygenation at a safe oxygen concentration. PEEP is incrementally increased (2 to 5 cm H_2O) followed by patient assessment. The lowest PEEP level that results in a $Pa_{O_2} \geq 60$ mmHg and/or $Sa_{O_2} \geq 90\%$ with $F_{IO_2} \leq 0.50$ to 0.60 is maintained. Minimum PEEP is easy to apply and results in the lowest PEEP level associated with satisfactory oxygenation. Minimum PEEP may avoid the adverse consequences sometimes associated with the application of high PEEP levels.

Optimal PEEP for Oxygen Delivery

Optimal or best PEEP can be defined as the PEEP that maximizes oxygen delivery to the tissues. Oxygen delivery ($\dot{D}O_2$) is simply arterial oxygen content (Ca_{O_2}) times cardiac output ($\dot{Q}T$) as described above. Ventilation-perfusion ($\dot{V}/\dot{Q}$) mismatch, right to left shunt, diffusion limitation, and hypoventilation may reduce arterial oxygenation and Ca_{O_2}. Specific factors that affect Ca_{O_2} include Pa_{O_2}, Sa_{O_2}, and hemoglobin level. F_{IO_2} and PEEP/CPAP may improve Pa_{O_2} and Sa_{O_2}. Cardiac output may be affected by cardiac disease or hypovolemia.

PEEP provided to maximize $\dot{D}O_2$ is increased in a stepwise fashion followed by measurement of variables associated with oxygenation and cardiac output. PEEP continues to be increased until one or more variables associated with cardiac output ($\dot{Q}T$) and tissue oxygen delivery decreases. The optimal PEEP is the PEEP level

just below that at which the decline occurred. Typical measures that have been used to assess tissue oxygen delivery to determine best or optimal PEEP include:

- Cardiac output ($\dot{Q}_T$): normal values 5 L/min (range 4 to 8 L/min)
- Cardiac index (CI = $\dot{Q}_T$/BSA): normal values 2.5 to 4 L/min/m^2
- Mixed venous oxygen tension ($P\bar{v}O_2$): normal values 40 mmHg (range 35 to 40 mmHg)
- Mixed venous oxygen saturation ($S\bar{v}O_2$): normal values 75% (70% to 75%)
- Arterial-venous oxygen content difference ($CaO_2 - C\bar{v}O_2$): normal values 5 vol% (3.5 to 5.0 vol%)
- Calculated oxygen delivery ($\dot{D}O_2$: normal value 1000 mL/min
- Arterial blood pressure (ABP): normal values 120/80 mmHg (range 90 to 140/60 to 90 mmHg)

Except for $CaO_2 - C\bar{v}O_2$, best or optimal PEEP (based on oxygen delivery) has been exceeded when these values (above) decline following an incremental increase in PEEP. $CaO_2 - C\bar{v}O_2$ increases when best or optimal PEEP has been exceeded. PEEP is returned to the level just below the level at which measures related to $\dot{D}O_2$ decline, and that value is considered the best or optimal PEEP.

Titration of PEEP to optimize tissue oxygen delivery has theoretic appeal for patients with hypoxemic respiratory failure (e.g., ARDS) and may improve arterial oxygenation. Measures reflecting $\dot{D}O_2$ can be time consuming and in some cases difficult to obtain. For example, mixed venous oxygen levels and invasive measures of cardiac output require a pulmonary artery catheter (although newer, less-invasive techniques to measure cardiac output are available). Titration of PEEP to optimize $\dot{D}O_2$ has not been shown to clearly improve other important patient outcomes (e.g., time to extubation, duration of ICU stay, or mortality) and cannot be recommended for routine application in most patients.[11,12]

Other high PEEP strategies employed in patients with ARDS may improve mortality in patients with moderate to severe ARDS but worsen it in patients with mild ARDS.[11] High PEEP strategies probably work best in ARDS patients with a large volume of recruitable lung.

PEEP–F_{IO_2} Tables

The use of PEEP–F_{IO_2} tables to adjust PEEP was first described in the landmark ARDSNet study, which demonstrated improvement in mortality in ARDS patients ventilated with lower tidal volumes.[13] In that study, the oxygenation goals were Pa_{O_2} 55 to 80 mmHg or Sp_{O_2} 88% to 95%. The tables provide higher and lower PEEP options; clinicians can choose based on the patient's condition. For example, patients expected to require higher PEEP for lung recruitment may benefit from the higher PEEP option if they are hemodynamically stable and have no barotrauma. The lower PEEP/higher F_{IO_2} option maintains PEEP in the range of 5 to 10 cm H_2O for F_{IO_2} of 0.30 to 0.60, while the higher PEEP option allows PEEP values in the range of 5 to 18 cm H_2O for F_{IO_2} of 0.30 to 0.50. Both tables allow PEEP levels of up to 24 cm H_2O on 100% oxygen. Allowable combinations of F_{IO_2} and PEEP to achieve these goals are found in **Table 7-4**. Additional information can be found at the ARDSNet website.

Compliance-Titrated PEEP

With acute hypoxemic respiratory failure patients often have reductions in pulmonary compliance and functional residual capacity (FRC). With such patients, lung compliance and FRC tend to increase as PEEP increases. Compliance-titrated PEEP seeks to identify the PEEP level at which compliance is optimized.

Compliance-titrated PEEP generally begins at a modest PEEP level (e.g., 5 cm H_2O), followed by measurement of static total compliance (C_{ST}) where:

$$C_{ST} = V_T \div (P_{plateau} - PEEP).$$

TABLE 7-4
ARDSNet PEEP–F_{IO_2} Tables

PEEP is employed in ARDS patients to improve oxygenation, facilitate alveolar recruitment, and reduce end-expiratory alveolar collapse. Patients with severe ARDS often require high initial oxygen concentrations. F_{IO_2} and PEEP are then titrated to achieve adequate oxygenation and reduce F_{IO_2}. Lower V_T (6 to 8 mL/kg) is used as part of a lung protective strategy. V_T begins at 8 mL/kg IBW and is reduced to 7 mL/kg and then to 6 mL/kg to maintain $P_{plateau} < 30$ cm H_2O. Additional V_T adjustments to maintain $P_{plateau} < 30$ cm H_2O may be necessary; respiratory rate is increased as needed to maintain $\dot{V}_E$.
PEEP–F_{IO_2} combinations are adjusted using the table below, starting with the lowest PEEP value listed for a given F_{IO_2} to achieve Pa_{O_2} 55 to 80 mmHg or Sp_{O_2} 88% to 95%. All patients receive at least 5 cm H_2O PEEP. Choice of the lower PEEP or higher PEEP strategy is optional.

Lower PEEP Strategy		Higher PEEP Strategy	
F_{IO_2}	PEEP (cm H_2O)	F_{IO_2}	PEEP (cm H_2O)
0.30	5	0.30	5 to 14
0.40	5 to 8	0.40	14 to 16
0.50	8 to 10	0.50	16 to 18
0.60	10	0.50 to 0.80	20
0.70	10 to 14	0.50 to 0.80	20
0.80	14	0.80	22
0.90	16 to 18	0.90	22
1.0	18 to 24	1.0	22 to 24

Data from National Institutes of Health (NIH) National Heart, Lung, and Blood Institute (NHLBI) ARDS Clinical Network Mechanical Ventilation Protocol summary. Available at www.ardsnet.org/files/ventilator_protocol_2008-07.pdf

CLINICAL FOCUS 7-2 Compliance-Titrated PEEP

A patient with acute hypoxemic respiratory failure is receiving mechanical ventilation in the assist-control volume ventilation mode. Initial ventilator settings include:

Mode: assist-control volume ventilation (aka VC-CMV)

Tidal volume: 8 mL/kg IBW

Set rate: 14 breaths/minute

F_{IO_2}: 1.0

PEEP: + 5 cm H_2O

The respiratory care clinician decides to provide compliance-titrated "best" PEEP for this patient and the following information is collected:

Time	F_{IO_2}	PEEP (cm H_2O)	Spo_2	V_T (mL)	$P_{plateau}$ (cm H_2O)	C_{ST} (mL/cm H_2O)
1	1.0	5	100%	500	30	20
2	1.0	8	100%	500	29	24
3	1.0	10	100%	500	28	28
4	1.0	12	100%	500	29	?
5	1.0	14	100%	500	34	?

Question 1. Calculate the patient's static total compliance (C_{ST}) at times 4 and 5.

$$C_{ST} = V_T \div (P_{plateau} - PEEP)$$

1. Answer for time #4 compliance:

$$C_{ST} = V_T \div (P_{plateau} - PEEP) = 500 \text{ mL} \div (29 \text{ cm } H_2O - 12 \text{ cm } H_2O) = 29 \text{ mL/cm } H_2O$$

2. Answer for time #5 compliance:

$$C_{ST} = VT \div (P_{plateau} - PEEP) = 500 \text{ mL} \div (34 \text{ cm } H_2O - 14 \text{ cm } H_2O) = 25 \text{ mL/cm } H_2O$$

Question 2. What is the PEEP level that results in the best static total compliance?

The best compliance value was obtained at a PEEP of 12 cm H_2O:

Time	PEEP (cm H_2O)	$P_{plateau}$ (cm H_2O)	C_{ST} (mL/cm H_2O)
1	5	30	20
2	8	29	24
3	10	28	28
4	12	29	29
5	14	34	25

Question 3. What PEEP level is most appropriate for this patient?

Compliance-titrated best PEEP is 12 cm H_2O. The resultant $P_{plateau}$ is 29 cm H_2O, which is acceptable. Suggested PEEP for this patient is 10 to 12 cm H_2O while maintaining $P_{plateau} < 30$ H_2O (slightly higher $P_{plateau}$ may be acceptable in patients with decreased thoracic compliance).

Following initial measurement of C_{ST}, PEEP is increased by 2 cm H_20 and C_{ST} measurement is repeated. PEEP continues to be increased in an incremental stepwise fashion until a decrease in compliance is observed. At that point, PEEP is lowered to the previous value that represents the best or optimal PEEP based on compliance. With nonuniform lung disease, regional overdistention can occur below the compliance-titrated PEEP level. PEEP increases mean airway and intrathoracic pressures, which may reduce venous return and cardiac output; cardiac output may be affected at PEEP levels below the optimal PEEP. **Clinical Focus 7-2** provides an example of compliance-titrated PEEP.

Pressure–Volume Curves

Static pressure–volume curves provide a visual representation of changes in pressure and volume as the lung is inflated in a stepwise fashion. To generate a static pressure–volume curve, the clinician increases volume in increments of approximately 100 mL measuring $P_{plateau}$ following each increase. The pressures and corresponding volumes are then plotted graphically (**Figure 7-6**). Often the result provides an easy to identify **lower inflection point (LIP)**, which represents the point when lung compliance improves due to alveolar recruitment. As incremental volume continues to be added, the curve tends to rise in a linear fashion until an **upper inflection point (UIP)** is reached, which represents the point at which the lung overdistention begins. PEEP is then set at approximately 2 cm above the LIP and tidal volume is adjusted to ensure that the UIP is not exceeded. Some patients, however, do not exhibit a LIP and interobserver variability can be significant. A lung recruitment maneuver may be done prior to assessing LIP for the purposes of titrating PEEP (see below). Figure 7-6 illustrates a static pressure–volume curve with

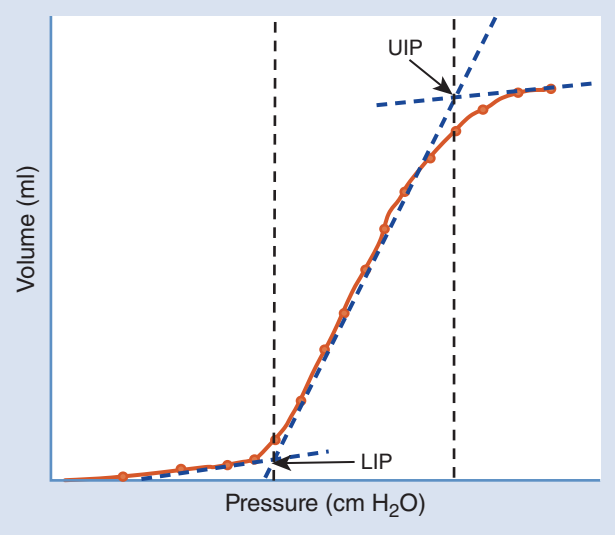

FIGURE 7-6 Static Pressure–Volume Curve Showing Upper and Lower Infection Points.

