CHAPTER

5

Indications for Mechanical Ventilation

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OUTLINE

OBJECTIVES

1. Explain the primary function of a mechanical ventilator.
2. Define respiratory failure and explain the differences between hypoxemic and hypercapnic respiratory failure.
3. Define acute ventilatory failure.
4. Describe each of the components of ventilation, including the relationship between tidal volume, respiratory rate, minute ventilation, physiologic dead space, and alveolar ventilation.
5. Define ventilatory capacity and describe factors that affect ventilatory capacity.
6. Define ventilatory requirements (aka ventilatory demand or load) and describe factors that affect ventilatory requirements.
7. Explain the relationship between ventilatory capacity and ventilatory requirements in terms of adequacy of ventilation and development of acute ventilatory failure.
8. Describe clinical conditions that may reduce or eliminate respiratory drive.
9. Describe factors that may impair lung function and explain how they may reduce ventilatory capacity.
10. Describe clinical conditions that increase ventilatory workload and may lead to ventilatory muscle fatigue and ventilatory failure.
11. Explain how changes in ventilatory muscle strength affect ventilatory capacity.
12. Describe the disease states or conditions that cause ventilatory muscle weakness or dysfunction and predispose patients to the development of respiratory failure, hypoventilation, and/or apnea.
13. Explain the relationship between alveolar ventilation ($\dot{V}_A$), arterial carbon dioxide tension ($Paco_2$), metabolic rate, and carbon dioxide production ($\dot{V}co_2$).
14. Describe the normal ventilatory response to hypoxemia.
15. Describe the effects of increased physiologic dead space on ventilatory requirements.
16. Explain how metabolic acidosis may affect ventilatory requirements.
17. List common causes of acute respiratory failure requiring mechanical ventilation.
18. Describe the clinical manifestations of acute respiratory failure associated with the need for mechanical ventilatory support.
19. Explain each of the seven primary goals of mechanical ventilatory support.
20. Provide examples of clinical causes of each of the four primary indications for institution of mechanical ventilation.
21. List values for bedside measures of pulmonary function that suggest the need for mechanical ventilatory support.
22. Explain why certain neuromuscular disorders may progress to ventilatory failure requiring mechanical ventilation.
23. Recognize the presence of severe oxygenation problems, including refractory hypoxemia.
24. Explain how PEEP and CPAP may improve oxygenation in certain patients.
25. Recognize patients for whom institution of mechanical ventilatory support is indicated.
26. Describe the major complications, hazards, and contraindications of mechanical ventilation.
27. Overview the initial ventilator settings for patients requiring mechanical ventilatory support.

KEY TERMS

acute respiratory distress syndrome (ARDS)
acute ventilatory failure
alveolar ventilation
apnea
asthma exacerbation
barotrauma
chronic ventilatory failure
continuous mandatory ventilation (CMV)
continuous positive airway pressure (CPAP)
continuous spontaneous ventilation (CSV)
dead space ventilation
hypercapnia
hypercapnic respiratory failure
hyperventilation
hypoventilation
hypoxemic respiratory failure
impending ventilatory failure
intermittent mandatory ventilation (IMV)
minute ventilation ($\dot{V}_E$)
neurologic disease
neuromuscular disorders
positive end-expiratory pressure (PEEP)
Pao_2/Fio_2 ratio (P/F ratio)
physiologic dead space
pressure control (PC)
respiratory drive
respiratory acidosis
respiratory failure
respiratory rate (f)
severe oxygenation problem
synchronized intermittent mandatory ventilation (SIMV)
tidal volume (V_T)
ventilatory capacity
ventilatory failure
ventilatory muscle fatigue
ventilatory requirements
ventilatory reserve
ventilatory workload
volume control (VC)
work of breathing (WOB)

Introduction

This chapter provides an overview of the indications for mechanical ventilatory support. Mechanical ventilation may be required when spontaneous breathing is insufficient or absent. The provision of mechanical ventilatory support entails the use of sophisticated life-support technology to support tissue oxygenation and removal of carbon dioxide. Simply put, the primary function of a mechanical ventilator is to augment or replace normal ventilation. Thus, absent ventilation (**apnea**) or inadequate ventilation (actual or **impending ventilatory failure**: clinically detected by tachypnea or hypercapnea) provide major indications for the initiation of mechanical ventilatory support. The other major indication for mechanical ventilation is a **severe oxygenation problem** (e.g., refractory hypoxemia).

In this chapter, we will review the basics of ventilation to include causes of hypoventilation and apnea. As described elsewhere, **respiratory failure** is the inability of the heart and lungs to maintain adequate tissue oxygenation and/or carbon dioxide removal.[1–4] Respiratory failure is sometimes classified as either **hypoxemic respiratory failure** (Type I respiratory failure), or **hypercapnic respiratory failure** (Type II respiratory failure).[1–4] Hypoxemic respiratory failure refers to a primary problem with oxygenation, usually due to lung failure. Hypercapnic respiratory failure is also known as **ventilatory failure**, and refers to a primary problem with ventilation resulting in an abnormal elevation of $Paco_2$.[1–4] **Acute ventilatory failure** (aka acute hypercapnic respiratory failure) is defined as a sudden increase in arterial Pco_2 with a corresponding decrease in pH.[4–6] In the intensive care unit (ICU), patients often suffer from both hypoxemic and hypercapnic respiratory failure.

Because respiratory failure is the most common reason for considering mechanical ventilation, we will briefly review the causes and clinical manifestations of respiratory failure. The goals of mechanical ventilation will be described, and the indications for the provision of mechanical ventilatory support will be discussed. As mechanical ventilation is not without significant risk, the contraindications, hazards, and possible complications of mechanical ventilation will be described. The chapter will conclude with a discussion of the assessment of the patient leading to the decision to initiate mechanical ventilatory support.

RC Insight

Mechanical ventilation may be required when spontaneous breathing is insufficient or absent.

Ventilation

Ventilation can be defined as the bulk movement of gas into and out of the lungs. Ventilation can be subdivided into **tidal volume (V_T)**, **respiratory rate (f)**, and **minute ventilation ($\dot{V}_E$)** where $\dot{V}_E = V_T \times f$. Exhaled tidal volume is simply the volume of gas passively exhaled after a normal inspiration, and respiratory rate is simply the number of breaths taken per minute. Adequate spontaneous ventilation requires a sufficient tidal volume, respiratory rate, and minute ventilation to support oxygenation and CO_2 removal, while maintaining acid-base homeostasis. While bedside measures of spontaneous breathing are sometimes useful (e.g., V_T, f, and $\dot{V}_E$), the single best clinical index of ventilation is measurement of arterial carbon dioxide tension ($Paco_2$).[7] For most patients, normal ventilation corresponds to a $Paco_2$ from 35 to 45 mmHg, while **hypoventilation** and **hyperventilation** are defined as a $Paco_2 > 45$ mmHg or < 35 mmHg, respectively. Since venous blood gases are frequently utilized to assess pH, a $Paco_2 > 50$ mmHg suggests possible **hypercapnia**. **Box 5-1** reviews terms often used to describe ventilation.

Ventilatory capacity is a general term indicating the amount of air that can be moved into and out of the lungs by the ventilatory pump. **Ventilatory requirements** (aka ventilatory demand or load) refers to the volume

BOX 5-1 Terms Used to Describe Ventilation

- **Tidal volume (V_T):** the volume of gas exhaled passively following a normal inspiration (i.e., **exhaled tidal volume**).
  - Normal adult V_T is approximately 500 mL (range 400 to 700 mL) or about 7 mL/kg of ideal body weight (IBW).
  - Formulas for estimating IBW vary and some (e.g., ARDSNet) use the term "predicted body weight" (PBW) where:
    - PBW males (kg) = 50 + 2.3 (height [in] − 60)
    - PBW females (kg) = 45.5 + 2.3 (height [in] − 60)
  - *Inhaled* V_T: the volume of gas inhaled normally following a passive expiration.
    - Inhaled V_T is sometimes measured and compared to *exhaled* V_T in patients receiving mechanical ventilatory support in order to verify and/or quantify air leaks (e.g., endotracheal tube cuff leak, chest tube air leak) in which inhaled V_T > exhaled V_T.
  - Actual V_T will vary depending on the patient's size, gender, and overall condition.
- **Respiratory rate (f):** number of breaths taken per minute.
  - Normal adult respiratory rate is approximately 12 breaths/min with a range of about 12 to 18 breaths/min.
  - *Tachypnea*: elevated respiratory rate; rapid shallow breathing is a common finding in patients with acute respiratory failure.
  - *Bradypnea*: abnormally slow respiratory rate; seen with sedative or narcotic drug overdose, head trauma, CNS disease, and other causes of respiratory center depression.
- **Minute ventilation ($\dot{V}_E$):** V_T times the respiratory rate ($\dot{V}_E = V_T \times f$).
  - Normal adult $\dot{V}_E$ is approximately 6 L/min (range 5 to 10 L/min).
- **Dead space ventilation (V_D):** the portion (or volume) of ventilation that does not participate in gas exchange (i.e., ventilation without perfusion). There are several types of dead space.
  - *Anatomic dead space* ($V_{D\ anatomic}$): refers to the volume of gas in the conducting airways (i.e., from the external nares (nostrils) down to and including the terminal bronchioles).
    - Normal anatomic dead space is approximately 1 mL per pound of IBW (about 150 mL in a normal adult).
    - Anatomic dead space will vary based on the patient's size.
  - *Alveolar dead space* ($V_{D\ alveolar}$): volume of ventilation received by alveoli that are ventilated but not perfused.
    - Emphysema is an important cause of increased alveolar dead space (e.g., capillaries destroyed from the toxic effects of cigarette smoking).
    - Pulmonary embolus (PE) may result in severe $\dot{V}/\dot{Q}$ problems with partial occlusion of a pulmonary vessel; with complete occlusion alveolar dead space will increase.
  - **Physiologic dead space** ($V_{D\ physiologic}$): total functional dead space volume that consists of the alveolar and anatomic dead space.
    - $V_{D\ physiologic} = V_{D\ anatomic} + V_{D\ alveolar}$.
    - Normally, $V_{D\ physiologic} \cong V_{D\ anatomic}$.
    - $V_{D\ physiologic}$ can be calculated at the bedside using the modified *Bohr equation*. $PaCO_2$ and mean exhaled carbon dioxide tension ($P\bar{E}CO_2$) are measured for calculation of the dead space to tidal volume ratio (V_D/V_T) where $V_D/V_T = (PaCO_2 - P\bar{E}CO_2) \div PaCO_2$.
    - Normal V_D/V_T is 0.30 (range: 0.20 to 0.40).
    - $V_{D\ physiologic} = V_D/V_T \times V_T$.
    - $V_{D\ physiologic} > V_{D\ anatomic}$ with dead space disease (e.g., emphysema or pulmonary embolus).
  - *Mechanical dead space*: the volume of rebreathed gas due to a mechanical device (e.g., large bore tubing placed between the patient "Y" and the endotracheal tube in intubated patients).
- **Alveolar ventilation** (aka effective ventilation): the volume of gas reaching alveoli that are ventilated AND perfused per breath (V_A) or per minute ($\dot{V}_A$).
  - Normal adult $\dot{V}_A$ is 4 to 5 L/min.
  - $\dot{V}_A$, CO_2 production ($\dot{V}CO_2$) and $PaCO_2$ are closely related where:
    $\dot{V}_A = (0.863 \times \dot{V}CO_2) \div PaCO_2$.
    - Normal $\dot{V}CO_2$ is about 200 mL/min.
    - Normal $PaCO_2$ is 40 mmHg (range 35 to 45 mmHg).
    - 0.863 is a conversion factor to convert mmHg and mL/min to L/min.
    - $PaCO_2$ and $\dot{V}_A$ are inversely proportional; as $\dot{V}_A$ decreases, $PaCO_2$ increases.
  - Clinically, $PaCO_2$ is the single best index of alveolar ventilation.

(*Continues*)

BOX 5-1 Terms Used to Describe Ventilation (*Continued*)

- **Normal ventilation:** $PaCO_2$ is 35 to 45 mmHg.
- **Hypoventilation:** abnormally increased level of ventilation; $PaCO_2 > 45$ mmHg.
- **Hyperventilation:** abnormally decreased level of ventilation; $PaCO_2 < 35$ mmHg.
- **Hypocapnea:** abnormally decreased $PaCO_2$ ($PaCO_2 < 35$ mmHg); the term *hypocapnea* is sometimes used in place of hyperventilation.
- **Hypercapnea:** abnormally elevated $PaCO_2$ ($PaCO_2 > 45$ mmHg); the term *hypercapnia* is sometimes used in place of hypoventilation.
- **Acute ventilatory failure:** a sudden (acute) increase in $PaCO_2$ with a corresponding decrease in pH.
- **Chronic ventilatory failure:** a chronically elevated $PaCO_2$, with a normal (compensated) or near-normal pH due to renal compensation. Note that renal compensation takes 3 to 5 days and increases HCO_3^- about 4 to 5 mEq/L for every 10-mmHg increase in $PaCO_2$.
- **Acute alveolar hyperventilation:** a sudden (acute) decrease in $PaCO_2$ with a corresponding increase in pH.
- **Chronic alveolar hyperventilation:** a chronic decrease in $PaCO_2$, with a normal or near-normal pH due to renal compensation.

of ventilation required to achieve adequate oxygenation and carbon dioxide removal. Put another way, ventilatory capacity is how much a patient *can breathe*, while ventilatory requirements are how much a patient *must breathe* in order to support oxygenation and carbon dioxide removal. The difference between ventilatory capacity and ventilatory requirements is the **ventilatory reserve**. In order to sustain adequate spontaneous ventilation, the patient's ventilatory capacity must meet or exceed his or her ventilatory requirements.

Ventilatory capacity is affected by a number of factors including **respiratory drive**, lung function, **ventilatory workload**, and ventilatory muscle strength. A patient's ventilatory requirements are determined by his or her oxygenation status, carbon dioxide production, lung function (e.g., dead space volume), circulatory status (e.g., cardiac output, blood pressure) and acid-base balance. When ventilatory requirements exceed ventilatory capacity, hypercapnic respiratory failure (aka ventilatory failure) may ensue. Each of the factors affecting ventilatory capacity and level of ventilation required (i.e., ventilatory demand) are described below.

RC Insight

Broadly defined, respiratory failure is the inability of the heart and lungs to maintain adequate tissue oxygenation and/or CO_2 removal.

Ventilatory Capacity

A patient's ventilatory capacity must be sufficient to maintain adequate tissue oxygenation and CO_2 removal and preserve acid-base homeostasis. When a patient's ventilatory capacity is insufficient to provide the level of ventilation required to maintain adequate tissue oxygenation and CO_2 removal, mechanical ventilatory support may be necessary. As noted above, factors that affect ventilatory capacity include respiratory drive, lung function, workload, and ventilatory muscle strength.

Respiratory Drive

The respiratory drive to breathe (aka ventilatory drive) resides primarily in the central respiratory control centers (i.e., medullary center, pontine centers), which respond to input from the central chemoreceptors in the medulla of the brainstem and the peripheral chemoreceptors of the carotid and aortic bodies.[8] Since carbon dioxide rapidly diffuses across the blood–brain barrier, an increase in PCO_2 will cause a decrease in cerebrospinal fluid pH, which will stimulate the central chemoreceptors to signal the need for an increase in ventilation; decreases in PCO_2 may decrease ventilatory drive, depending on whether other factors stimulating the respiratory drive are present. The peripheral chemoreceptors located in the carotid and aortic bodies are stimulated by low arterial oxygen tension ($PaO_2 < 50$ to 55 mmHg), decreased pH, or increased $PaCO_2$.[8] Thus, hypercarbia or acidosis will stimulate the central respiratory centers, and hypoxemia, acidosis, or hypercarbia will stimulate the peripheral chemoreceptors. In addition, input from thoracic neural receptors or higher brain centers (e.g., cerebral cortex) may affect the level of ventilation. For example, stimulation of J receptors or bronchial C receptors in the lung, as may occur with consolidative lung disease (e.g., pneumonia, pulmonary edema) or inflammation, will cause an increase in respiratory rate and may result in rapid, shallow breathing.[8] Other causes of an increased drive to breathe include exercise, pain, anxiety, and metabolic (hepatic

or uremic) encephalopathy. Correction of problems causing central or peripheral chemoreceptor stimulation (e.g., oxygen therapy, correction of metabolic acidosis) may allow ventilation to return to normal levels.

Respiratory drive can be reduced or abolished by administration of narcotics, sedatives, tranquilizers, or anesthetic gases. Other conditions that may reduce respiratory drive include metabolic alkalosis, **neurologic disease**, severe hypothyroidism, decreased metabolic rate, electrolyte disorders, and (possibly) very high $Paco_2$ (> 75 to 80 mmHg).[4,8] Shock, trauma, or myocardial infarction may lead to respiratory and cardiac arrest. Certain patients with chronic obstructive pulmonary disease (COPD) develop chronic hypercapnia with hypoxemia and oxygen therapy provided to such patients may worsen CO_2 retention (i.e., oxygen-associated hypercapnia).[4,9–11] Certain asthma patients (known as "underpercievers") may also exhibit a decreased respiratory drive and a reduced perception of dyspnea.[12] These patients are at special risk for the development of fatal **asthma exacerbation**. Neuromuscular blocking agents (e.g., pancuronium [Pavulon], vercuronium [Norcuron], atracurium [Tracium], and cistracurium [Nimbex]) block transmission of nerve impulses at the myoneural junction (aka neuromuscular junction) and may cause paralysis, apnea, and in some cases, prolonged ventilatory muscle weakness. Factors that affect respiratory drive are listed in **Box 5–2**.

BOX 5-2 Factors that Affect Respiratory Drive

A number of factors stimulate respiratory drive including hypoxemia, hypercarbia, and acidemia. Decreased or absent respiratory drive may result in hypoventilation or apnea (e.g., acute ventilatory failure or respiratory arrest). The terms *respiratory drive* and *ventilatory drive* are often used synonymously. Patients with inadequate or absent respiratory drive often require mechanical ventilatory support.

Causes of decreased or absent respiratory drive include:

- Overventilation during mechanical ventilation (induced hypocapnia)
- Severe hypoxia (e.g., cerebral hypoxia)
- Acute, severe hypercapnia ($Paco_2$ > 75 to 80 mmHg; initial increase in respiratory drive but may be followed by depressed level of consciousness and reduced respiratory drive)
- Cardiopulmonary collapse (cardiac arrest, acute MI, shock, and trauma)
- Neurologic disease (e.g., major stroke, brainstem tumor, cerebral hemorrhage, meningitis, encephalitis, hepatic encephalopathy, brainstem ischemia, and brain death)
- Head trauma
- Near-drowning
- Hypothermia
- Poisoning (carbon monoxide poisoning, cyanide poisoning, other)
- Electrical shock
- CNS depressants (opioids, barbiturates, benzodiazepines, and tricylic antidepressants)
- Intentional or accidental drug overdose (narcotics, heroin, barbiturates, and tranquilizers)
- Anesthesia (general)
- Alkalosis (respiratory alkalosis, metabolic alkalosis)
- Electrolyte disorders
- Chronic obstructive pulmonary disease (COPD) patients with chronic CO_2 retention and hypoxemia may have reduced respiratory drive ("blue bloater" profile)
- Oxygen-associated hypercapnia (sometimes seen in patients with chronic CO_2 retention/COPD following administration of oxygen)
- Certain asthma patients with severe hypoxemia and hypercapnia
- Severe hypothyroidism
- Starvation
- Decreased metabolic rate
- Sleep disorders (e.g., central or obstructive sleep apnea)
- Obesity hypoventilation
- Central hypoventilation syndrome (Ondine's curse)
- Apnea of prematurity

Causes of increased respiratory drive include:

- Hypoxemia
- Sepsis
- Metabolic acidosis
- Increased $Paco_2$
- Increased CO_2 production (exercise, fever, agitation, seizures, and shivering)
- Lung receptor stimulation (e.g., J receptors, bronchial C receptors).
- Certain drugs (theophylline [Theolair], acetazolamide [Diamox], and salicylate intoxication)
- Pain and anxiety
- Hypotension

Lung Function

Ventilatory capacity is also dependent on factors that affect *lung function*, including the conducting airways and gas exchange units, lung compliance, thoracic compliance, and airway resistance. For example, upper airway obstruction may detrimentally affect ventilatory capacity. Bronchospasm, mucosal edema, or secretions may also reduce ventilatory capacity. Reductions in lung compliance (e.g., pneumonia, pulmonary edema, and fibrotic lung disease) or thoracic compliance (e.g., chest wall deformity, obesity, and ascites [fluid in the peritoneal cavity]) may reduce ventilatory capacity. Alveolar filling (e.g., consolidative pneumonia, pulmonary edema), atelectasis, alveolar wall destruction (e.g., emphysema), or interstitial fibrosis may also reduce ventilatory capacity. Physiologic dead space may affect ventilatory capacity as an increase in dead space will reduce effective (alveolar) ventilation at a given tidal volume.

Workload

The work performed by the respiratory muscles to provide adequate ventilation is the ventilatory workload (that is, the **work of breathing [WOB]**). The ventilatory workload is primarily determined by the compliance of the lungs and thorax, and resistance to gas flow.[6] Ventilatory workload increases as compliance is reduced or resistance to gas flow increased. Conditions that decrease lung compliance include atelectasis, pneumonia, pulmonary edema, **acute respiratory distress syndrome (ARDS)**, and pulmonary fibrosis. Surfactant disruption, as occurs with respiratory distress syndrome (RDS) of the neonate, will also reduce lung compliance.[6] Pneumonia, pulmonary edema, ARDS, early lung dysfunction after transplant, and leakage of plasma proteins into the lung may disrupt surfactant in adults and thus reduce lung compliance. Conditions that decrease thoracic compliance include thoracic cage deformities (e.g., kyphoscoliosis, ankylosing spondylitis) or abdominal disorders (e.g., obesity or ascites).[6]

Causes of increased airway resistance include upper airway obstruction (e.g., epiglottitis, croup, angioedema, tumor, and foreign bodies) and lower airway disease (e.g., bronchospasm, mucosal edema, and increased secretions).[6] Disease states associated with increased airway resistance include asthma, emphysema, and conditions that decrease lung volumes (e.g., atelectasis, pneumonia).[6] Mechanical causes of increased resistance to air flow include artificial airways (e.g., endotracheal and tracheostomy tubes), ventilator demand flow systems, and ventilator circuits.

Disease states or conditions that reduce compliance or increase resistance to gas flow will require an increase in ventilatory work in order to maintain the same level of ventilation. At some point, ventilatory workload may exceed the capacity of the respiratory muscles and respiratory failure may ensue. A high ventilatory workload may lead to **ventilatory muscle fatigue**, ventilatory muscle weakness, and a reduction in ventilatory capacity. Causes of increased ventilatory workload are summarized in **Box 5-3**.

BOX 5-3 Causes of Increased Ventilatory Workload

An increase in ventilatory workload (increased WOB) may lead to ventilatory muscle fatigue and ventilatory failure. Ventilatory workload may increase due to:

- Decreased lung compliance
  - Atelectasis, pneumonia, pulmonary edema, ARDS, pulmonary fibrosis, and surfactant disruption
  - Pleural effusions, hemothorax, empyema, pneumothorax, and dynamic hyperinflation (air trapping)
- Decreased thoracic compliance
  - Obesity, ascites, pregnancy, and thoracic deformity (kyphoscoliosis, ankylosing spondylitis)
- Increased airway resistance
  - Bronchospasm, mucosal edema, and increased secretions (asthma, emphysema, and chronic bronchitis)
  - Tumor, foreign body obstruction, epiglottitis, croup, and epiglottitis
- Mechanical causes of increased resistance to gas flow (i.e., imposed WOB)
  - Artificial airways (endotracheal tubes, tracheostomy tubes)
  - Mechanical ventilators (ventilator circuits, demand flow systems, and inappropriate ventilator sensitivity or flow settings)
- Increased level of ventilation required
  - Hypoxemia/tissue hypoxia
  - Metabolic acidosis
  - Pain and anxiety
  - Increased $\dot{V}CO_2$ (trauma, infection, sepsis, fever, shivering, agitation, fighting the ventilator, and struggling against restraints)
  - Increased physiologic dead space (emphysema, pulmonary embolus with complete vessel obstruction)
  - Lung receptor stimulation (e.g., rapid shallow breathing)

Ventilatory Muscles

A reduction in ventilatory muscle strength or endurance will reduce ventilatory capacity. As noted above, ventilatory muscle fatigue sometimes occurs due to very high ventilatory workloads (e.g., reduced compliance, increased airway resistance). **Neuromuscular disorders** may compromise ventilation by causing ventilatory muscle weakness (e.g., Guillain-Barré, myasthenia gravis, or multiple sclerosis [MS]).[4,6] Poor health, inadequate nutrition or starvation, electrolyte disturbances, and advanced age may also cause ventilatory muscle weakness.[4,6] Certain drugs may affect neuromuscular transmission, such as aminoglycoside antibiotics, long-term adrenocortical steroids, and calcium channel blockers.[4,6] Patients with severe COPD may have a chronically elevated WOB just below the threshold which causes diaphragmatic fatigue. When these patients suffer an acute exacerbation of their COPD, the resultant ventilatory fatigue may result in acute hypercapnia, acidosis, and hypoxemia. Other major causes of ventilatory muscle dysfunction seen in the ICU include critical illness polyneuropathy, critical illness myopathy, and prolonged use of neuromuscular-blocking agents.[4,6,13] Prolonged periods of controlled mechanical ventilation may also lead to ventilatory muscle discoordination and atrophy.[13] Paralysis of the ventilatory muscles, as may occur with Guillain-Barré, botulism, or high cervical spinal cord injury, may result in complete cessation of effective breathing. Weakness of the diaphragm and accessory muscles of inspiration can reduce tidal volume, often with a compensatory increase in respiratory rate and rapid shallow breathing. Rapid shallow breathing may be effective in maintaining minute ventilation; however, because of increased dead space ventilation, alveolar (i.e., effective) ventilation may decline and $PaCO_2$ may rise. Rapid shallow breathing and the associated alveolar hypoventilation are often precursors to the need for mechanical ventilatory support. An increased respiratory rate, respiratory alternations (alteration between abdominal and rib cage motion), and abdominal paradox (inward movement of the abdomen during inspiration) are sometimes seen in patients with diaphragmatic fatigue resulting in inadequate ventilation. To summarize, absent or impaired ventilatory muscle function may reduce ventilatory capacity. If ventilatory requirements exceed ventilatory capacity, respiratory failure may ensue, and mechanical ventilation may be required. **Table 5-1** summarizes disorders that may cause ventilatory muscle weakness or dysfunction and reduced ventilatory capacity.