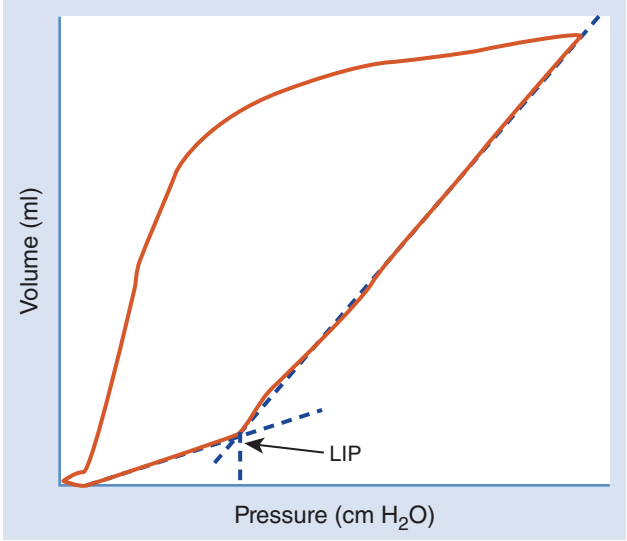

FIGURE 7-7 Slow-Flow Pressure–Volume Curve. Respiratory gas flow is approximately 6 L/min.

lower inflection point (LIP, aka p-flex) and upper inflection point (UIP) illustrated.

Development of a static pressure–volume curve is labor intensive, time consuming, and can be difficult. As an alternative, slow-flow (< 6 L/min) pressure–volume curves can be generated by most ventilator graphics packages to identify patients' lower inflection points and PEEP is set accordingly (e.g., LIP + 2 cm H_2O). **Figure 7-7** illustrates a slow-flow pressure–volume curve for identifying LIP for the purposes of setting PEEP.

Decremental PEEP Trials

Some authors suggest that the best method for identifying optimal PEEP with ARDS is a **decremental PEEP trial** performed following a lung recruitment maneuver.[14] To begin a decremental PEEP trial, a recruitment maneuver is first performed, such as the one described in **Box 7-3**. Immediately following a successful recruitment maneuver, the patient's ventilatory mode is adjusted to volume control with tidal volume in the range of 4 to 6 mL/kg IBW and an inspiratory time in the range of 0.6 to 0.8 seconds. Respiratory rate is set at a value that provides the desired minute volume without causing autoPEEP.

The decremental PEEP trial may begin with PEEP set at 20 to 25 cm H_2O (assuming those values were adequate to maintain the lung open during the recruitment maneuver).[14] The initial PEEP level chosen should be sufficient to keep the lung open based on recruitment maneuver results and may be higher in some cases. Static total compliance (Cst) is then measured and recorded (see compliance-titrated PEEP, above). The PEEP level is then decreased by 2 cm H_2O and measurement of Cst is repeated in 1 to 2 minutes (or as soon as compliance has stabilized). This process is repeated until the best PEEP based on Cst is identified. Generally, compliance improves with each decrease in PEEP until alveolar *derecruitment* and atelectasis occur, at which point Cst declines. The PEEP level immediately preceding the Cst decline is the best PEEP based on compliance using this method. The lung recruitment maneuver is repeated because derecruitment has occurred during the last Cst measurement. Following the recruitment maneuver, the applied PEEP level is adjusted to 2 to 3 cm H_2O above the best compliance PEEP to ensure optimal tissue oxygen delivery.[14]

PEEP and AutoPEEP

Intentionally applied PEEP is sometimes referred to as *extrinsic PEEP*. *Intrinsic PEEP* or *autoPEEP* is PEEP caused by incomplete gas expiration prior to the initiation of the next breath provided by the ventilator. AutoPEEP is most common in patients with obstructive lung disease; however, it may develop in any patient when inadequate expiratory time is provided. Common causes for the development of autoPEEP include inappropriate ventilator settings, high minute ventilation, expiratory flow limitation, and expiratory resistance.[10]

Minute ventilation ($\dot{V}E$) is a function of tidal volume (Vt) and respiratory rate (f). Large tidal volumes require adequate time to be exhaled while rapid respiratory rates reduce expiratory time. Bronchospasm, inflammation, or airway remodeling can cause expiratory flow limitation, which leads to hyperinflation.[10] Expiratory flow limitation is common with COPD, acute asthma, and other forms of obstructive lung disease; these patients require adequate expiratory time or dynamic hyperinflation may occur. Resistance to expiratory gas flow can occur due to the artificial airway (e.g., partially obstructed or kinked endotracheal tubes) or airway obstruction (e.g., thick secretions, tumor).

BOX 7-3 Lung Recruitment Maneuver

A variety of lung recruitment maneuvers have been suggested for ARDS to recruit closed alveoli and improve oxygenation. Recruitment maneuvers require that the patient be apneic and hemodynamically stable. Recruitment maneuvers should be performed early during the course of the disease, ideally soon after the initiation of mechanical ventilation. Recruitment maneuvers may improve oxygenation but have not been shown to improve patient outcomes. Overaggressive maneuvers may also be harmful. One method suggested for lung recruitment includes the following steps:

1. Assess the patient to ensure hemodynamic stability.
2. Apnea is required, and sedation may be necessary.
3. Adjust the ventilator to provide pressure-control ventilation (PCV) with the following settings:
   a. F_{IO_2} of 1.0
   b. PEEP of 20 to 25 cm H_2O
   c. PCV adjusted to 15 cm H_2O above set PEEP (e.g., PIP 35 to 40 cm H_2O)
   d. Respiratory rate of 15 to breaths/min
   e. I:E ratio of 1:1 or 1:2
4. Maintain settings for 2 to 3 minutes while observing patient response (heart rate, cardiac monitor, blood pressure, and Spo_2). Discontinue recruitment maneuver immediately if signs of distress appear ($Spo_2 < 85\%$; HR > 140 beats/min or < 60 beats/min; MAP < 60 mmHg or a decrease more than 20 mmHg).
5. Follow the recruitment maneuver immediately with a decremental PEEP trial.

If the lung recruitment maneuver is not successful in opening the lung, the maneuver can be repeated not sooner than 30 minutes following patient stabilization using incrementally higher PEEP levels (e.g., +5 cm H_2O). At no point should peak inspiratory pressure (PIP) during a recruitment maneuver exceed 50 cm H_2O.

HR: heart rate; MAP: mean arterial blood pressure.

Data from Kacmarek RM, Stoller JK, Heuer AJ. Initiating and adjusting invasive ventilatory support. In: Kacmarek RM, Stroller JK, Heuer AJ, Chatburn RL, Kallet RH, eds. *Egan's Fundamentals of Respiratory Care*. 11th ed. St. Louis, MO: Elsevier; 2017:1078–1110.

Resistance to expiratory gas flow will slow the rate of lung emptying and may cause autoPEEP. Inappropriate ventilator settings that may cause autoPEEP include large tidal volumes, low peak inspiratory flows, increased inspiratory time, and inadequate expiratory time.

AutoPEEP can be detected by physical assessment and observation of flow–time curves provided by the ventilator's graphics package. Breath sounds in which inspiratory airflow occurs before expiratory airflow ceases suggest the presence of autoPEEP.[10] Observation of the expiratory flow–time curves in which expiratory gas flow does not cease prior to the initiation of inspiration indicate autoPEEP. AutoPEEP can be measured directly (in the absence of patient inspiratory efforts) by applying an expiratory pause (e.g., 2 to 3 seconds) to allow airway pressure to equilibrate with alveolar pressure.[15] **Static autoPEEP** is calculated by subtracting the extrinsic PEEP from the observed end-expiratory pressure observed during the expiratory pause.[15] AutoPEEP can be difficult to measure accurately in spontaneously breathing patients and those with acute severe asthma due to airway closure.[10] **Dynamic autoPEEP** can be quantified in spontaneously breathing patients by observing the esophageal pressure change from the onset of the inspiratory effort to the point of zero flow as observed on the flow–time curve.[15]

Steps to correct autoPEEP should focus on identifying and correcting the underlying cause. Ventilator adjustments to correct or prevent autoPEEP include altering peak flow, inspiratory time, tidal volume, and respiratory rate to ensure adequate expiratory time and I:E ratio. Resistance to expiratory gas flow may be corrected by using larger endotracheal tubes and correcting (if possible) airway obstruction or mechanical factors (e.g., PEEP or expiratory valves) that are causing increased resistance. Bronchodilator and steroid administration may be helpful in the presence of expiratory flow limitation (e.g., asthma, COPD). AutoPEEP may cause triggering asynchrony and this can sometimes be corrected by the application of extrinsic PEEP of not more than 50% to 80% of the measured autoPEEP value. The use of extrinsic PEEP to correct autoPEEP should be reserved for those cases where correction of the underlying cause has been unsuccessful, and the presence of autoPEEP is causing triggering difficulty.

Application of PEEP

PEEP is commonly applied to improve oxygenation of ventilated patients in acute respiratory failure (e.g., ARDS). Extrinsic PEEP is also sometimes used to correct triggering difficulty due to autoPEEP.

Minimum PEEP

We suggest that most patients receive 5 cm H_2O of PEEP or CPAP to maintain lung volumes and prevent

atelectasis. Higher PEEP/CPAP is generally indicated for hypoxemia that is less responsive to oxygen therapy (e.g., $Pao_2 < 60$ mmHg, $Sao_2 < 90\%$ and $Fio_2 > 0.60$). Minimal PEEP to increase Pao_2 and oxygen saturation to acceptable levels while reducing Fio_2 to < 0.50 to 0.60 is a good general strategy for many patients.

ARDS

The principal causes of VALI in ARDS are thought to be alveolar overdistention and cyclic atelectasis. An **open lung strategy** may reduce the risk of VALI in ARDS patients. An open lung strategy that combines low tidal volume ventilation with a recruitment maneuver followed by titration of PEEP to maximize alveolar recruitment and minimize cyclic atelectasis has been suggested.[11] Acceptable plateau pressures (< 28 to 30 cm H_2O) are maintained to prevent alveolar overdistention.

The lack of convincing evidence that an open lung strategy is beneficial and does not cause harm suggests that this approach should not be used as an initial strategy for most patients.[11] While some clinical trials suggest that open lung ventilation may improve mortality and other important clinical outcomes, others have reported higher mortality with an open lung ventilation strategy.[11] Open lung strategies should probably be limited to patients with severe ARDS that does not respond to a conventional approach using low tidal volumes, $P_{plateau} < 28$ to 30 cm H_2O, and more conservative levels of PEEP.

Use of ARDSNet-suggested PEEP tables is probably a good initial approach for setting PEEP for most ARDS patients. Patients with severe ARDS, however, may require a *high PEEP strategy.* High PEEP can be effective in improving oxygenation in patients with recruitable lung. High PEEP may open collapsed alveoli and decrease alveolar overdistention because of the larger number of alveoli being ventilated. There is some evidence that a high PEEP strategy can improve oxygenation, increase ventilator-free days, and lower ICU mortality, although these results have not been consistently confirmed by later studies.[11] There is also evidence that a high PEEP strategy can be harmful in patients with mild ARDS.[11] It may be that a high PEEP strategy is beneficial in patients with severe ARDS with sufficient recruitable lung, but harmful in patients with little recruitable lung.[11] High PEEP should probably be avoided as an initial strategy. That said, a high PEEP strategy may be beneficial in patients with severe ARDS if they have sufficient recruitable lung.[11] **Box 7-4** illustrates a high PEEP strategy.

PEEP may cause barotrauma or VALI by increasing alveolar pressures. PEEP may also decrease venous return and reduce cardiac output. The optimal PEEP strategy for patients with ARDS has not been identified.[10,11] It is also of interest to note that lung ultrasound can be used to visualize the effects of PEEP on lung aeration in patients with ARDS, and this may prove to be of clinical value in PEEP titration in the future.[11]

BOX 7-4 High PEEP Strategy

High PEEP may be necessary in patients with severe ARDS when more conventional approaches are ineffective. The clinician should assess whether (or not) high PEEP is effective in improving oxygenation as certain patients may have limited recruitable lung (i.e., they are PEEP non-responders). A high PEEP strategy may employ the following combinations of Fio_2 and PEEP to achieve Pao_2 60 to 80 mmHg and Sao_2 90% to 95% at an $Fio_2 \leq 0.50$ to 0.60.

Fio_2	PEEP (cm H_2O)
0.30	12 to 14
0.40	14 to 16
0.50	16 to 18
0.50 to 0.80	20
0.80	22
0.90	22
1.0	22 to 24

Data from Brower RG, Lanken PH, MacIntyre N, et al. Higher versus lower positive end-expiratory pressures in patients with the acute respiratory distress syndrome. *N Engl J Med.* 2004;351(4):327–336. doi: 10.1056/NEJMoa032193.

AutoPEEP

AutoPEEP should be quickly identified and treated. Ventilator adjustments, bronchodilator, and steroid administration, and correction of any mechanical factors that are contributing to autoPEEP should be performed. In cases of persistent triggering difficulty, modest levels of extrinsic PEEP (e.g., 50% to 80% of measured autoPEEP) may be applied. A simple approach is to incrementally increase extrinsic PEEP by 1 cm H_2O until the patient is able to adequately trigger the ventilator. In no cases should intrinsic PEEP exceed 80% of the autoPEEP value.

Recruitment Maneuvers

Various recruitment maneuvers have been suggested to open collapsed alveoli and improve oxygenation in patients with ARDS. A common sustained-inflation maneuver known as "30 for 30" or "40 for 40" applies 30 cm H_2O of PEEP for 30 seconds or 40 cm H_2O of PEEP for

40 seconds. Another common method combines PCV with the peak pressures of 35 to 50 cm H_2O, inspiratory times of 1 to 2 seconds and PEEP set at 20 to 30 cm H_2O applied for a period of 1 to 3 minutes. A decremental PEEP study is performed immediately following the maneuver to identify the PEEP level necessary to maintain lung recruitment (see decremental PEEP above). Sigh breaths may also be considered a type of recruitment maneuver that may be beneficial in patients undergoing prone ventilation or with extrapulmonary causes of ARDS, although there is conflicting evidence that sigh breaths are beneficial.[11]

Recruitment maneuvers are most likely to be effective in patients with reduced FRC, and there is evidence that recruitment maneuvers improve oxygenation and ventilatory mechanics and reduce intrapulmonary shunt. They may be effective in postoperative patients with significant atelectasis and in certain patients with ARDS. There is currently little evidence that recruitment maneuvers improve important patient outcomes in ARDS (e.g., time to extubation, mortality).[16] There is wide variability in the approaches that have been used and it is uncertain if any specific approach is most effective.

Recruitment maneuvers can significantly increase peak inspiratory pressure, mean airway pressure, and intrathoracic pressure. Because recruitment maneuvers increase lung volumes, barotrauma may occur (e.g., pneumothorax). Increased intrathoracic pressures may reduce venous return and compromise cardiac output and blood pressure. Cardiac arrhythmias may develop up to and including cardiac arrest. Recruitment maneuvers require patients to be sedated to apnea and risks of the procedure must be balanced against possible benefit. Chapter 9 provides additional information regarding recruitment maneuvers.

RC Insight

When performing a recruitment maneuver carefully monitor the patient's heart rate, blood pressure, and cardiac monitor for development of arrhythmias.

Prone Positioning

Pulmonary blood flow varies with position because of gravity. Traditionally, mechanical ventilation is provided to patients lying in the supine position, which increases blood flow to the posterior portions of the lung. Prone positioning will increase blood flow to the anterior portions of the lung, which may be beneficial in improving oxygenation in ARDS patients.

With ARDS patients in the supine position, alveolar collapse is greater in posterior regions of the lung. Prone positioning will cause previously dependent portions of the lung to open and they will continue to receive most of the blood flow as now *nondependent* alveoli reopen.[16] Prone positioning is thought to improve oxygenation by placing the heart in a dependent position (the heart lies just behind the sternum), reducing the volume of dependent lung, increasing FRC, improving $\dot{V}/\dot{Q}$, and reducing shunt.[16] Prone positioning has been shown to improve oxygenation and may have a mortality benefit for those with severe ARDS.[16] Prone positioning has not been shown to reduce ICU length of stay, although it may increase the number of ventilator-free days.[16]

ARDS patients should receive a *lung protective strategy* including the use of small tidal volumes, limited plateau pressures, and the appropriate application of PEEP. Most ARDS patients can be effectively ventilated in the supine position. Prone positioning may be considered for patients with severe ARDS (e.g., $Pao_2/Fio_2 < 150$ with $Fio_2 \geq 0.60$ and PEEP ≥ 5 cm H_2O) and those with refractory hypoxemia (which can be defined as a Pao_2 rise < 5 mmHg following an increase in $Fio_2 \geq 0.10$) unresponsive to a more conventional ventilatory approach.[16] Prone ventilation should probably be initiated within the first 36 hours and maintained 18 to 20 consecutive hours.[16] Prone positioning may be stopped following patient improvement or for acute emergencies or specific procedures.[16]

Contraindications to prone positioning include shock, hemorrhage, multiple fractures or trauma, spinal instability, pregnancy, increased intracranial pressure, or recent tracheal surgery or sternotomy.[16] Prone positioning should be used with caution (if at all) in patients with severe burns, recent lung transplant, chest tubes with air leaks, major abdominal surgery, recent pacemaker insertion, or recent treatment for deep vein thrombosis (DVT).[16]

Prone positioning can be difficult and labor intensive to accomplish in the ICU. Enteral feeding can be problematic during prone positioning (e.g., vomiting) and should be approached cautiously.[16] Care should also be taken to avoid accidental extubation or dislodging vascular catheters or drainage tubes.[16] Electrocardiogram (ECG) monitoring leads can be placed on the posterior thorax and hemodynamic monitoring should continue.[16] Increased sedation is required and some patients may require neuromuscular blockade.[16] Rescue alternatives to prone positioning in ARDS include the use of ECMO or pulmonary vasodilators.[16]

Bronchial Hygiene

Bronchial hygiene techniques that may improve oxygenation in ventilated patients include suctioning and airway care, provision of adequate humidification, and administration of bronchodilators and inhaled anti-inflammatory agents. There is no strong evidence for

the effectiveness of nonpharmacologic airway clearance therapies (except in cystic fibrosis) to improve oxygenation, reduce time on the ventilator, reduce time in the ICU, or treat atelectasis and lung consolidation. Evidence for the effectiveness of bronchodilators or mucosal active medications to improve airway clearance and prevent complications such as atelectasis is also lacking. That said, absence of evidence is not the same as evidence of absence (in terms of benefit), and decision making should be made based on individual patient needs, response to therapy, and potential for harm.

Careful attention to appropriate humidification, airway suctioning, monitoring and correcting endotracheal tube position, and monitoring and adjusting airway cuff pressures is required. In cases where airway obstruction is suspected, bronchodilators and inhaled anti-inflammatory agents should be employed. Endotracheal tubes may cause reflex bronchoconstriction and we suggest routine aerosol bronchodilator administration for most invasively ventilated patients.

Early mobilization of ventilated patient may be helpful in improving oxygenation, as well as decreasing the consequences of ICU-acquired weakness.[14] This may include turning, sitting up in bed, sitting in a chair, and walking with support. The head of the bed should be elevated > 30 degrees in ventilated patients to reduce the incidence of ventilator-associated pneumonia.[14]

In summary, various methods have been used to improve oxygenation in ventilated patients including adjustment of F_{IO_2}, optimal PEEP techniques (e.g., minimum PEEP, compliance-titrated PEEP, decremental PEEP, and PEEP based on $\dot{D}O_2$), recruitment maneuvers, and prone positioning. Bronchial hygiene techniques that may improve oxygenation include bronchodilator and steroid/anti-inflammatory medications, suctioning and airway care, attention to proper humidification, and bronchopulmonary hygiene. Specific modes of ventilation may sometimes improve oxygenation in certain patients; these include pressure-control inverse-ratio ventilation (PC-IRV), airway pressure-release ventilation (APRV), and high-frequency oscillatory ventilation (HFOV). For most patients, providing the least PEEP to achieve adequate arterial oxygenation at a safe F_{IO_2} is a sound approach. PEEP tables are also a good place to start for patients with ARDS. High PEEP, open lung ventilation, recruitment maneuvers, prone positioning, PC-IRV, and rescue HFOV should be reserved for patients with severe ARDS that is refractory to a more conventional ventilatory approach.[11]

Ventilation

The primary purpose of mechanical ventilatory support is to augment or replace normal ventilation. Components of ventilation include tidal volume, respiratory rate, and minute ventilation. Ventilation directly affects carbon dioxide removal, and measurement of the arterial carbon dioxide tension (P_{aCO_2}) allows the respiratory care clinician to precisely assess the effectiveness of the ventilatory support provided and provides a guide for making needed ventilator adjustments.

Tidal Volume, Rate, and Minute Ventilation

Ventilation can be subdivided into tidal volume (V_T), respiratory rate (f), and minute ventilation ($\dot{V}_E$), where $\dot{V}_E = f \times V_T$. Ventilatory volumes and respiratory rate can be easily measured at the bedside using a handheld respirometer or with the ventilator's built-in monitoring system. Normal adult values for each of these variables are:

- f = 12 breath/min (normal range 12 to 20 breaths/min); f < 30 (but ≥ 10 breaths/min) is associated with adequate spontaneous breathing for adults in the ICU.
- V_T = 500 mL (normal range 400 to 700 mL [about 7 mL/kg IBW]); V_T > 5 mL/kg is associated with adequate spontaneous breathing.
- $\dot{V}_E$ = 6 L/min (normal range 5 to 10 L/min [about 100 mL/kg IBW]); $\dot{V}_E$ < 10 L/min but ≥ 5 L/min is associated with adequate spontaneous breathing; higher values are associated with distress.

Tachypnea, bradypnea, rapid, shallow breathing, and other abnormal breathing patterns commonly seen in adult ICU patients are described in **Box 7-5**.

Alveolar Ventilation

Alveolar ventilation per minute ($\dot{V}_A$) determines the effectiveness of ventilation and removal of carbon dioxide; $\dot{V}_A$ is determined by V_T, f, and dead space volume (V_D). The volume of gas in the conducting airways that does not participate in gas exchange is V_D anatomic, while alveoli which are ventilated but not perfused make up the V_D alveolar. V_D anatomic *plus* V_D alveolar is the physiologic dead space ($V_{D\ phys}$). Thus, alveolar ventilation ($\dot{V}_A$) is:

$$\dot{V}_A = (V_T - V_{D\ phys}) \times f.$$

Normal $V_{D\ phys}$ can be estimated at approximately 1 mL/lb IBW or 2.2 mL/kg IBW. Normal $V_{D\ phys}$ for a 150 lb (IBW) person would be about 150 mL. Thus, normal adult $\dot{V}_A$ is about 4.2 L/min (range: 4 to 5 L/min):

$$\dot{V}_A = (V_T - V_{D\ phys}) \times f = (500\ mL - 150\ mL) \times 12\ breaths/min = 4200\ mL/min = 4.2\ L/min$$

Dead space to tidal volume ratio (V_D/V_T) is sometimes measured at the bedside:

$$V_D/V_T = (P_{aCO_2} - P_{\bar{E}CO_2}) \div P_{aCO_2},$$

where P_{aCO_2} is arterial carbon dioxide tension (normally 40 mmHg; range: 35 to 45 mmHg) and $P_{\bar{E}CO_2}$

BOX 7-5 Ventilatory Pattern Alterations in ICU Patients

Alterations in spontaneous breathing are common in ICU patients and include:

- Tachypnea: f > 20 breaths/min (adults) although rates of 20 to 30 breaths/min are common in the ICU; f > 30 breaths/min is cause for concern.
  - Causes of tachypnea include anxiety, pain, hypoxemia, acute pulmonary disease, cardiac insufficiency, and metabolic acidosis.
  - f > 35 breaths/min with severe distress, air hunger, diaphoresis, and accessory muscle use may signal an impending respiratory arrest.
- Bradypnea in spontaneously breathing adults: f < 8 to 10 breaths/min.
  - Causes include excessive sedation, anesthesia, opioid drug overdose, excessive alcohol consumption, head trauma, increased intracranial pressure, neurologic disease, hypothermia, or cardiogenic shock.
- Abnormal ventilatory patterns include:
  - Rapid shallow breathing: in adults, this typically corresponds to V_T < 300 mL and f > 30 breath/min. Rapid, shallow breathing is ***not*** synonymous with hyperventilation. Most patients experiencing rapid shallow breathing are in fact *hypoventilating*.
  - Biot's breathing: rapid shallow breathing with periods of apnea sometimes seen with stroke or trauma.
  - Cheyne-Stokes breathing: cyclical increases and decreases in tidal volume with periods of apnea sometimes seen with cardiac or neurologic disease, sedation, or acid-base disturbances.
  - Kussmaul breathing: increased depth of breathing associated with diabetic ketoacidosis.
  - Obstructive sleep apnea (OSA): caused by repetitive collapse of the soft tissue of the upper airway during sleep resulting in frequent apneas, hypopneas, and respiratory effort–related sleep arousals. OSA may be seen in patients receiving inappropriate levels of support via noninvasive ventilation (NIV) and prior to endotracheal intubation and following extubation.

is mean exhaled CO_2 tension (normally 28 mmHg; range: 24 to 32 mmHg). $P\bar{E}CO_2$ should not be confused with end-tidal CO_2 (i.e. $P_{ET}\ CO_2$, which is normally about 35-40 mmHg and sometimes used as a surrogate for $PaCO_2$).