TABLE 5-1
Causes of Ventilatory Muscle Weakness or Dysfunction Associated with the Development of Respiratory Failure, Hypoventilation, and/or Apnea

Disease State or Condition	Description
Amyotrophic lateral sclerosis (ALS)	Chronic and relentless motor neuron disease resulting in progressive voluntary muscle weakness that eventually leads to respiratory failure. Patients with end-stage disease require mechanical ventilatory support in order to survive.
Botulism	Caused by ingestion of food contaminated with *Clostridium botulinum*, which produces a nerve toxin that affects the neuromuscular junction and may cause skeletal muscle paralysis and respiratory failure.
Critical illness myopathy and polyneuropathy	Associated with corticosteroid administration, neuromuscular-blocking agents, systemic inflammatory response, and other conditions sometimes seen in critically ill patients (e.g., sepsis). Causes generalized muscle weakness, including ventilatory muscle weakness, which may cause difficulty in weaning from mechanical ventilatory support.
Duchenne muscular dystrophy	A genetic disorder resulting in muscle weakness that progressively worsens with age. As the patient's condition declines, nocturnal noninvasive ventilation may be needed. Eventually, tracheostomy and invasive ventilation may be required.
Guillian-Barré syndrome	A motor neuron disease that causes progressive weakness and flaccid paralysis of the arms and legs. Involvement of the diaphragm requiring mechanical ventilation occurs in up to 30% of cases; however, generally resolves in about 4 weeks.
Malnutrition	Causes generalized skeletal muscle weakness, which may predispose patients to the development of respiratory failure.
Multiple sclerosis (MS)	A central nervous system disease that damages the myelin sheath of nerves and disrupts nerve transmission from the brain to other parts of the body. In advanced cases, patients may require tracheostomy and intermittent or continuous mechanical ventilatory support.
Myasthenia gravis	An autoimmune disease that affects the neuromuscular junction and may cause relapsing, chronic respiratory muscle weakness.

(*Continues*)

TABLE 5-1
Causes of Ventilatory Muscle Weakness or Dysfunction Associated with the Development of Respiratory Failure, Hypoventilation, and/or Apnea (*Continued*)

Disease State or Condition	Description
Neuromuscular blocking agents	Neuromuscular-blocking agents (e.g. pancuronium, vercuronium, atracurium, and cistracurium) block nerve transmission at the myoneural junction and cause ventilatory muscle paralysis.
Poliomyelitis	Polio virus infection causes loss of motor neurons and results in varying degrees of muscle weakness and paralysis. Post-polio syndrome may cause a syndrome of new or progressive disability.
Tetanus	Caused by infection with *Clostridium tetani* spores, which produce a toxin that produces uncontrolled skeletal muscle contractions.
Tick paralysis	Although this disease is rare in humans, certain ticks produce a toxin that may be transmitted following a tick bite and cause life-threatening paralysis.

Ventilatory Requirements

A patient's ventilatory requirements (aka ventilatory demand or ventilatory load) are determined by his or her oxygenation needs, CO_2 production, lung function, and acid-base status. The level of ventilation required to remove carbon dioxide is determined by metabolic rate, diet, and associated carbon dioxide production ($\dot{V}CO_2$). For example, at rest, normal $\dot{V}CO_2$ is about 200 mL/min and oxygen consumption ($\dot{V}O_2$) is about 250 mL/min requiring an alveolar ventilation ($\dot{V}A$) of 4 to 5 L/min to maintain a normal $PaCO_2$ of 40 mmHg. The relationship between $\dot{V}A$, $\dot{V}CO_2$, and $PaCO_2$ is as follows:

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

The required alveolar ventilation needed to achieve a normal $PaCO_2$ with a normal CO_2 production would be:

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

Inserting normal values for $\dot{V}CO_2$ and $PaCO_2$, this becomes:

$$\dot{V}A = (0.863 \times 200 \text{ mL/min}) \div 40 \text{ mmHg} = 4.3 \text{ L/min}.$$

If $\dot{V}CO_2$ increased to 300 mL/min, the required $\dot{V}A$ to achieve a normal $PaCO_2$ of 40 mmHg would be:

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

$$\dot{V}A = (0.863 \times 300 \text{ mL/min}) \div 40 \text{ mmHg} = 6.47 \text{ L/min}$$

This example illustrates that with increases in $\dot{V}CO_2$, alveolar ventilation must increase to maintain a normal $PaCO_2$. Metabolic rate, $\dot{V}CO_2$, and $\dot{V}O_2$ are increased with fever, shivering, agitation, trauma, sepsis, and other hypermetabolic states.[4,6] Overfeeding in the intensive care unit may also increase $\dot{V}CO_2$.[6] Simply put, increased $\dot{V}CO_2$ will require increased ventilation to remove CO_2. Put another way, an ICU patient's ventilatory requirements may increase due to increased production of carbon dioxide caused by fever, sepsis, agitation, trauma, overfeeding, and other hypermetabolic states.

The normal ventilatory response to hypoxemia is to increase ventilation. Common causes of hypoxemia seen in the ICU include hypoventilation, ventilation–perfusion mismatch (e.g., low $\dot{V}/\dot{Q}$ and right-to left shunt), and diffusion limitations (diffusion defects alone usually only cause exercise hypoxemia; however, often are combined with low $\dot{V}/\dot{Q}$ when interstitial lung disease [ILD] progresses). Causes of decreased tissue oxygen delivery seen in critically ill patients include problems with hemoglobin (e.g., anemia, abnormal Hb), and reductions in cardiac output (e.g., circulatory hypoxia) or tissue perfusion (e.g., shock). Hyperventilation decreases alveolar and arterial PCO_2 and generally will cause a corresponding increase in alveolar and arterial PO_2. Hyperventilation due to hypoxemia is a normal physiologic response that typically results in small, but occasionally clinically important increases in PaO_2. Hyperventilation secondary to hypoxemia represents an increase in ventilatory requirements.

Lung function may affect ventilatory capacity and, in some cases, ventilatory requirements. As noted above, impaired oxygen transfer across the lung may reduce arterial oxygenation, which may trigger an increase in the level of ventilation required (e.g., hyperventilation as a response to hypoxemia). COPD and pulmonary emboli (with complete vessel blockage) may increase physiologic dead space; increased physiologic dead space will require an increase in the level of ventilation needed to remove carbon dioxide. **Clinical Focus 5-1** provides an example of the effect of increased physiologic dead space on ventilatory requirements.

Acid-base balance may also affect the level of ventilation required. Hyperventilation is the normal compensatory response to metabolic acidosis. The expected respiratory compensation for a metabolic acidosis is a decrease in $PaCO_2$ roughly equal to the last two digits of the pH.[14] For example, if a metabolic acidosis results in a pH of 7.20, one would expect a compensatory hyperventilation resulting in a $PaCO_2$ of about 20 mmHg. The level of ventilation required to lower $PaCO_2$ in compensation for

CLINICAL FOCUS 5-1 Effect of Increased Physiologic Dead Space on Ventilatory Requirements

In this exercise, we will examine the effects of an increase in physiologic dead space on a patient's ventilatory requirements. First, we will review normal adult minute ventilation, alveolar ventilation, and physiologic dead space. We will then calculate the effects of a significant increase in physiologic dead space on the level of ventilation required in order to maintain a normal alveolar ventilation.

Question 1. Calculate normal adult minute ventilation (aka minute volume).
Answer: Minute ventilation ($\dot{V}_E$) is simply tidal volume (V_T) times respiratory rate (f):

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

Given a normal adult V_T of 500 mL and f of 12 breaths/min, minute ventilation is:

$$\dot{V}_E = V_T \times f = 500 \text{ mL} \times 12 = 6000 \text{ mL/min} = 6 \text{ L/min}.$$

Question 2. Calculate normal adult alveolar ventilation.
Answer: Recall that alveolar ventilation ($\dot{V}_A$) is simply tidal volume (V_T) minus dead space (V_D) times respiratory rate (f):

$$\dot{V}_A = (V_T - V_D) \times f.$$

- Normal V_T is about 500 mL and normal f is about 12 breaths/min.
- Clinically, physiologic dead space is sometimes quantified by measurement of V_D/V_T.
- Normal physiologic dead space to tidal volume ratio (V_D/V_T) is 0.30 (range 0.20 to 0.40).

Given a normal tidal volume of 500 mL and V_D/V_T of 0.30 (i.e., 30%), physiologic dead space volume (per breath) can be calculated as follows:

$$V_D = V_D/V_T \times V_T = 0.30 \times 500 \text{ mL} = 150 \text{ mL}.$$

Alveolar ventilation per minute ($\dot{V}_A$) can now be calculated:

$$\dot{V}_A = (V_T - V_D) \times f = (500 - 150) \times 12 = 4200 \text{ mL/min} = 4.2 \text{ L/min}.$$

Question 3. Calculate the effect of increased physiologic dead space on ventilatory requirements to maintain normal alveolar ventilation.
Answer: Given an increase in V_D/V_T to 0.60 (i.e., 60%) due to dead space causing disease, calculate physiologic dead space volume, assuming a normal V_T:

$$V_D = V_D/V_T \times V_T = 0.60 \times 500 \text{ mL} = 300 \text{ mL}$$

Question 4. Assuming no change in V_T, what respiratory rate would be needed to maintain a normal alveolar ventilation of 4.2 L/min?
Answer:

$$\dot{V}_A = (V_T - V_D) \times f = (500 - 300) \times f = 4200 \text{ mL/min}$$

$$(500 - 300) \times f = 4200$$

$$200 \times f = 4200$$

$$f = 4200 \div 200 = 21 \text{ breaths/min}$$

Thus, to maintain a $\dot{V}_A$ of 4.2 L/min with a tidal volume of 500 mL per breath, and a physiologic dead space volume of 300 mL (i.e., 60% of V_T), respiratory frequency (f) would have to increase to 21 breaths per minute.

Question 5. Calculate the effect of increased physiologic dead space on minute ventilation requirements to maintain normal alveolar ventilation.
Answer: Minute ventilation is simply tidal volume times respiratory rate. Given the data provided above, the minute ventilation would be:

$$\dot{V}_E = V_T \times f = 500 \text{ mL} \times 21 = 10{,}500 \text{ mL/min} = 10.5 \text{ L/min}.$$

This means that with an increase in physiologic dead space to 60% of the tidal volume, minute ventilation would have to increase from a normal value of 6 L/min to 10.5 L/min to maintain normal alveolar ventilation. This represents a significant increase in the level of ventilation required due to dead space causing disease.

metabolic acidosis will vary with the severity of the acidosis and is limited by the patient's ventilatory capacity.

Causes of a metabolic acidosis sometimes seen in the ICU include lactic acidosis due to severe hypoxemia, shock, or tissue hypoperfusion; acidosis due to renal failure; ketoacidosis (e.g., diabetic ketoacidosis, starvation, and alcoholic ketoacidosis); poisoning (e.g., salicylate poisoning, ingestion of products containing methanol, ethylene glycol, propylene glycol, or toluene); loss of HCO_3^- (e.g., diarrhea, pancreatic fistula); hyperalimentation; administration of carbonic anhydrase inhibitors (e.g., acetazolamide); and renal tubular acidosis.[15] As noted above, metabolic acidosis will increase ventilatory requirements in proportion to the severity of the acidosis.

Assessment of Ventilation

Clinically, assessment of ventilation often includes the patient history, physical examination, measurement of oxygen saturation, and arterial blood gas analysis. Bedside measures of pulmonary function are sometimes performed, which may include measurement of respiratory rate (f), tidal volume (V_T), minute ventilation ($\dot{V}_E$), vital capacity (VC), and maximum inspiratory pressure (MIP). Calculation of the rapid shallow breathing index (RSBI = f/V_T; normal is < 105 breaths/min/L) also provides a useful measure that is somewhat predictive of patients' ability to maintain effective spontaneous breathing. Recall, however, that the single best index of effective ventilation is measurement of P_{aCO_2}. **Box 5-4** provides bedside pulmonary function values suggestive of the need for mechanical ventilatory support. **Clinical Focus 5-2** provides a summary of the causes of inadequate ventilation.