Normal V_D/V_T is 0.30 (range: 0.20 to 0.40) although patients receiving invasive mechanical ventilation with positive pressure may have a higher V_D/V_T (e.g., ≥ 0.50). Some newer ventilators (e.g., the Dräger XL ventilator) are equipped with integrated CO_2 and volume measurement capabilities, which may allow for accurate calculation of V_D/V_T in ventilated patients without requiring a separate device to measure $P\bar{E}CO_2$.

Possible causes of increased $V_{D_{phys}}$ include emphysema (which can result in obliteration of pulmonary capillaries) and pulmonary embolus (with complete occlusion of the pulmonary vessel). Additional large-bore ventilator tubing placed between the patient "Y" and the endotracheal or tracheostomy tube connection adds additional rebreathed gas volume known as *mechanical dead space*.

Alterations in mechanical ventilatory support that increase $\dot{V}_A$ include increased V_T, increased f, and decreased mechanical dead space (if present). Ventilator changes that decrease $\dot{V}_A$ include decreased V_T, decreased f, and the addition of mechanical dead space.

Alveolar Ventilation and $Paco_2$

The relationship between alveolar ventilation ($\dot{V}_A$) and $PaCO_2$ is defined by the following equation:

$$\dot{V}_A = (0.863 \times \dot{V}CO_2) \div PaCO_2,$$

where:

- $\dot{V}_A$ is alveolar ventilation in L/min (normally 4 to 5 L/min).
- $\dot{V}CO_2$ is carbon dioxide production in mL/min (normally about 200 mL/min, although this varies with activity, metabolic rate, and diet).
- $PaCO_2$ is the partial pressure of arterial carbon dioxide in mmHg (normally 40 mmHg [range 35 to 45 mmHg]).
- 0.863 is a conversion factor.

The above equation can be rearranged as follows:

$$PaCO_2 = (0.863 \times \dot{V}CO_2) \div \dot{V}_A.$$

Inserting normal values, this becomes:

$$\dot{V}_A = (0.863 \times 200) \div 4.3 = 40 \text{ mmHg}.$$

Assuming $\dot{V}CO_2$ is constant, this can be further simplified to:

$$PaCO_2 = \frac{k}{\dot{V}_A}$$

This should make it clear that $Paco_2$ and $\dot{V}A$ are inversely proportional and as:

- $\dot{V}A$ increases → $Paco_2$ decreases.
- $\dot{V}A$ decreases → $Paco_2$ increases.

This allows the following definitions:

- Normal ventilation: $Paco_2$ of 40 mmHg (range 35 to 45 mmHg)
- Hyperventilation: $Paco_2 < 35$ mmHg
- Hypoventilation: $Paco_2 > 45$ mmHg

Thus, $Paco_2$ is the single best clinical indicator of alveolar ventilation and provides the best measure of the effectiveness of ventilatory support provided during mechanical ventilation. It is important to note, however, that changes in carbon dioxide production ($\dot{V}co_2$) may alter $Paco_2$. Causes of increased $\dot{V}co_2$ include fever, agitation, increased level of activity, "fighting the ventilator," overfeeding, and hypermetabolism seen with sepsis, burns, and trauma.[14,17] Decreased $\dot{V}co_2$ may occur with relaxation, sleep, sedation, general anesthesia, administration of paralytic drugs, cooling, or slowed metabolic rate.[14,17] The normal response to increased $\dot{V}co_2$ is increased $\dot{V}A$; $Paco_2$ will increase if the patient is unable to compensate for increased carbon dioxide production by increasing alveolar ventilation.

$Paco_2$ during Mechanical Ventilation

A major goal of mechanical ventilation is to provide ventilatory support resulting in satisfactory alveolar ventilation as assessed by measurement of $Paco_2$. For most patients, the goal is to normalize $Paco_2$ in the range of 35 to 45 mmHg. In the absence of a metabolic acid-base disorder, a normal $Paco_2$ should result in a normal arterial pH of 7.35 to 7.45.

An exception to the goal of normalizing $Paco_2$ in the range of 35 to 45 mmHg are COPD patients whose "normal" baseline state is *chronic ventilatory failure* (aka chronic hypercapnic respiratory failure). Such patients are chronically hypercapnic resulting in a normal or near-normal pH due to renal compensation. With acute exacerbation of their COPD, these patients may develop *acute ventilatory failure superimposed on chronic ventilatory failure* characterized by a further elevated $Paco_2$ and acidotic pH (e.g., < 7.35). The goal of ventilatory support for these patients is to return their $Paco_2$ to their baseline levels. In such cases, mechanical ventilation resulting in a $Paco_2$ of 50 to 60 mmHg will often return the pH to near the baseline value; pH in 7.30 to 7.35 is a reasonable target for such patients.[14]

Intentional Hyperventilation

Low arterial carbon dioxide tension produces cerebral vasoconstriction and reduces intracranial pressure (ICP). Certain patients with dangerously elevated ICP may be briefly hyperventilated to achieve a $Paco_2$ between 26 and 30 mmHg to cause cerebral vasoconstriction and reduce ICP. This is a short-term strategy to prevent the brain from herniating and the beneficial effects start to decrease after 6 to 12 hours. Patients that may benefit from this strategy include those with very high ICP concurrent with cerebral edema, intracranial hemorrhage, or bacterial meningitis. Such a strategy is not recommended as a part of initial ventilator setup (unless life-threatening brain herniation is feared) or for patients with stroke or traumatic brain injury, as it may reduce local cerebral perfusion.

Permissive Hypercapnia

Permissive hypercapnia refers to a ventilatory strategy that decreases VT and associated delivery pressures to reduce alveolar pressures and minimize alveolar overdistention. With permissive hypercapnia, $Paco_2$ rises and pH falls, resulting in a respiratory acidosis.

The respiratory rate is increased to minimize the degree of acidosis while avoiding the introduction of autoPEEP.[11] Permissive hypercapnia may improve outcomes in certain patients with severe ARDS. Permissive hypercapnia can also be a useful approach in the presence of severe bronchospasm with acute asthma exacerbation or exacerbation of COPD. Most patients will tolerate a $Paco_2$ in the range of 45 to 65 mmHg with pH in the range of 7.25 to 7.35 well.[18] There is no established upper limit for $Paco_2$ or lower limit for pH when pursuing a permissive hypercapnia strategy.[18] Ventilator changes that allow $Paco_2$ to rise should be made slowly and incrementally, limiting increases to a rate of 10 mmHg per hour or less.[18] Use of sodium bicarbonate to correct pH ≤ 7.20 to 7.25 should be considered.[18] Permissive hypercapnia should be avoided in patients with increased intracranial pressure (ICP), head trauma, cerebral edema, brain lesions, or seizure disorders.[18]

Ventilator Adjustments to Alter $Paco_2$

Ventilator adjustments that will decrease $Paco_2$ include increased VT, increased f, or decreased mechanical VD (if present). Ventilator adjustments that will increase $Paco_2$ include decreased VT, decreased f, or the addition of mechanical VD. Changes in alveolar ventilation ($\dot{V}A$) required to obtain a desired $Paco_2$ can easily be calculated (assuming no change in $\dot{V}CO_2$):[14,17]

$$\text{Initial } Paco_2 \times \text{Initial } \dot{V}A = \text{Desired } Paco_2 \times \text{Desired } \dot{V}A$$

This can be rearranged to calculate the alveolar ventilation required to make a desired change in $Paco_2$:

$$\text{Desired } \dot{V}A = (\text{Initial } Paco_2 \times \text{Initial } \dot{V}A) \div \text{Desired } Paco_2$$

For example, if a patient receiving mechanical ventilation has a $\dot{V}A$ of 3.5 L/min, resulting in a $Paco_2$ of

50 mmHg, the $\dot{V}_A$ needed to lower the patient's P_{aCO_2} to 40 mmHg would be 4.375 L/min:

$$\text{Desired } \dot{V}_A = (\text{Initial } P_{aCO_2} \times \text{Initial } \dot{V}_A) \div \text{Desired } P_{aCO_2} = (50 \times 3.5) \div 40 = 4.375 \text{ L}$$

Thus, if the patient's alveolar ventilation was increased from 3.5 L/min to 4.375 L/min, the P_{aCO_2} would to decrease from 50 mmHg to 40 mmHg.

Recall that alveolar ventilation is simply tidal volume minus dead space times respiratory rate:

$$\dot{V}_A = (V_T - V_{D\,phys}) \times f$$

Substituting tidal volume, dead space, and respiratory rate into our predictive equation, we have:

$$\text{Desired } \dot{V}_A = (\text{Initial } P_{aCO_2} \times \text{Initial } \dot{V}_A) \div \text{Desired } P_{aCO_2}$$

$$\text{Desired } ([V_T - V_{D\,phys}] \times f) = \text{Initial } (P_{aCO_2} \times ([V_T - V_{D\,phys}] \times f) \div \text{Desired } P_{aCO_2}$$

This equation has the potential to accurately predict the effect of changes in tidal volume, respiratory rate, or physiologic dead space on P_{aCO_2} (assuming no change in $\dot{V}_{CO_2}$). The equation is cumbersome to use and requires accurate input of all the variables. As an alternative, some clinicians substitute minute ventilation as follows:

$$\text{Desired } \dot{V}_E = (\text{Initial } \dot{V}_E \times \text{Initial } P_{aCO_2}) \div \text{Desired } P_{aCO_2}$$

This equation uses minute ventilation alone to predict changes in P_{aCO_2} and requires that $\dot{V}_{CO_2}$ and V_D remain unchanged. For example, if a patient's initial minute ventilation and P_{aCO_2} were 8 L/min and 25 mmHg respectively, the equation suggests that if the minute ventilation is reduced to 5 L/min the P_{aCO_2} will rise to 40 mmHg:

$$\text{Desired } \dot{V}_E = (\text{Initial } \dot{V}_E \times \text{Initial } P_{aCO_2}) \div \text{Desired } P_{aCO_2}$$

$$\text{Desired } \dot{V}_E = (8 \text{ L/min} \times 25 \text{ mmHg}) \div 40 \text{ mmHg} = 5 \text{ L/min}$$

This equation provides a rough estimate of the effect changes in $\dot{V}_E$ on P_{aCO_2} and assumes V_D and $\dot{V}_{CO_2}$ are constant.

Rate Changes Effect on P_{aCO_2}

Tidal volume for patients receiving mechanical ventilatory support generally is initiated at 6 to 8 mL/kg IBW and titrated up or down to ensure $P_{plateau} < 28$ to 30 cm H_2O. This leaves ventilator rate adjustments as the primary tool for altering the patient's P_{aCO_2}. In apneic patients it is very easy to predict the effect of a specific rate adjustment on the patient's P_{aCO_2} (assuming V_T and V_D have not changed). Recall that alveolar ventilation is simply tidal volume minus dead space times respiratory rate:

$$\dot{V}_A = (V_T - V_{D\,phys}) \times f$$

Substituting tidal volume, dead space, and respiratory rate into our earlier predictive equation, we have:

$$\text{Desired } \dot{V}_A = (\text{Initial } P_{aCO_2} \times \text{Initial } \dot{V}_A) \div \text{Desired } P_{aCO_2}.$$

$$\text{Desired } ([V_T - V_{D\,phys}] \times f) = \text{Initial } (P_{aCO_2} \times ([V_T - V_{D\,phys}] \times f) \div \text{Desired } P_{aCO_2}$$

Assuming no change in V_T or $V_{D\,phys}$, this becomes:

$$\text{Desired } f = (\text{Initial } P_{aCO_2} \times f) \div \text{Desired } P_{aCO_2}.$$

If an apneic patient receiving mechanical ventilation has a respiratory rate of 12 breaths/min, resulting in a P_{aCO_2} of 50 mmHg, the rate needed to lower the patient's P_{aCO_2} to 40 mmHg would be 15 breaths/min:

$$\text{Desired } f = (\text{Initial } P_{aCO_2} \times \text{Initial } f) \div \text{Desired } P_{aCO_2} = (50 \times 12) \div 40 = 15 \text{ breaths/min}$$

Tidal Volume and P_{aCO_2}

Alterations in tidal volume will affect alveolar ventilation and P_{aCO_2}. With apnea during time-triggered volume ventilation, the respiratory care clinician can easily adjust V_T to obtain a desired P_{aCO_2} using a modification of our predictive equation:

$$\text{Desired } V_T = (\text{Initial } P_{aCO_2} \times \text{Initial } V_T) \div \text{Desired } P_{aCO_2}$$

Assuming respiratory rate and dead space remain constant, if an apneic patient receiving mechanical ventilation has a V_T of 400 mL resulting in a P_{aCO_2} of 50 mmHg, the V_T needed to lower the patient's P_{aCO_2} to 40 mmHg would be 500 mL:

$$\text{Desired } V_T = (\text{Initial } P_{aCO_2} \times \text{Initial } V_T) \div \text{Desired } P_{aCO_2} = (50 \times 400) \div 40 = 500 \text{ mL}.$$

This predictive equation requires that $\dot{V}_{CO_2}$ and V_D be constant. $\dot{V}_{CO_2}$ may vary with changes in metabolic rate, although these changes are less likely within the time interval typically used to adjust V_T and obtain followup ABGs. Dead space, however, may change with changes in V_T. For example, during positive-pressure ventilation, an increase in V_T will often be accompanied by increased airway pressure. This increased airway pressure may increase inspiratory mechanical bronchodilation. Put another way, the conducting airways may increase in diameter due to the positive pressure resulting in a small increase in anatomic dead space. The reverse may occur with decreases in V_T during positive-pressure ventilation.

Tidal volume adjustments will also affect peak inspiratory pressure and $P_{plateau}$. For most patients, V_T should

be maintained in an appropriate range (e.g., 6 to 8 m/kg IBW), and any adjustments made should not cause $P_{plateau}$ to increase beyond 28 to 30 cm H_2O.

Control Mode Volume Ventilation (Time-Triggered VC-CMV)

For apneic patients in whom the respiratory care clinician has control over the patient's tidal volume, respiratory rate, and minute ventilation (e.g., time-triggered volume ventilation), it is very easy to predict the ventilator changes required to achieve a desired $PaCO_2$ using one of the methods described above. To decrease $PaCO_2$, the clinician may increase the respiratory rate or increase V_T using the formulas provided. Typically, the change is made followed by an arterial blood gas (ABG) in 20 or 30 minutes to confirm that the desired $PaCO_2$ has been reached. It is generally a safe assumption that there will be little or no change in $\dot{V}CO_2$ or V_D within that time interval. To increase $PaCO_2$, the clinician simply decreases V_T or f as described followed by an ABG in 20 to 30 minutes.

The addition of mechanical dead space volume provides another method to alter $PaCO_2$ during mechanical ventilation in the control mode. Large-bore tubing may be added between the ventilator connection and the patient "Y" in order to increase rebreathed volume and $PaCO_2$. Dead space tubing is typically added in increments 6 inches in length, each of which adds 50 to 70 mL of mechanical dead space.[14,17] While the application of mechanical dead space provides an additional method to alter $PaCO_2$, the results are less predictable. This method should *not* be used in patients able to trigger the ventilator or modes that incorporate spontaneous breathing. The effect of mechanical dead space increases with small tidal volumes. The removal of V_D should decrease $PaCO_2$, and the effect can be significant when smaller tidal volumes are being employed. It also should be noted that heat moisture exchange (HME) humidifiers increase mechanical dead space, and the amount added varies by brand.

Most patients receiving mechanical ventilatory support are breathing spontaneously and have some control of their respiratory rate as the case with assist-control ventilation. Other modes of ventilation such as PSV, PAV, and NAVA provide the patient a great deal of control over their respiratory rate, tidal volume, and inspiratory time. While this is good for patient–ventilator synchrony, it makes ventilator adjustments to achieve a desired $PaCO_2$ much less precise.

Assist-Control Ventilation

Assist-control ventilation may be employed as assist-control volume ventilation (VC-CMV) or assist-control pressure-control ventilation (PC-CMV). With assist-control ventilation, a backup respiratory rate is set by the clinician; however, the patient may trigger the ventilator as often as desired above that minimum rate threshold. With properly set trigger sensitivity, each patient's inspiratory effort results in a mandatory breath. Should the patient cease inspiratory efforts, the respiratory rate will fall to the set minimum. Typical backup rate settings are 10 to 12 breaths/min or 2 to 4 breaths/min less than the patient's resting trigger rate.
In traditional assist-control volume ventilation, the mandatory breath delivers a set tidal volume, and the clinician determines the peak flow, flow waveform, and inspiratory time. The respiratory rate and expiratory time are determined by the patient. Should the patient cease triggering the ventilator, a minimum guaranteed minute ventilation will be provided. Normally, the backup rate is set to assure a minimum minute ventilation should the patient become apneic.

With *assist-control PCV*, the clinician determines the inspiratory pressure and inspiratory time, while patient effort (assuming appropriate trigger sensitivity) determines the respiratory rate. Tidal volume is determined by the inspiratory pressure, inspiratory time, and patient effort. Inspiratory pressure for mandatory breaths will be constant, but V_T will vary with the patient's pulmonary mechanics (compliance and resistance) and inspiratory effort. There are also dual and adaptive control modes that allow for patient-triggered breaths to set the rate and provide a volume guarantee (on average for adaptive targeting) using pressure control (e.g., *PRVC,* available with the Maquet Servo-i and Servo-u). Should the patient cease triggering the ventilator, a minimum guaranteed backup ventilation rate will provided.

With controlled ventilation, the clinician can set the respiratory rate and tidal volume or inspiratory pressure to achieve the desired level of ventilatory support. With assist-control ventilation, patients set their own respiratory rate and can trigger mandatory breaths as often as needed or desired. $PaCO_2$ is determined by the assist rate, which is set by the patient. Patients may increase or decrease their respiratory rates, based on their physiologic needs. Should apnea occur due to sedation or other reasons, the minimum backup rate is provided.

In most cases, the patient's respiratory center will dictate a trigger rate resulting in an appropriate level of alveolar ventilation, $PaCO_2$, and pH. Some patients, however, will trigger the ventilator too rapidly, resulting in alveolar hyperventilation, decreased $PaCO_2$, and respiratory alkalosis. Common causes of rapid ventilator triggering include pain, anxiety, hypoxemia, respiratory distress, bronchospasm, airway secretions, inappropriate ventilator settings, and metabolic acidosis. Sepsis and hepatic encephalopathy are additional conditions that may result in hyperventilation. Rapid trigger rates can result in reduced expiratory time, poor I:E ratio, increased mean airway pressure, and the development of autoPEEP. Patient–ventilator asynchrony may result, increasing the WOB and causing the patient to fight the ventilator.

The respiratory care clinician should promptly identify and correct causes of rapid triggering. Anxiety can sometimes be relieved by reassuring the patient. Pain assessment tools should be employed, and appropriate pain management protocols utilized.[19] Hypoxemia should be recognized and immediately addressed by adjustments in F_{IO_2} and PEEP and correction of treatable causes (e.g., bronchospasm, airway secretions). Causes of metabolic acidosis should be identified and treated. Inappropriate ventilator settings should be corrected promptly. This may include adjustment of peak inspiratory flow, inspiratory time, tidal volume, inspiratory pressure, trigger sensitivity (e.g., autotriggering), or mode of ventilation.

An alternative to assist-control ventilation is SIMV with pressure support. SIMV with pressure support allows the patient to continue to spontaneously breathe in between mandatory breaths, but the volume for spontaneous breaths will be reduced and alveolar hyperventilation less likely. SIMV with pressure support should also reduce mean airway pressure as compared to continuous mandatory ventilation.

Sedation may improve patient–ventilator synchrony and reduce inappropriate trigger rates. Sedation protocols should be employed that include intermittent sedation with daily interruption. Administration of neuromuscular-blocking agents will allow for complete control of the patient's ventilation; however, these should not be employed except as a last resort (see below).

IMV/SIMV and P_{aCO_2}

SIMV intersperses mandatory breaths and spontaneous breathing. SIMV may be employed to deliver volume- or pressure-control mandatory breaths. Spontaneous breaths may be provided with pressure augmentation (pressure support or automatic tube compensation [ATC]) and PEEP/CPAP may be added.

With volume SIMV (V-SIMV), tidal volume is typically initiated in the range of 6 to 8 mL/kg IBW with the mandatory respiratory rate sufficient to provide full ventilatory support (e.g., 12 to 14 breath/min). Care is taken to ensure $P_{plateau} < 28$ to 30 cm H_2O. PEEP/CPAP is initially set at 5 cm H_2O and adjusted in combination with F_{IO_2} to meet oxygenation goals. Pressure support is provided in the range of 5 to 10 cm H_2O to balance the imposed WOB of the endotracheal or tracheostomy tube. Pressure support is often adjusted to assure the patient's spontaneous tidal volumes are at or above the patient's estimated dead space (1 mL/lb IBW). Patients may take as many or as few spontaneous breaths in between mandatory breaths as desired. Factors that affect alveolar ventilation and P_{aCO_2} with V-SIMV include:

- Mandatory V_T
- Mandatory rate (f)
- Spontaneous V_T
- Spontaneous f
- Pressure-support level

In general, as the mandatory rate is decreased, patients will tend to increase their level of spontaneous breathing and the effect on P_{aCO_2} is difficult to predict. As mandatory rate increases, P_{aCO_2} tends to decrease. As the PSV increases, patients' spontaneous V_T tends to increase, and this should reduce WOB and may reduce P_{aCO_2}. With V-SIMV, once appropriate V_T, rate, and PSV values have been determined, SIMV rate is simply titrated up and down to meet the patient's ventilatory needs. As with other forms of volume-control ventilation, SIMV trigger sensitivity must be appropriate and mandatory breath peak flow, flow waveform, and inspiratory time must be adjusted to avoid patient–ventilator asynchrony.

Pressure-control SIMV (P-SIMV) is initiated in a similar fashion as V-SIMV. The primary difference is that inspiratory pressure and inspiratory time are set by the clinician, and mandatory breath tidal volume varies with the patient's pulmonary mechanics and patient effort. Generally, P-SIMV is initiated at the pressure-control level necessary to obtain V_T in the range of 6 to 8 mL/kg IBW with the mandatory respiratory rate sufficient to provide full ventilatory support (e.g., 12 to 14 breath/min). PSV and PEEP/CPAP are set in a similar fashion to V-SIMV. The primary advantage of P-SIMV is that inspiratory pressures are consistent and will not change with changes in the patient's pulmonary mechanics or inspiratory effort. This ensures that alveolar pressures and $P_{plateau}$ will remain in a safe range (e.g., $P_{plateau} < 28$ to 30 cm H_2O) assuming appropriate pressure-control values are set by the clinician. As with all pressure-control modes, mandatory breath V_T will vary with changes in the patient's pulmonary mechanics and inspiratory effort. As with V-SIMV, P-SIMV mixes mandatory breaths with spontaneous breathing and the effect of ventilator changes on P_{aCO_2} are difficult to predict. Trigger sensitivity, inspiratory pressure, and inspiratory time must be adjusted to meet the patient's needs and avoid patient–ventilator asynchrony. Once appropriate initial ventilator settings have been determined, P-SIMV mandatory rate is simply titrated up and down to meet changes in the patient's ventilatory needs.