BOX 5-4 Assessment of Ventilation and the Need for Mechanical Ventilatory Support

Bedside measures sometimes used for assessment of the adequacy of ventilation and values suggestive of the possible need for the institution of mechanical ventilatory support include:

- **Respiratory rate (f):** f > 30 or < 8 breaths/min suggests a need for mechanical ventilation. Normal adult rate is 12 to 18 breaths/min.
- **Tidal volume (V_T):** V_T < 5 mL/kg IBW is below normal and (along with other assessment findings) may suggest the need for mechanical ventilation. Normal adult V_T is about 400 to 700 mL or about 7 mL/kg IBW.
- **Minute ventilation ($\dot{V}_E$):** Normal adult $\dot{V}_E$ is 5 to 10 L/min. $\dot{V}_E$ > 10 L/min suggests an underlying problem causing an increase in ventilation (e.g., severe hypoxemia, metabolic acidosis, or pulmonary embolus with increased dead space).
- **Rapid shallow breathing index (RSBI = f/V_T). RSVB** ≥ 105 suggests the need for mechanical ventilation.
- **Vital capacity (VC):** VC < 15 to 20 mL/kg IBW suggests the need for mechanical ventilation.
- **Maximum inspiratory pressure (MIP):** MIP > −20 to −30 cm H_2O suggests the need for mechanical ventilation.
- **Maximum expiratory pressure (MEP):** MEP < 40 cm H_2O is associated with an inability to generate an effective cough.
- **20-30-40 Rule:** institution of mechanical ventilation is suggested for patients with neuromuscular disorders when VC < 20 mL/kg IBW and MIP > −30 cm H_2O and MEP < 40 cm H_2O.
- **P_{aco_2} and pH:** *acute ventilatory failure* as defined by a sudden increase in P_{aCO_2} (> 45 to 50 mmHg) with a corresponding decrease in pH (≤ 7.25) suggests the need for mechanical ventilation.

CLINICAL FOCUS 5-2 Causes of Inadequate Ventilation Requiring Mechanical Ventilatory Support

The primary purpose of mechanical ventilation is to augment, support, or replace normal spontaneous breathing. Put another way, mechanical ventilatory support may be required for patients who *won't breathe*, *can't breathe*, or *can't breathe enough*, as outlined below[4]:

1. **Patients won't breathe.** Common causes of an absent or decreased respiratory drive to breathe include central nervous system (CNS) depressants (e.g., opioid narcotics, barbiturates, and tranquilizers) and CNS disease (e.g., neurologic disease, stroke, head trauma, and brain death).
2. **Patients can't breathe.** Peripheral nervous system disorders, ventilatory muscle disorders, and chest wall, pleural, or upper airway problems make breathing difficult or ineffective. High cervical spine injury (e.g., C2 or C3) may result in diaphragmatic paralysis.
   - Neuromuscular-blocking agents (e.g., pancuronium, vercuronium, atracurium, and cisatracurium) may paralyze the ventilatory muscles. Botulism produces a nerve toxin that may also cause ventilatory muscle paralysis, while tetanus toxin causes uncontrolled skeletal muscle contractions.
   - Guillain-Barré syndrome is a motor neuron disease that causes progressive skeletal muscle weakness and paralysis. Other neuromuscular

disorders may interfere with ventilatory muscle function. For example, multiple sclerosis can interfere with nerve transmission, while myasthenia gravis affects the neuromuscular junction.

- Ventilatory muscle weakness and fatigue may occur in the presence of very high ventilatory workloads due to pulmonary disease (e.g., decreased pulmonary compliance [ARDS, pneumonia, and interstitial lung disease], obstructive lung disease [COPD]), or thoracic disorders (e.g., decreased thoracic compliance).
- Massive pleural effusion may reduce the effectiveness of the ventilatory pump, and upper airway obstruction may interfere with the flow of gas into the lung while increasing WOB.

3. **Patients can't breathe enough.** This is caused by increased ventilatory demand (i.e., increased ventilatory requirements) due to oxygenation problems, increased carbon dioxide production, or increased physiologic dead space.
   - The normal response to hypoxemia is hyperventilation. Patients with already compromised lung function (e.g., obstructive lung disease, decreased pulmonary compliance, increased airway resistance, bronchospasm, and mucosal edema), reduced ventilatory muscle strength and endurance, or ventilation/perfusion abnormalities may not be able increase ventilation sufficiently (i.e., *can't breathe enough*).
   - Increased carbon dioxide production will increase the level of ventilation required to maintain normal acid-base homeostasis. Causes of increased CO_2 production seen in the ICU include fever, shivering, agitation, trauma, sepsis, overfeeding, and fighting the ventilator. Patients with compromised lung function or ventilatory muscle dysfunction may not be able to increase ventilation sufficiently.
   - Increased physiologic dead space will require an increase in minute ventilation to maintain the same level of alveolar ventilation. Patients with otherwise compromised lung function or ventilatory muscle weakness may not be able to increase ventilation sufficiently.

RC Insight

MIP > −20 to − 30 mmHg and/or VC < 15 to 20 mL/kg ideal body weight (IBW) are associated with impending or actual ventilatory failure.

In summary, when ventilatory requirements exceed ventilatory capacity, hypercapnic respiratory failure (aka ventilatory failure) may ensue, and mechanical ventilatory support may be required. Ventilatory requirements are determined by oxygenation needs, carbon dioxide production, lung function, and acid-base status. Ventilatory capacity is determined by respiratory drive, lung function, ventilatory workload, and ventilatory muscle strength. Common causes of increased ventilatory requirements include hypoxia, increased metabolic rate, increased physiologic dead space, and metabolic acidosis. Common causes of decreased ventilatory capacity include suppression or absence of ventilatory drive (e.g., opioids, neurologic disease, and cardiac arrest), increased ventilatory workload (e.g., decreased pulmonary compliance or increased airway resistance), decreased ventilatory muscle strength (e.g., ventilatory muscle fatigue), and impaired pulmonary function (e.g., airway obstruction, decreased compliance, and increased resistance). Bedside measures of the adequacy of ventilation include tidal volume, respiratory rate, RSBI, minute ventilation, vital capacity, and maximum inspiratory pressure (MIP). However, the single best index of the adequacy of ventilation is measurement of $PaCO_2$.

RC Insight

Mechanical ventilation should be considered in patients with an acute increase in $PaCO_2$ > 45 to 50 mmHg, resulting in a pH ≤ 7.25.

Clinical Manifestations of Respiratory Failure

The most common reason for initiating mechanical ventilatory support is acute respiratory failure. Common causes of acute respiratory failure requiring mechanical ventilation include pneumonia, ARDS, trauma, sepsis, postoperative respiratory failure, COPD exacerbation, heart failure, coma, neuromuscular disease, sedative or narcotic drug overdose, and pulmonary aspiration.[2–4] Other causes of respiratory failure that may require mechanical ventilatory support include

inhalational injury (e.g., smoke, toxic gases, and fumes), near-drowning, chest trauma (flail chest, pulmonary contusion, and pneumothorax), cardiogenic pulmonary edema, pulmonary embolism, upper airway obstruction (e.g., tumor, laryngeal edema), acute asthma exacerbation, high cervical spine injury, pulmonary hemorrhage, and massive pleural effusion.[2–4]

Early clinical manifestations of acute respiratory failure include tachycardia, tachypnea, diaphoresis, anxiety, and respiratory distress, followed by depressed mental status, confusion, somnolence, and coma as the patient's condition deteriorates. Physical findings associated with increased WOB include accessory muscle use, intercostal retractions, and asynchronous chest wall to diaphragmatic movement. Alterations in ventilation initially include increased respiratory rate, and rapid shallow breathing, sometimes followed by slowed or irregular breathing and periods of apnea or respiratory arrest as the patient's condition worsens. Initially, arterial blood gases may show hypoxemia, hyperventilation, and alkalosis, followed by hypoventilation, hypercapnia, and **respiratory acidosis** as the patient's condition gets worse. **Clinical Focus 5-3** summarizes the clinical manifestations of acute respiratory failure.

CLINICAL FOCUS 5-3 Clinical Manifestations of Acute Respiratory Failure Associated with the Need for Mechanical Ventilatory Support

The respiratory care clinician should be alert to the presence of the clinical manifestations of acute respiratory failure, which may suggest the need for mechanical ventilatory support. These include alterations in ventilatory status, cardiac function, CNS/mental status, oxygenation, and acid-base balance, as described below.

- **Respiratory/ventilatory status**
  - *Tachypnea* ($f > 20$) is associated with respiratory distress and hypoxemia.
    - $f \geq 30$ is a sensitive marker of respiratory distress and is often associated with the actual or impending ventilatory failure.
  - *Bradypnea* ($f < 8$) is associated with CNS problems (brain damage, head injury), sedatives or narcotic drug overdose, severe hypoxemia, and impending respiratory arrest.
  - *Respiratory distress/increased work of breathing*
    - *Dyspnea/respiratory distress* is generally due to increased respiratory drive (e.g., hypoxemia, hypercapnia, and acidosis) or impaired ventilatory mechanics (e.g., increased WOB, decreased lung compliance, increased airway resistance, and obstructive lung disease).
    - *Accessory muscle use*, including contractions of the inspiratory accessory muscles (i.e., scalenes, sternocleidomastoids, and pectoralis major), are associated with respiratory distress and increased WOB. For example, palpable scalene muscle use during inspiration suggests a markedly increased WOB. Palpable abdominal muscle tensing during expiration suggests increased expiratory work associated with obstruction.
    - *Intercostal retractions* are associated with significant negative pleural pressures on inspiration, sometimes seen with upper airway obstruction, decreased lung compliance, or inadequate gas flow to the mechanically ventilated patient.
    - *Chest wall to diaphragmatic asynchrony*, involving asynchronous or spasmodic diaphragmatic contractions, is associated with respiratory muscle fatigue and may signal an impending respiratory arrest.
    - *Diaphoresis* occurs in patients with acute distress and may be associated with increased WOB.
    - *Nasal flaring* is associated with marked increased inspiratory efforts, especially in infants and children.
  - *Rapid shallow breathing* is a common finding in patients with acute respiratory failure. In adults, $V_T < 300$ mL with $f > 30$ is associated with the need for mechanical ventilatory support.
    - *Rapid shallow breathing index (RSBI = f/V_T)* quantifies the degree of rapid shallow breathing; $RSBI \geq 105$ is associated with the need for mechanical ventilatory support.
  - *Reduced chest expansion* with bilateral limitation is often seen with COPD and neuromuscular disease. Unilateral disorders such as lobar atelectasis or lobar pneumonia may cause unilateral limitation of chest wall movement.
  - *Slowed or irregular breathing* manifests as irregular or asynchronous breathing, periods of apnea, or rapid shallow breathing; these are all

suggestive of the need for mechanical ventilatory support.
  - *Apnea* is the complete cessation of breathing and provides a clear indication for mechanical ventilation.
- **Cardiac/cardiovascular**
  - *Tachycardia* (heart rate [HR] > 100 in adults) is an initial (early) response to hypoxemia.
  - *Bradycardia* (HR < 60) is a late response associated with severe hypoxemia that may signal impending cardiac arrest.
  - *Hypertension* (blood pressure [BP] ≥ 140/90 mmHg) is an initial response to hypoxemia.
  - *Hypotension* (BP < 90/60 mmHg) is associated with decreased cardiac output, peripheral vasodilation, or low circulating blood volume. Common causes include dehydration, blood loss, sepsis, heart disease, and shock. Hypotension is a late response to severe hypoxemia.
  - *Cardiac arrhythmias* are a common response to severe hypoxemia and include sinus tachycardia, premature ventricular contractions (PVCs), ventricular tachycardia, irregular heartbeat, heart block, and atrial fibrillation; severe hypoxia may lead to cardiac arrest.
- **CNS/mental status**
  - The brain is especially sensitive to hypoxia and hypercarbia.
  - Excitement, overconfidence, restlessness, anxiety, headache, and altered mental status are early findings with acute respiratory failure.
  - Confusion, somnolence, unconsciousness, unresponsiveness, and coma may occur as the patient's condition deteriorates.
- **Oxygen desaturation**
  - Oxygen desaturation is commonly assessed by pulse oximetry (Spo_2) or arterial blood gas analysis (Sao_2, Pao_2).
  - *Spo_2 85% to 90%* is associated with a Pao_2 of approximately 50 to 59 mmHg or moderate hypoxemia.
  - *Spo_2 = 75% to 84%* is associated with a Pao_2 of approximately 40 to 49 mmHg or moderate to severe hypoxemia.
  - *Spo_2 < 75%* is associated with a Pao_2 < 40 mmHg or very severe hypoxemia.
    - *Severe oxygenation problems* (e.g., refractory hypoxemia) provide a possible indication for institution of mechanical ventilation and the use of PEEP or CPAP.
  - *Cyanosis* is a variable finding that may not be present in hypoxemic patients with anemia.
- **Acid-base disturbances**
  - *Hypoxemia, hyperventilation, and respiratory alkalosis* are typically seen in the initial stages of acute respiratory failure.
    - Pao_2 < 60 mmHg; $Paco_2$ < 35 mmHg with a corresponding increase in pH > 7.45.
    - May signal *impending ventilatory failure.* Impending ventilatory failure is a possible indication for institution of mechanical ventilation.
  - *Severe hypoxemia, hypoventilation, and respiratory acidosis* are seen as acute respiratory failure worsens.
    - *Acute ventilatory failure* (defined as a sudden increase in $Paco_2$ with a corresponding decrease in pH) provides a major indication for institution of mechanical ventilation.
    - Pao_2 < 40 to 60 mmHg; $Paco_2$ > 45 mmHg with a corresponding decrease in pH < 7.35 provides criteria for severe hypoxemia, hypoventilation, and respiratory acidosis (aka acute ventilatory failure).