PSV and P_{aCO_2}

Pressure support may be used as the primary mode of ventilatory support. When used as the primary mode of ventilation, the PSV level is generally adjusted to achieve a tidal volume in the range of 4 to 8 mL/ kg IBW at a patient-triggered respiratory rate of ≤ 25 breaths/min. Pressure support allows the patient to trigger and cycle each breath and the patient has control of his or her respiratory rate, inspiratory and expiratory times, and I:E ratio. Tidal volume is determined by inspiratory pressure and patient effort. PSV should provide good patient–ventilator interaction and

reduce the likelihood of patient–ventilator asynchrony. Because the patient sets the respiratory rate, the clinician has little control over the $Paco_2$. Assuming an intact, properly functioning respiratory control center, the result should be an appropriate $Paco_2$ and pH. The patient can then vary his or her respiratory rate as their physiologic needs change.

Assuming a patient with an intact and properly functioning respiratory control center, problems associated with PSV are primarily related to inappropriate ventilator settings. Slow rise times or inappropriate expiratory cycle criteria can result in increased WOB and patient–ventilator asynchrony. Care should also be taken to set an appropriate inspiratory pressure level that results in adequate gas flow and volume that meets the patient's inspiratory needs. PSV does not allow for the setting of a backup control rate and PSV should *not* be used in patients who experience periods of apnea or who have irregular breathing patterns. If PSV is employed as the primary mode of ventilatory support, care should be taken to ensure that an appropriate backup apnea ventilation mode has been set.

Acid-Base Balance

Patients in respiratory failure often experience acid-base disorders and the patient's ventilatory status can have a significant impact on acid-base balance as described by the simplified form of the Henderson-Hasselbalch equation:

$$pH = pK_a + \log \frac{[HCO_3^-]}{[H_2CO_3]}$$

and

$$pH = pK_a + \log \frac{[HCO_3^-]}{[Pco_2 \times 0.03]}$$

Where pK_a is the $-\log(K_a) = 6.1$, HCO_3^- is the bicarbonate ion concentration (mEq/L), H_2CO_3 is the carbonic acid concentration, Pco_2 is the partial pressure of carbon dioxide in mmHg, and 0.03 is the solubility constant for CO_2 in plasma ($H_2CO_3 = Pco_2 \times 0.03$).

Normal arterial blood pH is 7.40 with a range of 7.35 to 7.45, while normal $Paco_2$ is 40 mmHg (range 35 to 45 mmHg) and normal bicarbonate concentration (HCO_3^-) is 24 mEq/L (range 22 to 28 mEq/L).

Because mechanical ventilatory support has the potential to significantly alter patients' alveolar ventilation and $Paco_2$, the respiratory care clinician must understand the relationship between $Paco_2$ and pH when making ventilator adjustments. Increases in V_T, f, and $\dot{V}_E$ generally result in decreased $Paco_2$ while decreases in these values generally result in increased $Paco_2$.

Acute increases in $Paco_2$ will cause a corresponding decrease in pH while acute decreases in $Paco_2$ will increase pH. The effects of acute changes in $Paco_2$ on pH and HCO_3^- are as follows:

- For every 10-mmHg increase in $Paco_2$ (acutely), the pH decreases approximately 0.08 units; so for every 1-mmHg increase, the pH decreases 0.008 units.
- For every 10-mmHg increase in $Paco_2$ (acutely) HCO_3^- will increase about 1 mEq/L. This small increase in HCO_3^- is due to increased CO_2 and does not represent renal compensation; every 1-mmHg of increase will increase HCO_3^- about 0.1 mEq/L.

For example, a sudden rise in $Paco_2$ from 40 to 60 mmHg due to a change in the level of mechanical ventilatory support provided would cause the pH to decrease from 7.40 to 7.24; HCO_3^- would increase from 24 mEq/L to 25 mEq/L (assuming normal initial values).

With respect to sudden decreases in $Paco_2$, the relationships between $Paco_2$, pH, and HCO_3^- are as follows:

- For every 10-mmHg decrease in $Paco_2$ (acutely), pH increases approximately 0.08 units.
- For every 10-mmHg decrease in $Paco_2$ (acutely), HCO_3^- decreases about 2 mEq/L.

For example, a sudden decrease in $Paco_2$ from 40 to 30 mmHg due to an increase in the level of ventilatory support provided, would cause the pH to increase from 7.40 to 7.48; HCO_3^- would decrease from 24 mEq/L to 22 mEq/L (assuming normal initial values).

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For acute increases in $Paco_2$, every 1-mmHg increase in $Paco_2$ will decrease pH by 0.008; for acute decreases in $Paco_2$, every 1-mmHg decrease in $Paco_2$ will increase in pH by 0.008.

Chronic alterations in the level of ventilation and $Paco_2$ will also affect acid-base balance. A chronic increase in $Paco_2$ of 10 mmHg will cause plasma HCO_3^- to increase about 4 to 5 mEq/L due to renal compensation, which takes 3 to 5 days to complete. With chronic decreases in $Paco_2$ of 10 mmHg, HCO_3^- will decrease about 4 to 5 mEq/L due to renal compensation. With chronic alterations in the level of ventilation and $Paco_2$, pH will often return to near-normal due to renal compensation; this process generally takes at least 3 to 5 days to complete.

Clinically, patients may be inappropriately over- or underventilated (as compared to their baseline status) following ventilator initiation, and this will immediately

affect their pH. If overventilation continues for a period of days, renal compensation will ensue, and the result will be an artificially created compensated respiratory alkalosis. When ventilator discontinuance is attempted, patients may continue to try and spontaneously hyperventilate to maintain their pH.

If underventilation occurs for a period of days, renal compensation will also occur, resulting in an artificially created compensated respiratory acidosis. When ventilator discontinuance is attempted, these patients may continue to spontaneously hypoventilate in order to maintain their pH. The goal for mechanical ventilatory support should be to rapidly achieve a normal or near-normal $Paco_2$ and pH for that patient. **Table 7-5** lists normal arterial blood gas values.

TABLE 7-5
Normal Arterial Blood Gas Values

Analyte (units)	Description	Normal (range)
pH	–log [H^+]	7.40 (7.35 to 7.45)
$Paco_2$ (mmHg)	Arterial carbon dioxide tension	40 (35 to 45)
Pao_2 (mmHg)	Arterial oxygen tension	95 (80 to 100)
Sao_2 (%)[a]	Arterial oxygen saturation	97.5 (95 to 98)
CoHb (%)[a]	Carboxyhemoglobin	0.5 to 1.5
MetHb (%)[a]	Methemoglobin	0.0 to 1.5
Hb (g/dL)[a]	Hemoglobin	15 (men: 13.5 to 16.5; women: 12 to 15)
CaO_2 (mL/dL or vol%)[a]	Arterial oxygen content	19.8 (17 to 21)
Plasma HCO_3^- (mEq/L)[b]	Plasma bicarbonate	24 (22 to 28)[c]
B.E./B.D. (mEq/L)[b]	Base excess or deficit	0 (±2)
TCO_2 (mmol/L or mEq/L)[b,d]	Total CO_2	25 (22 to 30)

[a]Requires hemoximetry for measurement (e.g., co-oximetry).
[b]Calculated values, usually based on algorithms incorporated into the blood gas analyzer.
[c]Clinical range for plasma bicarbonate varies by reference source; HCO_3^- range of 21 to 27 mEq/L has been suggested [Emmett, M. Simple and mixed acid-base disorders. In: Sterns RH, Forman JP, eds., *UpToDate*; 2013]. Others have suggested a normal HCO_3^- range of 22 to 26 mEq/L and 22 to 28 mEq/L [Post TW, Burton RD. Approach to the patient with metabolic acidosis. *UpToDate*; 2013].
[d]Total CO_2 range based on the Siggard-Andersen nomogram would be 23 to 27 mmol/L (arterial blood) and 24 to 29 mmol/L (venous blood).

Respiratory Acidosis

Most patients receiving mechanical ventilatory support continue to breathe spontaneously, and their level of spontaneous ventilation can be affected by multiple factors. Patients' respiratory drive may be decreased due to respiratory or metabolic alkalosis, CNS depressants (sedatives, tranquilizers, and opioids), neurologic disease, electrolyte disorders, decreased metabolic rate, or pain. Chronic elevations in $Paco_2$ as seen with chronic CO_2 retention may depress the respiratory drive to breathe.

Neuromuscular disease or ventilatory muscle fatigue may decrease patients' ability to spontaneously ventilate. Causes of increased ventilatory workload include decreased compliance; increased resistance; or increased ventilatory demand due to hypoxia, metabolic acidosis, fear and anxiety, pain, increased CO_2 production, or pulmonary disease.

Mechanical ventilatory support allows the clinician to provide a sufficient level of ventilation to correct inadequate spontaneous breathing. However, prompt ventilator liberation will require that issues related to decreased respiratory drive, neuromuscular disease, or increased ventilatory workload be addressed.

Respiratory Alkalosis

Some spontaneously breathing patients may have an increased respiratory drive while receiving mechanical ventilatory support. Causes of increased respiratory drive include hypoxemia, metabolic acidosis, increased CO_2 production, lung receptor stimulation, pain, anxiety, and decreased blood pressure. Increased respiratory drive may cause patients receiving assist-control ventilation (e.g., PC-CMV or VC-CMV) to trigger the ventilator at excessively high rates resulting in an inappropriate respiratory alkalosis. Increased respiratory drive may also contribute to the patient–ventilator asynchrony and increased WOB and make ventilator weaning and discontinuance problematic. Issues causing increased respiratory drive should be identified and addressed promptly.

Metabolic Acidosis

Common causes of metabolic acidosis seen in the ICU include lactic acidosis (acute severe hypoxia, cardiac arrest, cardiac failure, hypovolemia, sepsis, and shock), ketoacidosis (uncontrolled diabetes mellitus), and kidney failure. Other causes include ingestion of acids, diarrhea, pancreatic fistula, and intravenous hyperalimentation.

Hyperventilation is the normal physiologic response to metabolic acidosis. Hyperventilation decreases $Paco_2$ and raises pH. Normal respiratory compensation for metabolic acidosis will decrease $Paco_2$ about 1.2 mmHg for each 1-mEq/L decrease in HCO_3^-. A quick estimate

of the expected respiratory compensation for metabolic acidosis is simply the last two digits of the pH. For example, if pH is 7.20 due to metabolic acidosis, the expected respiratory compensation would be a $PaCO_2$ of 20 mmHg.

Patients in respiratory failure often are unable to spontaneously hyperventilate on their own in compensation for metabolic acidosis. When receiving mechanical ventilatory support in the assist-control mode, these patients will tend to rapidly trigger the ventilator, lowering $PaCO_2$ and increasing in pH. Rapid triggering may cause patient–ventilator asynchrony, patient discomfort, and result in the patient fighting the ventilator. A common but *inappropriate* clinician response to this condition is to sedate the patient, sometimes heavily. While this may slow the patient's trigger rate, $PaCO_2$ will rise, worsening the metabolic acidosis. In such cases, identification and treatment of the underlying cause is best, while assuring that there are not significant swings in pH caused by inappropriate manipulation of the ventilator settings.

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Normal respiratory compensation for metabolic acidosis results in a decrease in $PaCO_2$ of about 1.2 mmHg for each 1-mEq/L decrease in HCO_3^-.

Metabolic Alkalosis

Common causes of metabolic alkalosis seen in the ICU include vomiting, nasogastric (NG) tube suction, renal loss of hydrogen ions, hypokalemia, hypovolemia, and sodium bicarbonate administration. Normal respiratory compensation for metabolic alkalosis typically results in an increase in $PaCO_2$ of about 0.7 mmHg for each 1-mEq/L increase in HCO_3^-. A quick estimate of the expected respiratory compensation for a metabolic alkalosis is simply the last two digits of the pH. For example, if the pH is 7.55 expected respiratory compensation would be a $PaCO_2$ of about 55 mmHg. Compensation for a metabolic alkalosis may be reduced since hypercapnia often creates a drive to increase the respiratory rate and/or tidal volume in most patients.

In ventilated patients, a metabolic alkalosis will tend to decrease patients' respiratory drive, which may result in hypoventilation in modes that require patients to contribute significantly to their minute ventilation. Metabolic alkalosis may also be problematic in terms of ventilator weaning and discontinuance.

Treatment of metabolic alkalosis should be aimed at the cause. The most common clinical causes of a metabolic alkalosis are hypokalemia and volume depletion. In cases of severe metabolic alkalosis, where kidney function is compromised and dialysis is not an option, administration of ammonium chloride or an infusion of dilute hydrochloric acid solution may be considered.