Goals of Mechanical Ventilatory Support

Mechanical ventilation can normalize alveolar ventilation and $Paco_2$, correct both respiratory and metabolic acidosis, reverse hypoxemia, relieve respiratory distress, and allow for recovery from ventilatory muscle fatigue by unloading the ventilatory muscles.[2,3,16] Mechanical ventilation may also allow for deep sedation and neuromuscular blockade, in order for certain procedures to be performed.[2,3,16] Deep sedation (with or without the use of neuromuscular-blocking agents) is also sometimes useful in certain cases of severe distress and agitation, delirium, or severe, refractory, or life-threatening oxygenation disorders (e.g., severe ARDS).[2,3,16] In general, however, sedation should be kept to the minimum necessary for the comfort and safety of the patient and neuromuscular-blocking agents

should be used only when absolutely necessary. The primary goals of mechanical ventilatory support are to:

1. Provide adequate alveolar ventilation.
2. Ensure adequate tissue oxygenation.
3. Restore and maintain acid-base homeostasis.
4. Reduce the WOB.
5. Ensure patient safety and comfort.
6. Minimize harmful side effects and complications.
7. Promote liberation of the patient from the ventilator.

Mechanical ventilation may reduce cardiac work by supporting oxygenation and relieving the stress on the heart caused by increased cardiac output in compensation for hypoxemia.[17] Mechanical ventilation may also help restore or maintain lung volumes and prevent or treat atelectasis by restoring adequate lung volumes and incorporating **positive end-expiratory pressure (PEEP)** or **continuous positive airway pressure (CPAP)**.[17] Mechanical ventilation may be helpful for internal stabilization of the chest wall in cases of severe chest trauma (e.g., flail chest) requiring mechanical ventilatory support for respiratory failure.[18]

Indications for Mechanical Ventilation

Because mechanical ventilation supports or replaces the normal ventilatory pump, its primary indication is inadequate or absent spontaneous breathing. Mechanical ventilation will also allow for the application of PEEP or CPAP, as well as certain other techniques useful in the support of patients with severe oxygenation problems. The respiratory care clinician should be on the alert for the presence of disease states or conditions that predispose patients to the development of acute respiratory failure requiring mechanical ventilatory support.

The primary indications for institution of mechanical ventilation are:

1. Apnea
2. Acute ventilatory failure
3. Impending ventilatory failure
4. Severe/refractory oxygenation problems

Apnea

Apnea is the complete cessation of breathing, and failure to institute mechanical ventilatory support in the presence of extended periods of apnea may lead to cardiac arrest and brain death in minutes. Apnea may be caused by a number of disease states or conditions, including cardiac disease, neurologic disease, shock, trauma, spinal cord injury, and sedative or narcotic drug overdose. Cardiac arrest is a common cause of apnea seen in the acute care setting. Myocardial ischemia, myocardial infarction, cardiac arrhythmias, shock, trauma, severe hypotension, and severe hypoxemia all may cause cardiac arrest. Administration of general anesthesia or neuromuscular-blocking agents may also cause apnea.

Airway obstruction can completely block airflow into the lungs, although respiratory efforts will often continue until cardiac arrest ensues. Possible causes of complete airway occlusion include upper airway foreign body aspiration (e.g., food, other objects), upper airway swelling due to anaphylaxis (e.g., insect bites, medications, and food allergy), epiglottitis, airway trauma, laryngospasm post-extubation with associated swelling, and angioedema.

The initial treatment of apnea in the acute care setting includes immediately securing the airway and providing ventilatory support. This may include insertion of an oral pharyngeal airway and positive-pressure ventilation using a bag-mask manual resuscitator bag. If spontaneous breathing does not rapidly resume, endotracheal intubation should be performed and mechanical ventilatory support provided. Upper airway obstruction or acute laryngospasm occasionally requires emergent tracheostomy. While respiratory arrest occasionally occurs alone in the acute care setting, more commonly, patients suffer cardiac and respiratory arrest together. In the case of concurrent cardiac and respiratory arrest, institution of advanced cardiac life support (ACLS) protocols should begin immediately. **Box 5-5** summarizes common causes of apnea. **Clinical Focus 5-4** provides a discussion of a patient with apnea.

Acute Ventilatory Failure

Acute ventilatory failure (AVF) may be defined as a sudden increase in $PaCO_2$ with a corresponding decrease in pH. For example, an acute increase in $PaCO_2$ of 10 mmHg should result in a decrease in pH of about 0.08 units. Acute ventilatory failure is also known as acute hypercapnic respiratory failure; AVF initially results in an uncompensated respiratory acidosis. While arbitrary cut points should not be imposed, generally speaking, an acute increase in $PaCO_2$ resulting in a decrease in pH to about 7.25 or below provides a clear indication for mechanical ventilation.

RC Insight

Acutely, for every 1-mmHg increase in $PaCO_2$ there will be a decrease in pH of about 0.008 units.

BOX 5-5 Causes of Apnea

Apnea is the complete cessation of breathing, which may be caused by a number of different disease states and conditions including:

- Cardiac arrest due to myocardial ischemia and infarction; cardiac arrhythmias; other heart disease; shock; trauma; upper airway obstruction; acute, severe pulmonary embolus; severe electrolyte or acid-base disturbances; or acute, severe hypoxia.
- Brain death or severe brain injury; brain death is the irreversible loss of all brain function resulting in a coma, absence of brainstem reflexes, and apnea.
- Trauma, including head trauma, chest trauma, accidents, near-drowning, and electrical shock.
- Shock and hypotension to include cardiogenic shock, hypovolemic shock, neurogenic shock, anaphylactic shock, and septic shock.
- Drug overdose involving narcotic, sedative, or benzodiazepine tranquilizer drugs may result in apnea.
- Cervical spine injury at the level of C2, C3, or C4 may result in partial or complete paralysis of the diaphragm.
- Neurologic disease including massive stroke, brainstem tumor, cerebral hemorrhage, hepatic encephalopathy, meningitis, encephalitis, and other conditions causing coma.
- Neuromuscular disease resulting in ventilatory muscle paralysis (e.g., Guillain-Barré, ALS, poliomyelitis, botulism).
- Administration of general anesthesia.
- Paralytic drugs (i.e., neuromuscular-blocking agents).
- Respiratory failure with severe hypoxemia can lead to apnea.
- Central, obstructive, and mixed sleep apneas, which generally do not require invasive mechanical ventilatory support. Nighttime noninvasive ventilatory support (i.e., BiPAP), however, is sometimes used in the treatment of obstructive sleep apnea.
- Apnea of prematurity is a disorder sometimes seen in premature infants.

CLINICAL FOCUS 5-4 Apnea

A 62-year-old male patient is transferred to the intensive care unit following a sudden cardiac arrest that occurred on a general medical–surgical floor. The patient had been admitted to the hospital for abdominal surgery and the arrest occurred following admission. The patient was intubated, and advanced cardiac life support (ACLS) protocols were initiated. Cardiac function and blood pressure were restored; however, spontaneous breathing remains absent. The patient is being supported using a bag-valve mask manual resuscitator with supplemental oxygen. Oxygen saturation (Spo_2) by pulse oximetry is 98%.

Question 1. Does the patient have any of the indications for institution of invasive mechanical ventilatory support?

Answer: The primary indications for institution of mechanical ventilatory support are *apnea, acute ventilatory failure*, *impending ventilatory failure*, and *severe oxygenation problems*. Apnea is defined as the complete absence of spontaneous breathing while the term *acute ventilatory failure* generally is used for patients that have an inadequate level of spontaneous breathing. The term *impending ventilatory failure* refers to situations in which acute ventilatory failure is likely in the near future. Severe oxygenation problems are identified by the presence of inadequate arterial oxygen levels while receiving conventional oxygen therapy. The patient described above has no spontaneous breathing and meets the criteria for apnea. Assuming adequate spontaneous breathing does not rapidly resume, mechanical ventilatory support is indicated.

Question 2. Are any contraindications for mechanical ventilation present?

Answer: The contraindications for mechanical ventilation include:

1. *Pneumothorax without chest tubes*. Pneumothorax is not an uncommon complication of external chest compressions performed during basic and advanced life support (BLS/ACLS). While the information provided does not indicate the presence of a pneumothorax, the respiratory care clinician should

(*Continues*)

CLINICAL FOCUS 5-4 Apnea (*Continued*)

be on the alert for the presence of any of the signs of pneumothorax. These include:

- Respiratory distress.
- Alterations in vital signs (e.g., tachycardia, bradycardia, cardiac arrhythmia, hypotension, and tachypnea).
- Oxygen desaturation.
- Absent or reduced breath sounds on one side.
- Uneven chest motion on one side.
- Apparent unilateral lung hyperinflation.
- Tracheal shift and/or shift of the cardiac point of maximal impulse (PMI) may suggest development of a tension pneumothorax.
- Hyperresonance (tympanic) to percussion on one side or area of the chest.
- Development of subcutaneous emphysema.

2. *Absence of indications for mechanical ventilation*. Apnea is a clear indication for mechanical ventilation.
3. *Rapid resolution of the patient's apnea is likely without the need for continued mechanical ventilatory support*. Many patients who are successfully resuscitated following cardiac arrest begin adequate spontaneous breathing very quickly. This patient, however, remains apneic even though enough time has passed for the patient to be transported to the intensive care unit. Because the patient remains apneic, institution of mechanical ventilation at this time is indicated.
4. *Institution of mechanical ventilation would be futile.* The patient has been successfully resuscitated and cardiac function and blood pressure restored. Failure to provide mechanical ventilatory support in the presence of apnea could result in the rapid death of the patient.
5. *Institution of mechanical ventilation would be against the patient's wishes.* No information is provided regarding the patient's wishes and consequently withholding mechanical ventilation at this time would be inappropriate.

The respiratory care clinician should be on the alert for the presence of any of the many disease states or conditions that predispose patients for the development of acute ventilatory failure. These include problems with the conducting airways, alveolar gas exchange, respiratory drive, or ventilatory workload. Other risk factors for the development of ventilatory failure include neuromuscular disease, thoracic or abdominal surgery, chronic pulmonary disease, significant pleural disease, and cardiac disease. Shock, trauma, sepsis, severe burns, and severe obesity (BMI ≥ 40 kg/m^2 or ≥ 35 kg/m^2 in the presence of comorbidities) are also risk factors for the development of AVF. **Box 5-6** summarizes the disease states or conditions associated with the development of acute ventilatory failure and the need to institute mechanical ventilatory support.

Acute ventilatory failure should not be confused with chronic ventilatory failure, in which $PaCO_2$ is chronically elevated and pH is normal or near-normal due to metabolic compensation. With chronic ventilatory failure, the acid-base state is typically compensated or partly compensated respiratory acidosis (usually back to a pH of 7.34 to 7.36). Chronic ventilatory failure is associated with chronic lung disease, such as end-stage cystic fibrosis, interstitial lung disease, or certain patients with COPD. Patients with chronic ventilatory failure may develop *acute ventilatory failure superimposed on chronic ventilatory failure.* For example, a COPD patient with chronic CO_2 retention may experience an acute viral or bacterial infection. This acute exacerbation of COPD may result in an increase in WOB and an acute increase in $PaCO_2$ and corresponding decrease in pH. COPD patients with markedly elevated respiratory rate, accessory muscle use, acute change in mental status, and hypoxemia that is only partially responsive to oxygen therapy have potentially life-threatening exacerbations of their chronic lung disease. Acute ventilatory failure superimposed on chronic ventilatory failure may require mechanical ventilatory support. **Clinical Focus 5-5** provides an example of a patient with acute ventilatory failure.

Impending Ventilatory Failure

The term *impending ventilatory failure* refers to situations where ventilatory failure is likely to occur in the immediate future. In these cases, ventilatory support may be initiated prior to the development of an acute, severe respiratory acidosis. The decision to begin ventilatory support is based on patient assessment, knowledge of the typical progression of the patient's disease state or condition, and the clinical judgment that the patient will progress to acute ventilatory failure in the near future.

Markedly elevated respiratory rates and severe distress use may signal an impending respiratory arrest.[2–4] Clinical manifestations of impending ventilatory failure include extreme tachypnea ($f \geq 35$), severe dyspnea, accessory muscle use, intercostal retractions, significant diaphoresis, dusky skin, and altered mental status.[2–4] Patients often have difficulty speaking in

BOX 5-6 Conditions Predisposing Patients to the Development of Acute Ventilatory Failure (AVF)

AVF occurs when ventilatory requirements exceed ventilatory capacity. *Ventilatory capacity* decreases because of diaphragmatic fatigue or ventilatory muscle dysfunction, neurologic or neuromuscular disease, diminished or absent respiratory drive, airway obstruction, and impaired lung function. *Ventilatory requirements* may increase due to hypoxemia, increased metabolic rate, increased physiologic dead space, or metabolic acidosis. Problems predisposing patients to the development of AVF include:

- Conducting airways problems
  - Upper airway obstruction, laryngeal edema [croup], epiglottis, and upper airway trauma [inhaled smoke, flames, or noxious gases])
  - Lower airway disease including bronchospasm, mucosal edema, and excessive secretions
- Alveolar gas exchange problems
  - ARDS, pneumonia, atelectasis, and pulmonary edema
  - Aspiration
  - Near-drowning
  - Pulmonary embolus
- Respiratory drive depression or absence
  - Excessive sedation
  - General anesthesia
  - Narcotic or sedative drug overdose
  - Head trauma
  - Neurologic disease (massive stroke, tumor, cerebral hemorrhage, and infectious disease)
- Disorders affecting neuromuscular function
  - Guillain-Barré, ALS, myasthenia gravis, multiple sclerosis, and polio
  - Spinal cord injury (C2, C3, and C4)
  - Botulism and tetanus
- Increased ventilatory workload
  - Decreased lung compliance
    - Atelectasis, pneumonia, pulmonary edema, and ARDS
  - Decreased thoracic compliance
    - Obesity, ascites, and thoracic deformity
  - Increased airway resistance
    - Acute asthma exacerbation, COPD exacerbation
    - Airway inflammation, mucosal edema, bronchospasm, and increased secretions
- Thoracic or abdominal surgery
  - Cardiac surgery
  - Lung resection
- Chronic pulmonary disease
  - COPD (emphysema, chronic bronchitis), asthma, bronchiectasis, and cystic fibrosis
  - Interstitial lung disease
- Pleural disease
  - Large pleural effusion, pneumothorax
- Cardiac disease
  - Congestive heart failure, myocardial ischemia and infarction, and other cardiac disease
- Shock, sepsis, trauma, and severe burns
- Severe obesity (BMI $\geq$ 40 kg/m^2 or $\geq$ 35 kg/m^2 in the presence of comorbidities)

CLINICAL FOCUS 5-5 Acute Ventilatory Failure

A 26-year-old male with a history of opioid abuse arrives, unconscious and unresponsive, in the emergency department via EMS. He is suspected of taking an overdose of an unknown substance. The patient was found in a collapsed state in his apartment by a friend. His friend believes that the patient may have consumed pain medications in addition to an unknown quantity of alcohol. His vital signs include tachycardia (HR = 140), irregular pulse, bradypnea (f = 8), and decreased blood pressure (90/60 mmHg). Breath sounds are diminished. An arterial blood gas sample taken on oxygen by partial rebreathing mask reveals:

pH = 7.18
$Paco_2$ = 70 mmHg
HCO_3^- = 28 mmHg
Base excess (BE) = 1.0
Pao_2 = 90 mmHg
Sao_2 = 0.96 mmHg

(*Continues*)

CLINICAL FOCUS 5-5 Acute Ventilatory Failure (*Continued*)

Question 1. Based on the information now available, how would you describe this patient's oxygenation and ventilatory status?

Answer: The arterial pH in combination with an elevated $PaCO_2$ and normal HCO_3^- and base excess indicate an acute (uncompensated) respiratory acidosis; clinically this blood gas result would be described as *acute ventilatory failure.*

The patient's PaO_2 while breathing oxygen by mask is 90 mmHg. Typical partial rebreathing oxygen masks provide an FIO_2 ranging from about 40% to 70% (0.40 to 0.70). A healthy young person with normal lung function should have a significantly elevated PaO_2 ($>$ 140 mmHg) while breathing moderate to high concentrations of supplemental oxygen by mask. In this case, the patient's PaO_2 is much less than expected due to severe hypoventilation.

Question 2. Is mechanical ventilatory support indicated for this patient?

Answer: Acute ventilatory failure is one of the primary indications for mechanical ventilation. While specific criteria should not be arbitrarily imposed, generally speaking, mechanical ventilation should be seriously considered when pH $\leq$ 7.25 due to an elevated $PaCO_2$. Based on the patient's history, physical assessment, and arterial blood gas results, this patient meets the criteria for initiation of mechanical ventilatory support. Because the patient is unconscious and unresponsive, endotracheal intubation should be performed in order to secure and protect the airway and invasive mechanical ventilation begun.

It should be noted that a number of different conditions may cause coma in adults. These include drugs and medications (e.g., sedatives, hypnotics, barbiturates, tranquilizers, opiates, and alcohol), sepsis, electrolyte disturbances, and cerebral vascular disease (e.g., cerebral vascular accident [CVA]). Other causes include infection (e.g., bacterial meningitis, viral encephalitis), metabolic disease (e.g., ketoacidosis, lactic acidosis, and hypoglycemia), and poisonings (e.g., cyanide, carbon monoxide). The patient workup should include measurement of serum glucose to verify the patient's condition is not due to hypoglycemia. Serum acetaminophen concentration should be measured if it is thought that an opioid medication was consumed that included acetaminophen. Chest imaging is appropriate if signs of pulmonary aspiration are present (e.g., abnormal breath sounds). In cases of opioid overdose, administration of a short-acting opioid antagonist (e.g., naloxone [Narcan]) by IV route may restore spontaneous ventilation in a short period of time; however, ventilatory support should be provided until adequate spontaneous ventilation returns. Complications of opioid overdose include aspiration, lung injury, and ARDS.

complete sentences or lying supine due to dyspnea. In such cases, emergent intubation and initiation of mechanical ventilation may be appropriate. With certain diseases, such as COPD and pulmonary edema, a short course (30 to 120 minutes) of noninvasive ventilation may be attempted prior to intubation but should always be performed in the setting of close observation. Use of high-flow, heated/humidified nasal cannulas have also become popular in supporting patients with impending respiratory failure by allowing the delivery of high concentrations of oxygen and small amounts of inspiratory and expiratory pressures.

RC Insight

Respiratory rate $\geq$ 35 breaths/min, severe respiratory distress with air hunger, diaphoresis, and accessory muscle use may signal impending respiratory arrest and the need to institute mechanical ventilatory support.

Acute, severe asthma exacerbation represents a potentially life-threatening condition. The term *status asthmaticus* refers to severe bronchospasm that is unresponsive to routine therapy.[12] Asthma patients seen in the emergency department typically show a mild respiratory alkalosis and often respond to routine therapy. Patients with acute, severe asthma that is unresponsive to conventional therapy may exhibit depressed mental status, slowed spontaneous respiratory rate, and hypoxemia despite administration of O_2.[12] In such patients, increasing $PaCO_2$ is an ominous sign because the patient's condition may rapidly progress to acute ventilatory failure and respiratory arrest.[12] Hypercapnia that fails to respond to bronchodilator therapy suggests the need for mechanical ventilation and institution of ventilatory support should be performed prior to respiratory arrest. In such cases, mechanical ventilation may be considered prior to the development of severe respiratory acidosis.[19]

Certain neuromuscular disorders may also progress to ventilatory failure requiring mechanical ventilation. Guillain-Barré syndrome is an acute immune-mediated

polyneuropathy that sometimes occurs following a flu-like illness in otherwise healthy adults. Guillain-Barré syndrome typically, but not always, causes ascending, symmetrical muscle weakness and paralysis.[20] Weakness usually begins in the legs, although the initial weakness sometimes occurs in the arms or facial muscles. Most patients have decreased or absent deep tendon reflexes, and they may experience paresthesias (tingling) in the affected arms or legs.[20] Patients with suspected Guillain-Barré should be admitted to the hospital and monitored carefully for declines in vital capacity and inspiratory muscle strength. Muscle weakness and paralysis typically progresses over a period of days and may reach a plateau in about 2 weeks, with recovery occurring 2 to 4 weeks later.[20]

Ventilatory muscle weakness or paralysis requiring the institution of mechanical ventilation occurs in up to 30% of cases.[20] Frequent (e.g., every 1 to 2 hours) bedside pulmonary function testing should be initiated in all Guillain-Barré patients and continued as the disease progresses. Impending ventilatory failure is identified by a reduction in vital capacity (VC < 20 mL/kg), maximum inspiratory pressure (MIP > –30 cm H_2O), and maximum expiratory pressure (MEP < 40 cm H_2O). When these measures decline below the suggested values, mechanical ventilatory support may be initiated. Others have suggested that mechanical ventilation should be instituted when the vital capacity falls to less than 1.0 L (or 15 mL/kg IBW).[4] Other neuromuscular diseases that may involve the diaphragm and ventilatory muscles and require the institution of mechanical ventilatory support include myasthenia gravis, severe muscular dystrophy, and amyotrophic lateral sclerosis (ALS).[4] **Clinical Focus 5-6** provides an example of a patient with impending ventilatory failure due to neuromuscular disease.

CLINICAL FOCUS 5-6 Impending Ventilatory Failure

A 35-year-old man has been diagnosed as having Guillain-Barré syndrome. The patient experienced a flu-like illness followed by progressive muscle weakness in his legs and difficulty walking over the past several days. The patient was admitted to the hospital this morning, and the respiratory care clinician was asked to evaluate the patient's ventilatory status. The patient was awake and alert, resting comfortably, and in no apparent respiratory distress.

Question 1. What bedside pulmonary function tests should be frequently performed in order to monitor this patient?

Answer: Bedside measures of ventilatory function in patients with neuromuscular disease include maximum inspiratory pressure (MIP), vital capacity (VC), and maximum expiratory pressure (MEP). It may also be useful to measure the patient's spontaneous tidal volume (V_T), respiratory rate (f), and minute ventilation ($\dot{V}_E$).

Initial values for bedside pulmonary function tests for this patient at 10:00 a.m. were VC = 3.5 L, MIP = −40 cm H_2O, and MEP = + 50 mmHg. The patient's weight is 70 kg, and the patient is not overweight.

Question 2. What is your assessment of the results of the bedside pulmonary function tests performed at 10:00 a.m.?

Answer: VC = 3.5 L. Normal vital capacity in adults is about 70 mL/kg or about 4.9 L for this patient (70 mL/kg × 70 kg = 4900 mL or 4.9 L). Vital capacity is reduced to about 71% of predicted; however, the patient's vital capacity is still sufficient to support adequate spontaneous breathing.

MIP = −40 cm H_2O. Normal MIP varies with age and gender and can be as much as −100 cm H_2O in healthy young men. Generally speaking, MIP < −30 cm H_2O is consistent with adequate spontaneous ventilation, and MIP < −60 cm H_2O can be considered normal.

MEP = +50 mmHg. Maximum expiratory pressure varies with age and gender and can exceed +100 cm H_2O in healthy young adults. MEP ≥ 80 to 100 cm H_2O may be considered normal, and values ≥ 40 cm H_2O are associated with the ability to spontaneously cough and deep breathe.

VC, MIP, and MEP values are reduced; however, not to a level suggesting the need for mechanical ventilation at this time. The respiratory care clinician recommends monitoring bedside pulmonary function values to assess ventilation every 1 to 2 hours because of the progressive nature of the disease.

The following data was collected that evening at 6:00 p.m. on the patient:

V_T = 490

f = 20 breaths/min

$\dot{V}_E$ = 9.8 L/min

VC = 950 mL

MIP = −18 cm H_2O

MEP = +30 cm H_2O

F_{IO_2} = 0.21

(*Continues*)

CLINICAL FOCUS 5-6 Impending Ventilatory Failure (*Continued*)

pH = 7.45
Pa_{O_2} = 85
Pa_{CO_2} = 38
F_{IO_2} = 0.21
HCO_3^- = 26
BE = +1
Sa_{O_2} = 96%

Question 3. What is your assessment of this patient's condition at 6:00 p.m.?
Answer: The patient's tidal volume is normal, although his respiratory rate and minute ventilation are slightly elevated. The patient's expected VC would be about 70 mL/kg of ideal body weight (IBW), which corresponds to a predicted VC of about 4.9 L. Normal values for MIP are < −30 cm H_2O and normal MEP is > +40 C; the patient's MIP and MEP are −18 cm H_2O and +30 cm H_2O respectively. The patient's arterial oxygen tension and saturation while breathing room air are normal and the patient's pH and Pa_{CO_2} are normal, indicating normal ventilatory and acid-base status.

While the patient is ventilating adequately at 6:00 p.m., VC, MIP and MEP are much lower than normal. Generally speaking, when VC declines to less than 1.0 L in adults (or VC < 15 to 20 mL/kg IBW or < 60% predicted) due to neuromuscular disease with progressive muscle weakness, mechanical ventilation should be considered. Predicted VC for this patient is about 4.9 L and the patient's current VC < 1.0 L and < 60% of predicted. Others suggest the "20-30-40 Rule," which calls for the institution of mechanical ventilation when VC < 20 mL/kg IBW, MIP > −30 cm H_2O, and MEP < +40 cm H_2O.

Question 4. Is initiation of mechanical ventilatory support indicated for this patient at this time?
Acute ventilatory failure (i.e., hypercapnia with acidosis) is not yet present based on current arterial blood gas results. However, VC, MIP, and MEP values all suggest that mechanical ventilation should be initiated now because of impending ventilatory failure. Because the patient is not yet in acute distress, initiation of mechanical ventilation at this time will allow the process of establishing an artificial airway and beginning ventilatory support to proceed in an orderly and controlled fashion. The decision to proceed with mechanical ventilation at this time is based on the clinician's judgment that acute hypercapnia with acidosis (i.e., ventilatory failure) will occur in the near future, and delay would place the patient at increased risk.

RC Insight

Rapid shallow breathing (f > 30 breaths/min; V_T ≤ 300 mL in adults) may signal impending ventilatory failure requiring mechanical ventilatory support.

To summarize, with impending ventilatory failure, intubation and the institution of mechanical ventilation may occur prior to the onset of acute respiratory acidosis. By intervening before the patient is an acute distress, establishing an artificial airway and beginning ventilatory support can proceed in a more orderly and controlled fashion. The decision to initiate mechanical ventilation is based on the diagnosis, patient assessment, and sound clinical judgment.