In summary, ventilation can have a significant impact on acid-base balance, and the respiratory care clinician must take this into account when considering adjustments in the level of ventilatory support provided. Identification and treatment of underlying causes of acid-base disorders should be performed. The clinician should also be aware that respiratory and metabolic disorders often coexist in critically ill patients.

Cardiac and Cardiovascular Support

Oxygen delivery is dependent on adequate cardiac output, blood pressure, and tissue perfusion. Heart failure, acute myocardial infarction, shock, sepsis, and blood loss will reduce tissue oxygen delivery. Heart failure can be left sided, right sided, or both. Cor pulmonale is a form of right-sided heart failure associated with chronic lung disease. Heart failure can be characterized as ischemic (e.g., acute myocardial infarction [MI]), nonischemic (e.g., idiopathic cardiomyopathy), or valvular (e.g., mitral regurgitation). Left-ventricular myocardial dysfunction is the most common cause of heart failure seen in the ICU. This type of heart failure is heart failure due to systolic (pump) failure (HFrEF, or heart failure with reduced ejection fraction). Chronic heart failure is often caused by untreated or suboptimally treated hypertension where the heart fails to relax during diastole and results in heart failure with preserved ejection fraction (HFpEF). Treatment of heart failure is dependent on the cause and may include diuretics to treat fluid retention and the use of pharmacologic agents to improve cardiac function.

Acute decompensated heart failure is a potentially life-threatening problem, requiring careful assessment and monitoring. Treatment of acute decompensated heart failure may include noninvasive ventilatory support, diuretic therapy, and assessment for vasodilator administration. Invasive mechanical ventilatory support with PEEP may be required. In some patients, heart failure may cause acute pulmonary edema, resulting in respiratory failure with severe hypoxemia.

There are three broad types of acute coronary syndromes and myocardial infarction (MI) based on ECG findings: ST segment elevation MI (STEMI), non-ST segment elevation MI (NSTEMI), and unstable angina; treatment protocols for each should be employed.

Shock generally is caused by circulatory failure and results in systemic hypotension, decreased oxygen delivery, and tissue hypoxia. Types of shock include cardiogenic, hypovolemic, obstructive, and distributive shock. There are three common types of distributive shock: septic shock, neurogenic shock, and anaphylactic shock. As shock progresses, patients may experience dyspnea, restlessness, diaphoresis, and cool, clammy skin. Hypotension, oliguria, and metabolic acidosis may then lead to tissue hypoxia, organ damage, multiorgan system failure, and death. **Table 7-6** provides normal values for hemodynamic measurements.

TABLE 7-6
Adult Hemodynamic Measurements

Parameter	Normal (Range)	Abnormal Values
Heart Rate (HR)	80 (60–100) beats/min	> *100* – Tachycardia < *60* – Bradycardia
Arterial Blood Pressure (ABP) Systolic Blood Pressure Diastolic Blood Pressure Mean Arterial Blood Pressure (MAP)	 120 (90–140) mmHg 80 (60–90) mmHg 90 (80–100) mmHg	 > *140/90* – Hypertension < *90/60* – Hypotension *MAP* > *100* – elevated *MAP* < *80* – decreased MAP > 65 with adequate tissue perfusion may be an acceptable goal for most patients in the ICU
Central Venous Pressure (CVP)	4–8 mmHg	> *6* – fluid overload, right ventricular failure, pulmonary hypertension, valvular stenosis, pulmonary embolus, cardiac tamponade, pneumothorax, positive pressure ventilation, PEEP, left ventricular failure < *2* – hypovolemia, blood loss, shock, peripheral vasodilation, cardiovascular collapse
Pulmonary Artery Pressure (PAP)	25/10 (20–35)/(5–15) mmHg	> *35/15* – pulmonary hypertension, left ventricular failure, fluid overload < *20/5* – pulmonary hypotension, hypovolemia, cardiovascular collapse
Mean Pulmonary Artery Pressure (MPAP)	15 (10–20) mmHg	> *20* – same as ↑ PAP above < *10* – same as ↓ PAP above
Pulmonary Capillary Wedge Pressure (PCWP)	6–12 (< 18) mmHg	> *18* – left ventricular failure, fluid overload > *20* – interstitial edema may occur > *25* – alveolar filling may occur > *30* – frank pulmonary edema may occur < *5* – hypovolemia, shock, cardiovascular collapse
Pulmonary Vascular Resistance (PVR)	110–250 dynes/sec/cm^5	> *250* – pulmonary hypertension, severe atelectasis, lung over distension, hypoxemia, ↑ pH, ↓ $Paco_2$, vasopressors, emboli, emphysema, interstitial fibrosis, pneumothorax < *110* – pulmonary vasodilators, nitric oxide, oxygen, calcium blockers
Cardiac Output ($\dot{Q}_T$ or C.O.)	5 (4–8) L/min	> *8* – elevated, dependent on patient size (see cardiac index) < *4* – decreased, dependent on size (see cardiac index)
Cardiac Index (C.I.)	2.5–4.0 L/min/m^2	> *4* – Stress, septic shock, fever, hypervolemia, drugs (dobutamine, dopamine, epinephrine, isoproterenol, digitalis, etc.) < *2.5* – left ventricular failure, myocardial infarction, pulmonary embolus, high levels of positive pressure ventilation, PEEP, pneumothorax, blood loss, hypovolemia
System Vascular Resistance (SVR)	800–1200 dynes/sec/cm^2	> *1400* – cardiogenic shock, systemic hypertension, volume depletion/hypovolemia, vasoconstrictors (dopamine, norepinephrine, epinephrine, others), hypovolemia, late septic shock < *900* – distributive shock (e.g. sepsis), acidosis, vasodilators (nitroglycerin, nitroprusside, morphine, others), early septic shock. $P\bar{V}O_2$ < 27 mmHg and $S\bar{V}O_2$ < 50% associated with lactic acidosis
Mixed Venous Oxygen $P\bar{V}O_2$ $C\bar{V}O_2$ $S\bar{V}O_2$	 35–40 mmHg 15 Vol% 75% (70%–77%)	*Increased mixed venous oxygen values* (e.g. $S\bar{V}O_2$ > 77%) may be caused by peripheral shunt (e.g.; sepsis), left-to-right cardiac shunt, marked elevation is cardiac output, cyanide poisoning, hypothermia, wedged PA catheter when syringe sample is drawn *Decreased mixed venous oxygen* values may be caused by decreased CaO_2, decreased C.O., increased $C\bar{V}O_2$ An acceptable goal in critically ill patients may be in $S\bar{V}O_2$ of 60% to 75% or ≥ 70% in sepsis
$C(a\text{-}v)O_2$	3.5–5 vol%	*Increased* $C(a\text{-}v)O_2$ may be caused by increased CaO_2 or decreased $C\bar{V}O_2$ *Decreased* $C(a\text{-}v)O_2$ may be caused by decreased CaO_2 or increased $C\bar{V}O_2$

TABLE 7-7
Hemodynamic Changes with Common Cardiopulmonary Disorders

Condition	CVP	PAP	PCWP	PVR	SVR	CO	BP
Fluid overload	↑	↑	↑	↑or N	↑or N	↑or N	↑or N
Left-ventricular failure	↑	↑	↑	↑	↑or N	↓	↓
Hypovolemic shock	↓	↓	↓	↑or N	↑	↓	↓
Septic shock	↓or N	↓or N	↓or N	↓or N	↓	↑	↓
Cardiogenic shock	↑	↑	↑	↑or N	↑	↓	↓
Pulmonary embolus	↑	↑	↓or N	↑	↑	↓or N	↓or N
Lung over distension	↑	↑	↓	↑	↑	↓	↓
ARDS	↓or N	↑	↓or N	↑or N	↑or N	N	↑or N

↑, increase; ↓, decrease; BP, blood pressure; CO, cardiac output; CVP, central venous pressure; N, normal; PAP, pulmonary artery pressure; PCWP, pulmonary capillary wedge pressure; PVR, pulmonary vascular resistance; SVR, systemic vascular resistance.

Hemodynamic monitoring may be accomplished by use of a central venous catheter or pulmonary artery catheter. Often noninvasive hemodynamic monitoring is performed by assessing arterial waveform analysis via an arterial line. A conservative approach to fluid management may help reduce pulmonary edema. A conservative approach to fluid management should not be at the expense of maintaining adequate systemic blood pressure. Hemodynamic changes seen with cardiac and cardiovascular disorders often seen in the ICU are described in **Table 7-7**.

Positive-pressure ventilation increases mean airway and intrathoracic pressures, reduces venous return, and may compromise cardiac output. Steps to reduce the harmful cardiovascular side effects of positive-pressure ventilation include decreasing peak and mean airway pressures. Ventilator adjustments to reduce airway pressures include decreasing tidal volume, limiting inspiratory pressure, reducing rate, increasing expiratory time, improving I:E ratio, altering inspiratory flow waveform, reducing PEEP/CPAP, and use of modes that incorporate spontaneous breathing (e.g., SIMV).

Use of Sedation and Neuromuscular Blockade

Pain, anxiety, fever, and fighting the ventilator will increase the WOB and oxygen consumption. Proper sedation and pain management can improve patient–ventilator synchrony and patient comfort and reduce oxygen consumption. Frequent pain assessment should be performed to document the severity, response to medication, and development of side effects.[19] The use of pain scales (e.g., Critical Care Pain Observation Tool [CPOT]) will allow the clinician to quantify pain and assess the effectiveness of treatment. Sedation protocols and the use of sedation scales (e.g., Richmond Agitation–Sedation Scale) should be employed, including routinely waking patients each day.[19] Intravenous administration of opiates generally is preferred for the treatment of pain in critically ill patients. Side effects of opioids include respiratory drive depression, hypotension, and the release of histamine. Gradual weaning of opioids has been suggested to avoid withdrawal symptoms.

Neuromuscular-blocking agents paralyze skeletal muscle and are sometimes used in the ICU to achieve controlled mechanical ventilation. **Neuromuscular blockade** can eliminate patient–ventilator asynchrony, and some have speculated that it may benefit patients with severe ARDS during the initial phases of mechanical ventilation.[11] The use of neuromuscular-blocking agents should be reserved for patients with persistent ventilatory asynchrony or severe oxygenation problems and for relatively short periods of time. Neuromuscular-blocking agents have no sedative or analgesic properties and must be used in combination with appropriate sedation and treatment of pain. As patients are unable to spontaneously breathe, a ventilator malfunction or disconnect can be catastrophic. Neuromuscular-blocking agents can also cause allergic reactions, cardiovascular side effects, prolonged paralysis, and ICU-acquired muscle weakness. Because of issues regarding safety and possible adverse effects, the use of neuromuscular-blocking agents is inappropriate for most patients. Exceptions may include the ventilation of patients with acute, severe asthma and patients who cannot be otherwise successfully ventilated.

Summary

Following ventilator initiation, patients should be assessed for the adequacy of oxygenation, ventilation,

and acid-base balance. Proper ventilator function and appropriate patient–ventilator interaction should be reviewed, and adjustments made to reduce or eliminate patient–ventilator asynchrony, reduce the WOB, ensure patient safety and comfort, and minimize harmful side effects. Support provided should promote prompt liberation from the ventilator. Alteration of ventilatory pressures, flows, volumes, and inspiratory time may be helpful to improve patient–ventilator synchrony.

Ventilator adjustments may be necessary to improve oxygenation, adjust the level of ventilation provided, and insure adequate acid-base balance. Techniques to improve oxygenation include adjustment of FIO_2 and PEEP. Other techniques which may be helpful in some patients include prone positioning, recruitment maneuvers, and use of alternative modes of ventilation (e.g., PC-IRV, APRV, and HFOV). Provision of adequate humidification, suctioning and airway care, and administration of bronchodilator therapy may be helpful. Early mobilization of patients may also improve outcomes.

Alteration of the level of ventilation provided may be required based on arterial blood gas assessment. Ventilator adjustments may include changes in tidal volume, respiratory rate, minute ventilation, or mode. The clinician should always consider the effect of $PaCO_2$ on pH when considering ventilator adjustments. Care should also be taken to minimize possible harmful cardiovascular side effects associated with positive-pressure ventilation.