Severe Oxygenation Problems

Hypoxemia (Pa_{O_2} < 60 mmHg; Sa_{O_2} < 90%) while breathing increased oxygen concentrations (F_{IO_2} > 0.40) suggests a significant oxygenation problem. The term *refractory hypoxemia* refers to an oxygenation problem that does not respond to conventional oxygen therapy. The **Pa_{O_2}/F_{IO_2} ratio (P/F ratio)** provides a simple measure of the effectiveness of oxygen transfer across the lung. A normal P/F ratio is in the range of 380 to 476 mmHg, while P/F ratios ≤ 300 mmHg are associated with oxygenation problems. For patients with ARDS, the P/F ratio is used in classifying the severity of disease where:

- P/F ≤ 300 mmHg but > 200 mmHg (while receiving 5 cm H_2O PEEP) = mild ARDS
- P/F ≤ 200 mmHg but > 100 mmHg (while receiving 5 cm H_2O PEEP) = moderate ARDS
- P/F ≤ 100 mmHg (while receiving 5 cm H_2O PEEP) = severe ARDS

RC Insight

Refractory hypoxemia is present when an increase in F_{IO_2} ≥ 0.10 results in an improvement of Pa_{O_2} < 5 mmHg.

Patients with severe oxygenation problems may require the use of PEEP, CPAP, or other techniques to improve arterial oxygenation (e.g., inverse ratio ventilation), which are best applied during invasive mechanical ventilation. PEEP is applied during expiration following a pressure- or volume-controlled inspiration provided by a mechanical ventilator, while CPAP is defined as spontaneous breathing with an elevated baseline pressure.

Patients with ARDS have severe oxygenation problems due to increased intrapulmonary right-to-left shunt. Intrapulmonary shunt (aka physiologic shunt) occurs when venous blood is carried from the right side of the heart to the lungs via the pulmonary arteries and then to pulmonary capillaries adjacent alveoli that are not ventilated ($\dot{V}/\dot{Q} = 0$). This unoxygenated blood is then returned to the left side of the heart without participating in gas exchange. In addition to ARDS, other causes of intrapulmonary R-to-L shunting commonly seen in the ICU include consolidative pneumonia, severe pulmonary edema with alveolar filling, significant atelectasis, complete airway obstruction, and large pneumothorax. Recall that pulmonary edema may be cardiogenic or noncardiogenic and noncardiogenic causes of pulmonary edema include ARDS and neurogenic pulmonary edema.

Patients with large intrapulmonary shunts experience significant hypoxemia that does not respond well to low to moderate concentrations of oxygen therapy (i.e., refractory hypoxemia). PEEP or CPAP may restore functional residual capacity (FRC), keep alveoli open throughout the ventilatory cycle, increase alveolar volume, improve lung compliance, improve P/F ratio, and reduce intrapulmonary shunt.[17] PEEP or CPAP may increase Pa_{O_2} at a given F_{IO_2} in patients with severe oxygenation problems and these patients may require PEEP or CPAP in order to achieve an adequate Pa_{O_2} using a safe F_{IO_2} (i.e., $Pa_{O_2} \geq 60$ mmHg and $F_{IO_2} \leq 0.50$).

Increased WOB due to decreased lung compliance is common in patients with acute, restrictive lung disease (e.g., pneumonia, ARDS). Although adequate spontaneous breathing may be present, these patients often tire, and hypoventilation and ventilatory failure ensue. Early initiation of mechanical ventilation in such patients allows for the use of PEEP or CPAP, pressure support, **pressure control**, or other techniques that may improve oxygenation and reduce the WOB. Institution of mechanical ventilatory support also allows for the use of sophisticated alarms and monitoring systems that are incorporated in modern critical care ventilators. It should be noted that CPAP alone may be useful to improve oxygenation in patients with refractory hypoxemia in the presence of adequate spontaneous ventilation. CPAP may reduce the WOB while improving Pa_{O_2}. CPAP may be delivered using a spontaneous breathing apparatus and a face mask; however, in the ICU setting CPAP is sometimes applied using a conventional mechanical ventilator in the "spontaneous" mode. Other techniques applied during mechanical ventilation that may be helpful in improving oxygenation include use of prolonged inspiratory times, inverse ratio ventilation, prone positioning, and rotational therapy.[21,22] Patients with "nonpulmonary" oxygenation problems including inadequate arterial blood oxygen content (e.g., carbon monoxide poisoning, severe anemia due to blood loss), inadequate oxygen delivery (e.g., heart failure, sepsis, and shock) or inadequate tissue utilization (e.g., cyanide poisoning) may also require mechanical ventilatory support. **Clinical Focus 5-7** provides an example of a patient with severe oxygenation problems. **Clinical Focus 5-8** provides an example of a patient with acute ventilatory failure superimposed on chronic ventilatory failure.

CLINICAL FOCUS 5-7 Severe Oxygenation Problems

A 24-year-old female patient is admitted to the hospital with severe bilateral pneumonia. The patient is awake and alert, but in severe respiratory distress. Blood gases on a partial rebreathing mask at 10 L/min are as follows:

- pH = 7.52
- Pa_{CO_2} = 28 mmHg
- Pa_{O_2} = 48 mmHg
- Respiratory rate = 28 breaths/min
- HCO_3^- = 23 mEq/L
- BE = 2
- Sa_{O_2} = 0.89
- Heart rate = 118

Question 1. What is your assessment of this patient?
Answer: The patient currently exhibits tachycardia, tachypnea, and respiratory distress, which are consistent with acute respiratory failure. The patient's oxygenation status suggests refractory hypoxemia. The F_{IO_2} delivered via partial rebreathing mask at 5 to 10 L/min is in the range of 40% to 70%, yet the resultant Pa_{O_2} is only 48 mmHg at 10 L/min of O_2. Arterial blood gases indicate acute alveolar hyperventilation

(*Continues*)

CLINICAL FOCUS 5-7 Severe Oxygenation Problems (*Continued*)

(aka uncompensated respiratory alkalosis) with severe hypoxemia (the patient's Pa_{O_2} on room air would be < 40 mmHg). The patient is able to ventilate adequately, and she is currently hyperventilating ($Pa_{CO_2} = 28$), probably due to severe hypoxemia. Additional assessment information and review of the patient's chest imaging results would be helpful.

Question 2. Is mechanical ventilatory support indicated for this patient?

Answer: Indications for mechanical ventilation are apnea, acute ventilatory failure, impending ventilatory failure, and severe oxygenation problems. Currently, the patient is hyperventilating (probably due to acute, severe hypoxemia) and is experiencing severe oxygenation problems (i.e., refractory hypoxemia). PEEP or CPAP is indicated for the severe hypoxemia. PEEP/CPAP improves oxygen transfer across the lung by increasing FRC and reducing or eliminating end-expiratory alveolar collapse. PEEP is indicated in most patients with hypoxemic respiratory failure, including ARDS. A trial of CPAP by mask or noninvasive ventilation (NIV) with PEEP/CPAP may be considered; acute hypoxemic respiratory failure sometimes responds to NIV. Invasive mechanical ventilation with PEEP should be considered if ventilatory failure is imminent due to ventilatory muscle fatigue and worsening ventilatory status.

CLINICAL FOCUS 5-8 Acute Ventilatory Failure Superimposed on Chronic Ventilatory Failure

A 68-year-old male patient with a longstanding history of COPD with chronic CO_2 retention enters the emergency department. The patient is diaphoretic, confused, and hypotensive. Heart rate and respiratory rate are elevated (tachycardia and tachypnea) and the patient appears to be in respiratory distress with accessory muscle use and oxygen desaturation ($Spo_2 = 62\%$). An arterial blood gas sample is analyzed with the following results:

$Fio_2 = 0.21$
pH = 7.23
$Pa_{CO_2} = 85$ mmHg
$Pa_{O_2} = 38$ mmHg
$Sa_{O_2} = 0.60$
$HCO_3^- = 37$ mEq/L
BE (base excess) = +5

Question 1. What disease state or condition (other than COPD) should the respiratory care clinician be concerned about in this case?

Answer: Common causes of acute respiratory failure requiring mechanical ventilation include pneumonia, ARDS, trauma, sepsis, postoperative respiratory failure, COPD exacerbation, heart failure, neurologic disease, neuromuscular disease, and sedative or narcotic drug overdose. This patient has a long-standing history of COPD with chronic CO_2 retention and is predisposed to the development of acute respiratory failure due to COPD exacerbation.

Early clinical manifestations of acute respiratory failure include tachycardia, tachypnea, diaphoresis, anxiety, and respiratory distress followed by depressed mental status, confusion, somnolence, and coma as the patient's condition deteriorates. Physical findings associated with increased WOB are common, and rapid shallow breathing or slowed or irregular breathing may be present. This patient is currently exhibiting many of the clinical manifestations of acute respiratory failure.

Question 2. What is your assessment of the patient's blood gas data?

Answer: Suspected respiratory failure is best evaluated by analysis of arterial blood gases. The patient is currently breathing room air with a Pa_{O_2} of 38 mmHg and Sa_{O_2} of 0.60, which would be classified as severe hypoxemia (normal Pa_{O_2} and Sa_{O_2} while breathing room air are 80 to 100 mmHg and 0.96 to 0.98, respectively). The patient's acid-base status is as follows:

- pH = 7.23 → acidosis (normal pH is 7.35 to 7.45)
- $Pa_{CO_2} = 85$ mmHg → respiratory acidosis (normal Pa_{CO_2} is 35 to 45 mmHg; $Pa_{CO_2} > 45$ mmHg is respiratory acidosis while $Pa_{CO_2} < 35$ mmHg is respiratory alkalosis)
- $HCO_3^- = 37$ mEq/L → metabolic alkalosis (normal HCO_3^- is 22 to 28 mEq/L: $HCO_3^- < 22$ mEq/L

is metabolic acidosis, while $HCO_3^- > 28$ mEq/L is metabolic alkalosis)

BE = +5 → metabolic alkalosis (normal base excess or deficit [BE/BD] is ± 2.0 mEq/L; BD < −2.0 is metabolic acidosis while BE > +2.0 is metabolic alkalosis)

Using conventional nomenclature, this blood gas result would be classified as a *partially compensated respiratory acidosis*. However, this patient has a long-standing history of chronic CO_2 retention and his "normal" acid-base status probably is *chronic ventilatory failure* (i.e., chronically elevated $Paco_2$ with normal or near-normal pH due to renal compensation). Chronic ventilatory failure is also known as chronic hypercapnic respiratory failure. Patients with chronic ventilatory failure who become acutely ill may develop *acute ventilatory failure superimposed on chronic ventilatory failure* (aka acute on chronic hypercapnia).

Question 3. What respiratory care would you suggest for this patient at this time?
Answer: The patient most likely is experiencing an acute exacerbation of his COPD with severe hypoxemia while breathing room air. Further evaluation should include a patient history and physical assessment; imaging studies, complete blood count (CBC), serum electrolytes, and serum glucose should be obtained. Hospital treatment should include oxygen therapy, inhaled bronchodilators, glucocorticoids, antibiotics, and supportive care. Institution of mechanical ventilatory support should be considered if the patient's condition continues to deteriorate.
Assessment of follow-up care: The patient is placed on a nasal cannula at 2 L/min, given a short acting beta-2 adrenergic bronchodilator and observed closely. Two hours later, the patient's condition has not improved. Blood gases at this time reveal:

Oxygen: 2 L/min cannula

pH = 7.22

$Paco_2$ = 90 mmHg

Pao_2 = 48 mmHg

HCO_3^- = 36 mEq/L

BE = +8

Sao_2 = 75%

Question 4. What is your assessment of the patient's condition at this time?
Answer: Moderately severe hypoxemia is present while breathing low-concentration oxygen therapy via nasal cannula. The patient's hypercapnia and acidosis have worsened, and acute ventilatory failure superimposed on chronic ventilatory failure continues (aka acute on chronic hypercapnia). Mechanical ventilatory support is now indicated, although a trial of noninvasive ventilation (NIV) may be a good place to begin.

Complications, Hazards, and Contraindications

Mechanical ventilation has a number of potential complications and hazards that may result in increased patient morbidity and mortality. These include **barotrauma**, airway injury, infection, ventilator–associated pneumonia, pulmonary embolus, and gastrointestinal bleeding. Common forms of barotrauma associated with mechanical ventilation include pneumothorax, pneumomediastinum, and subcutaneous emphysema. Ventilatory muscle atrophy and dysfunction can occur, particularly with prolonged controlled mechanical ventilation and the use of neuromuscular-blocking agents.[13,23] The addition of positive pressure to the airways reduces venous return to the right side of the heart (since right atrial pressure equals central venous pressure [CVP] minus pleural pressure). Thus, in the setting of hypovolemia, initiation of mechanical ventilation may result in hypotension. In addition, catastrophic failure of the ventilator or artificial airway can result in life-threatening complications, including death.