Pain, anxiety, fever, and fighting the ventilator will increase the WOB and oxygen consumption. Proper sedation and pain management can improve patient–ventilator synchrony and comfort and reduce oxygen consumption.

Key Points

- An immediate assessment should be completed following initiation of mechanical ventilation.
- Initial assessment should include: physical assessment of the patient, assessment of ventilator settings and patient–ventilator interaction, cardiovascular assessment, oximetry, and measurement of arterial blood gases.
- Initiation of mechanical ventilation may lead to respiratory problems, which may include right mainstem intubation, misplaced endotracheal tube, cuff leak or malfunction, large air leak, inappropriate ventilator settings, or ventilator malfunction or disconnect.
- During assist-control volume ventilation, inspiratory peak flow should meet or exceed the patient's ventilatory needs. Inadequate flow will increase the work of breathing (WOB) while excessive flow may result in immediate and persistent tachypnea.
- Patient–ventilator interaction refers to patient–ventilator synchrony, comfort, and work of breathing during ventilator-assisted breaths.
- A sustained increase in ventilatory workload can lead to ventilatory muscle fatigue and structural injury. Muscle fatigue requires a minimum of 24 hours for recovery.
- When set appropriately, ventilator mode and settings should reduce WOB while avoiding ventilatory muscle atrophy.
- Several modes may be selected to reduce inspiratory effort without eliminating respiratory muscle use.
- Patient-ventilator asynchrony occurs when the patient's respiratory efforts do not coordinate with the ventilator's set respiratory efforts.
- Asynchrony may be detected through physical assessment and observation of ventilator graphics.
- Patient–ventilator asynchrony is associated with adverse outcomes including increased WOB, hypoxemia, inadequate or ineffective ventilation, hemodynamic compromise, increased risk of complications, and prolonged ventilator dependency.
- Patient-triggered breaths may be pressure triggered or flow triggered. Trigger sensitivity should be adjusted so that trigger work is minimal without autocycling.
- The pressure trigger is typically set –0.5 to –1.5 cm H_2O below the baseline expiratory pressure; flow trigger is typically set 1 to 2 L/min below the baseline or bias flow.
- Trigger asynchrony occurs when the patient's inspiratory effort does not match the beginning of the ventilator-supported breath.
- Trigger work is the amount of patient's WOB required to trigger the machine breath; inappropriate trigger sensitivity settings and autoPEEP can increase trigger work.
- There are five types of trigger asynchrony: missed triggering, trigger delay, double triggering, reverse triggering and autotriggering.
- Missed triggering is when the patient's inspiratory effort does not trigger the ventilator breath.
- Trigger delay occurs when there is a delay between the time the patient initiates inspiration and when the machine actually delivers the breath.
- Double triggering occurs when the ventilator cycles into expiration while the patient is still making an inspiratory effort, resulting in double triggering and two consecutive breaths before the patient exhales.
- Autotriggering occurs when the ventilator initiates inspiration without a corresponding patient effort due to inappropriate trigger sensitivity settings.
- Reverse triggering may occur during controlled ventilation in which a time-triggered ventilator breath stimulates the diaphragm, resulting in diaphragmatic contraction which then triggers the next breath.
- Flow asynchrony occurs when the inspiratory gas flow from the ventilator does not match the patient's inspiratory flow demand.
- Cycle asynchrony occurs when there is poor coordination between the patient's respiratory drive and the ventilator.

- Mode asynchrony occurs when the mode selected does not match the patient's spontaneous ventilatory efforts.
- Tissue oxygenation is determined by inspired oxygen concentration, alveolar ventilation, ventilation–perfusion relationships, diffusion across the alveolar–capillary membrane, arterial oxygen content, cardiac output, and peripheral perfusion.
- Appropriate oxygenation values for most patients are Pa_{O_2} 60 to 80 mmHg and Sa_{O_2} 90% to 95% with F_{IO_2} ≤ 0.50 to 0.60.
- Improved oxygenation can be achieved by adjusting F_{IO_2}, PEEP, and CPAP. Other methods for improving oxygenation include recruitment techniques, open lung ventilation, and prone positioning.
- F_{IO_2} should be rapidly titrated down from 1.0 to avoid oxygen toxicity and related complications.
- Complications of high F_{IO_2} include absorption atelectasis, cellular injury, accentuation of hypercapnia, airway injury, parenchymal injury, potentiation by bleomycin, and retinopathy of prematurity in premature infants.
- PEEP or CPAP is used to prevent or treat atelectasis by opening collapsed alveoli and reducing alveolar overdistention.
- PEEP may help to reduce the incidence of ventilator-associated pneumonia (VAP) and ventilator-associated lung injury (VALI); PEEP may cause pulmonary barotrauma, reduced venous return, or negatively affect cardiac output and blood pressure.
- Methods for PEEP application include minimum PEEP, optimal PEEP, and compliance-titrated PEEP.
- Minimum PEEP is the least PEEP needed to achieve adequate arterial oxygenation at a safe oxygen concentration.
- Optimal or best PEEP can be defined as the PEEP that maximizes oxygen delivery to the tissues.
- Compliance-titrated PEEP is the best PEEP based on static total compliance (C_{ST}).
- A decremental PEEP trial is a method used to identify optimal PEEP for patients with ARDS following a lung recruitment maneuver.
- Intrinsic PEEP or autoPEEP occurs when gas is not completely exhaled before beginning the next inspiratory phase.
- Static autoPEEP is calculated by subtracting the extrinsic PEEP from the end-expiratory pressure observed during the expiratory pause.
- Dynamic autoPEEP can be assessed in spontaneously breathing patients by observing the flow–time curve.
- High PEEP can be effective in improving oxygenation in patients with severe ARDS with recruitable lung but harmful to patients with mild ARDS who have little recruitable lung.
- Various recruitment maneuvers have been suggested to improve oxygenation in patients with ARDS or those with reduced functional residual capacity (FRC), which include a "30 for 30" or "40 for 40" maneuver, sigh breaths, or a variation of pressure-control ventilation.
- It is important to monitor the patient's heart rate, blood pressure, and cardiac monitor while performing a recruitment maneuver.
- Prone positioning may improve oxygenation for patients with severe ARDS.
- Contraindications to prone positioning include shock, hemorrhage, multiple fractures or trauma, spinal instability, pregnancy, increased intracranial pressure, or recent tracheal surgery or sternotomy.
- Bronchial hygiene techniques may improve oxygenation for ventilated patients. Techniques include suctioning and airway care, provision of adequate humidification, and administration of bronchodilators and inhaled anti-inflammatory agents.
- Early mobilization of ventilated patient may improve oxygenation and decrease consequences of ICU-acquired weakness.
- Pa_{CO_2} is the single best clinical indicator of alveolar ventilation and allows for accurate evaluation of adequate ventilation.
- Arterial blood gases are typically drawn 20 to 30 minutes following a parameter change to confirm appropriate settings.
- Patients with dangerously elevated intracranial pressure (ICP) may be hyperventilated for a short period of time to lower Pa_{CO_2} and ICP.
- Permissive hypercapnia is a ventilatory strategy that reduces delivered volumes and pressures to reduce alveolar pressure and overdistension. This strategy may be useful for patients with severe ARDS, severe bronchospasm with acute asthma exacerbation, or exacerbation of COPD.
- A decrease in Pa_{CO_2} may be achieved by increasing tidal volume or frequency, and decreasing mechanical dead space (if present).
- An increase in Pa_{CO_2} may be achieved by decreasing tidal volume or frequency and adding or increasing mechanical dead space.
- Tidal volume is initially set to 6 to 8 mL/kg IBW and titrated up or down to ensure $P_{plateau}$ ≤ 30 cm H_2O.
- Patients in respiratory failure often experience acid-base disorders; the patient's ventilatory status can have a significant impact on acid-base balance.
- Acute increases in Pa_{CO_2} will cause a corresponding decrease in pH while acute decreases in Pa_{CO_2} will increase pH.
- Each time there is an acute change and Pa_{CO_2} increases by 1 mmHg, pH will decrease by 0.008, and each time there is an acute change and Pa_{CO_2} decreases by 1 mmHg, pH will increase by 0.008.
- Appropriate pain management and sedation protocols should be employed in ventilated patients.

- Cardiac and cardiovascular problems may impair tissue oxygen delivery.
- Neuromuscular blockade should be reserved for patients with persistent ventilatory asynchrony or severe oxygenation problems and for relatively short periods of time.
- Ventilator failure or accidental disconnection can be catastrophic in patients undergoing neuromuscular blockade.

References

1. Chatburn RL, El-Khatib M, Mireles-Cabodevila E. A taxonomy for mechanical ventilation: 10 fundamental maxims. *Respir Care*. 2014;59(11):1747–1763. doi:10.4187/respcare.03057.
2. Chatburn RL, Volsko TA, Hess DR, et al. Mechanical ventilators: classification and principles of operation. In: Hess DR, MacIntyre NR, Galvin WF, Mishoe SC, eds. *Respiratory Care: Principles and Practice*. 3rd ed. Burlington, MA: Jones & Bartlett Learning; 2016: 462–492.
3. Hyzy RC. Physiologic and pathophysiologic consequences of mechanical ventilation. In: Parsons PE, Finlay G, eds. *UpToDate*; April 2018.
4. Blanch L, Villagra A, Sales B, et al. Asynchronies during mechanical ventilation are associated with mortality. *Intens Care Med*. 2015;41:633–641.
5. Kacmarek RM, Stoller JK, Heuer AJ. Patient-ventilator interactions. In: Kacmarek RM, Stroller JK, Heuer AJ, eds. *Egan's Fundamentals of Respiratory Care*. 11th ed. St. Louis, MO: Elsevier; 2017: 1058–1077.
6. Akoumianaki E, Lyazidi A, Rey N, et al. Mechanical ventilation-induced reverse-triggered breaths: a frequently unrecognized form of neuromechanical coupling. *Chest*. 2013;143:927–938.
7. Marini JJ, Capps JS, Culver BH. The inspiratory work of breathing during assisted mechanical ventilation. *Chest*. 1985;87:612–618.
8. Malhotra A, Schwartzstein RM. Oxygen toxicity. In: Manaker S, Finlay G, eds. *UpToDate*; May 2018.
9. Mechem CC. Pulse oximetry. In: Parsons PE, Finlay G, eds. *UpToDate*; December 2017.
10. Sagana R, Hyzy RC. Positive end-expiratory pressure (PEEP). In: Pearson PE, Finlay G, eds. *UpToDate*; 2017.
11. Siegel MD, Hyzy RC. Mechanical ventilation of adults in acute respiratory distress syndrome. In: Parsons PE, Finlay G, eds. *UpToDate*; November 2017.
12. Rosen IM, Manaker S. Oxygen delivery and consumption. In: Parsons PE, Finlay G, eds. *UpToDate;* June 2017.
13. Acute Respiratory Distress Syndrome Network, Brower RG, Matthay MA, et al. 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*. 2000;342:1301–1308.
14. Kacmarek RM, Stoller JK, Heuer AJ. Initiating and adjusting invasive ventilatory support. In: Kacmarek RM, Stroller JK, Heuer AJ, Chatburn RL, Kallet RH, eds. *Egan's Fundamentals of Respiratory Care*. 11th ed. St. Louis, MO: Elsevier; 2017: 1078–1110.
15. Blanch L, Bernabe F, Lucangelo U. Measurement of air trapping, intrinsic positive end-expiratory pressure, and dynamic hyperinflation in mechanically ventilated patients. *Respir Care*. 2005;50(1):110–123.
16. Malhotra A, Kacmarek RM. Prone ventilation for adult patients with acute respiratory distress syndrome. In: Parsons PE, Finlay G, eds. *UpToDate;* April 2018.
17. Shelledy DC, Peters JI. Initiating and adjusting ventilatory support (Chapter 44). In: Wilkins RL, Stoller JK, Kacmarek RM. *Egan's Fundamentals of Respiratory Care*. 9th ed. St. Louis, MO: Elsevier; 2009:1045–1090.
18. Hyzy RC, Hidalgo J. Permissive hypercapnia during mechanical ventilation in adults. In: Parsons PE, Finlay G, eds. *UpToDate*; February 2018.
19. Panharipande P, McGrane S. Pain control in the critically ill adult patient. In: Parsons PE, O'Connor MF, Finlay G, Nussmeier NA, eds. *UpToDate*; September 2018.