Contraindications to Mechanical Ventilation

While there are a number of relative contraindications to mechanical ventilation, failure to provide mechanical ventilatory support when needed may result in the patient's death. Contraindications may include pneumothorax without chest tubes, an absence of indications for mechanical ventilation, rapid resolution of the underlying condition, situations in which life-support interventions are futile, and situations in which mechanical ventilation is contrary to the patient's wishes. Pneumothorax without chest tubes is considered a contraindication for the use of positive-pressure ventilation because a tension pneumothorax may result. In such cases, prompt recognition, decompression, and insertion of chest tubes will allow for safe administration of positive-pressure ventilation. Initiation of mechanical ventilation without clear indications exposes patients to the potentially serious hazards and complications associated with mechanical ventilation. Some conditions resolve rapidly and may only require bag-valve mask manual resuscitator support in the interim. In

these cases, intubation and initiation of mechanical ventilation may not be required. In other cases, life-support interventions may be futile; however, the decision to withhold mechanical ventilatory support may be fraught with legal and ethical implications. Lastly, some patients may not wish to have extraordinary life-support measures. Careful attention to any advanced directives in place regarding end-of-life care may provide guidance in cases where the patient is unable to communicate directly. Thus, the decision to initiate mechanical ventilatory support is not without risk and careful consideration of the indications, contraindications, clinical goals, and potential hazards and complications is required. **Box 5-7** summarizes the contraindications, potential complications, and hazards of mechanical ventilation.

BOX 5-7 Complications and Hazards of Mechanical Ventilation

Adverse pulmonary effects

- Ventilator-associated lung injury (VALI) is lung injury associated with mechanical ventilation thought to be due to cyclic alveolar distention and collapse resulting in alveolar edema and hemorrhage indistinguishable from ARDS; a lung protective ventilation strategy may help avoid VALI.
- Barotrauma is most often due to alveolar rupture and release of air into the pleural space. It includes:
  - Pneumothorax
  - Pneumomediastinum
  - Pneumoperitoneum
  - Subcutaneous emphysema
- Ventilator-associated pneumonia (VAP) is a type of nosocomial pneumonia that develops following institution of mechanical ventilation.
- Atelectasis may be caused by mucus plugging or use of low tidal volumes with normal pulmonary mechanics.
- Decreased mucociliary transport (decreased mucus clearance).
- Hyperventilation (decreased $Paco_2$, respiratory alkalosis).
- Hypoventilation (increased $Paco_2$, respiratory acidosis).
- Increased physiologic dead space.
- Uneven distribution of inspired gas (overventilation of nondependent portions of the lung).
- Redistribution of pulmonary blood flow (due to positive pressure).
- AutoPEEP.
- Increased WOB (often due to inappropriate ventilator settings).
- Patient–ventilator asynchrony.
- Diaphragmatic muscle atrophy (associated with controlled ventilation).
- Oxygen toxicity (associated with $Fio_2 > 0.50$ for prolonged periods of time).

Artificial airways

- Cuff leaks
- Aspiration (often due to leakage around airway cuffs)
- Excessive cuff pressures
- Inadvertent extubation
- Accidental bronchial intubation
- Airway occlusion (partial or complete)
- Esophageal intubation
- Airway trauma (may be associated with traumatic intubation)
- Sore throat, hoarse voice, and stridor (following extubation)
- Laryngeal edema (e.g., glottic and subglottic edema), vocal cord paralysis, and granuloma formation
- Tracheal stenosis or other tracheal lesions (e.g., tracheomalacia, tracheoesophageal fistula, and innominate artery erosion)
- Tracheostomy complications (stomal infection, hemorrhage, subcutaneous emphysema, and pneumomediastinum)

Ventilator system failure

- Patient disconnect
- Air leaks in the ventilator system or patient circuit
- Power failure or power disconnect
- Alarm failure or improper alarm settings
- Humidification system failure (inadequate humidification, overheating)
- Improper assembly of the ventilator circuit
- Inappropriate ventilator settings (hypoventilation, hyperventilation, increased WOB, and patient–ventilator asynchrony)

Cardiac and cardiovascular adverse effects of positive-pressure ventilation

- Reduced venous return to the right heart
- Decreased right ventricular output
- Decreased cardiac output
- Hypotension

Other organs and systems

- Renal failure
- Increased intracranial pressure
- Gastrointestinal (GI) complications
  - GI tract bleeding
  - Decreased splanchnic perfusion
  - GI hypomotility
- Generalized skeletal muscle weakness (associated with prolonged immobilization)
- Generalized inflammation
- Sleep deprivation
- Psychological distress—posttraumatic stress disorder

Patient Assessment for Ventilator Initiation

The decision to initiate mechanical ventilatory support should be based on a thorough patient assessment, sound clinical judgment, and understanding of the indications and associated contraindications, complications, and hazards of mechanical ventilation. As noted, the most common reason for initiating mechanical ventilation is acute respiratory failure and the respiratory care clinician must be on the alert for the presence of disease states or conditions that predispose patients for the development of respiratory failure. Recall also that respiratory failure may be classified as hypoxemic respiratory failure, which may cause severe oxygenation problems and hypercapnic respiratory failure, commonly referred to as ventilatory failure. Conditions that may cause ventilatory failure include those that reduce or eliminate the normal respiratory drive to breathe (see Box 5-2), conditions that increase ventilatory workload beyond ventilatory capacity (see Box 5-3), and conditions that result in ventilatory muscle weakness or dysfunction (see Table 5-1). Generally speaking, causes of inadequate ventilation requiring mechanical ventilatory support can be classified as conditions in which the *patient won't breathe* (i.e., absent or decreased respiratory drive), *can't breathe* (e.g., high cervical spine injury, ventilatory muscle dysfunction, and impairment of the ventilatory pump) or *can't breathe enough* (e.g., hypoxemia, compromised lung function, and ventilatory muscle weakness).[4]

Conditions predisposing patients to the development of acute ventilatory failure can be further classified as problems with the *conducting airways* (e.g., upper airway obstruction, bronchospasm, mucosal edema, and excessive secretions), *alveolar gas exchange problems* (e.g., ARDS, pneumonia, atelectasis pulmonary, and edema), *disorders affecting neuromuscular function or ventilatory drive* (e.g., neuromuscular disease, spinal cord injury, botulism, tetanus, and narcotic or sedative drug overdose), and *increased ventilatory workload* (e.g., decreased compliance, increased airway resistance). Other at-risk groups for the development of respiratory failure requiring mechanical ventilatory support include patients following *thoracic or abdominal surgery*, and those with *chronic lung disease* (e.g., COPD, severe asthma, and interstitial pulmonary fibrosis), *pleural disease* (e.g., pneumothorax, large pleural effusion), or *cardiac disease* (see Box 5-6). Patients with *sepsis, shock, and trauma; poisoning* (e.g., carbon monoxide, cyanide, opiods, and botulism); *severe burns*; and *severe obesity* are also at high risk for development of acute respiratory failure.

Assessment of patients for the clinical manifestations of acute respiratory failure include review of patients' oxygenation and ventilatory status, acid-base balance, cardiac and cardiovascular function, and CNS and mental status. Abnormal respiratory rate ($f \geq 30$ to 35 or $f \leq 8$ to 10 in adults), respiratory distress (e.g., severe dyspnea, accessory muscle use, intercostal retractions, chest wall to diaphragm asynchrony, and sweating), rapid shallow breathing, reduced chest expansion, and slowed or irregular breathing or periods of apnea suggest the possible need for mechanical ventilatory support.[1–4]

Abnormal bedside measures of pulmonary function including reduced vital capacity (VC < 15–20 mL/kg), inadequate maximum inspiratory pressure (MIP > –20 to –30 cm H_2O), reduced maximum expiratory pressure (MEP < 40 cm H_2O), or increased rapid shallow breathing index (RSBI [f/VT] ≥ 105) are also suggestive of the need for the institution of mechanical ventilatory support.

Cardiac and cardiovascular assessment findings suggestive of the possible need for mechanical ventilatory support include tachycardia, bradycardia, abnormal blood pressure, and the presence of cardiac arrhythmias. The brain is especially sensitive to hypoxia and agitation, confusion, somnolence, unconsciousness, unresponsiveness, and coma all suggest the possible need for mechanical ventilatory support. Wherever possible, the presence of respiratory failure should be confirmed by measurement of arterial oxygen saturation (Sao_2), arterial oxygen tension (Pao_2) and oxygen content (Cao_2), and arterial blood gas analysis for assessment of acid-base balance.

To summarize, respiratory failure is suspected based on the patient's history, presence of conditions that predispose the development of respiratory failure, and related assessment findings. The presence of oxygen

desaturation is commonly determined by pulse oximetry or arterial blood gas analysis. Assessment of acid-base balance and $PaCO_2$ requires arterial blood gas analysis, or the use of venous blood gases. Acute respiratory failure is defined as a sudden fall in arterial oxygenation with or without CO_2 retention. Apnea is defined as complete cessation of breathing. Acute ventilatory failure is defined as a sudden rise in arterial carbon dioxide tension ($PaCO_2$) with a corresponding decrease in pH. It may also be considered when a normal end-tidal CO_2 (35 to 40) acutely rises on capnography, although clinicians must be aware of the limitations of capnography for the assessment of ventilation. Impending ventilatory failure is a clinical judgment in which the development of acute respiratory acidosis is thought to be imminent. Severe oxygenation problems generally are associated with refractory hypoxemia, often caused by large intrapulmonary (physiologic) shunts. The decision to institute mechanical ventilatory support is based on clinical assessment and evaluation of the factors listed below.

- Predisposing factors for the development of acute respiratory failure are present.
  - Acute lung disease (e.g., ARDS, pneumonia, pulmonary embolus, airway obstruction, and pulmonary aspiration)
  - Chronic lung disease (e.g., asthma, COPD, and interstitial lung disease)
  - Cardiac disease (e.g., myocardial ischemia, myocardial infarction, and heart failure)
  - Sepsis
  - Shock (cardiogenic, septic, neurogenic, hypovolemic, and anaphylactic
  - Trauma (e.g., chest trauma, head trauma, neardrowning, and smoke inhalation)
  - Poisoning (e.g., carbon monoxide, cyanide)
  - Neurologic disease (e.g., brain stem tumor, cerebral hemorrhage, massive stroke, meningitis, and coma)
  - Neuromuscular disease (e.g., Guillain-Barré, myasthenia gravis, ALS, critical illness, and myopathy)
  - Sedative, tranquilizer, or narcotic drug overdose
  - Postoperative abdominal or thoracic surgery
- Clinical manifestations of acute respiratory failure are present.
  - Tachycardia, bradycardia, arrhythmias, hypertension, and hypotension
  - Tachypnea, rapid shallow breathing, irregular breathing, bradypnea, and periods of apnea
  - Anxiety, dyspnea, and respiratory distress
  - Accessory muscle use, intercostal retractions, asynchronous chest wall to diaphragm movement, and reduced chest wall movement
  - Sweating, cyanosis, and pallor
  - Depressed mental status, confusion, somnolence, and coma
- Indications for mechanical ventilation are present.
  - Apnea
  - Acute ventilatory failure
  - Impending ventilatory failure
  - Severe oxygenation problems
- Other possible indications include:
  - General anesthesia administration
  - Need for deep sedation and/or neuromuscular blockade
- Contraindications to mechanical ventilation:
  - Indications for mechanical ventilation are not present.
  - Rapid resolution of underlying condition occurs. For example, narcotic overdose patients may be given an opioid antagonist (e.g., naloxone) and supported in the interim using a bag-valve mask manual resuscitator until adequate spontaneous ventilation returns.
  - Pneumothorax without chest tubes.
  - Life-support interventions are futile.
  - Mechanical ventilation is contrary to the patient's wishes.
- Consideration of possible complications and hazards including:
  - Ventilator-associated lung injury, barotrauma, and ventilator-associated pneumonia
  - Inappropriate ventilator settings, hyperventilation, hypoventilation, and increased WOB
  - Airway problems (accidental extubation, bronchial intubation, cuff leaks, and airway trauma)
  - Ventilator system failure
  - Impaired cardiac output, hypotension
  - Increased intracranial pressure
  - Other organ system complications (GI bleeding, renal failure, and generalized inflammation)
  - Generalized skeletal muscle weakness
  - Psychological distress, sleep deprivation, and traumatic stress disorder

Initial Ventilator Settings

A number of choices must be made following the decision to institute mechanical ventilatory support. For example, certain patients may do well with noninvasive ventilation (NIV), while others may require invasive mechanical ventilation. Many ventilators allow the clinician to choose between providing partial and full ventilatory support. Apneic patients require full ventilatory support, while partial ventilatory support using some form of **synchronized intermittent mandatory ventilation (SIMV)** may be useful in certain patients who are spontaneously breathing.

A large number of different ventilator modes are currently available, and the clinician must choose between **continuous mandatory ventilation (CMV)**,

intermittent inventory ventilation (IMV), and **continuous spontaneous ventilation (CSV)**.[24] Initiation of ventilator breaths may be time triggered or patient triggered, and patient-triggered breaths may be initiated based on a pressure or flow signal (i.e., pressure triggered or flow triggered). Ventilator breaths may be volume limited, pressure limited, or time limited. Ventilator breaths may be terminated following delivery of a specific volume (volume cycled), achievement of an inspiratory pressure (pressure cycled), when the inspiratory flow drops to a certain value (flow cycled), or following a preset time interval (time cycled). Spontaneous breathing may be allowed, which may or may not include some form of pressure support.

A recommended taxonomy for mechanical ventilation suggests five basic ventilatory patterns or modes, as follows.[24]

Volume Control-Continuous Mandatory Ventilation (VC-CMV)

For **volume-control (VC)** ventilation, the control variable is volume and both volume and flow are preset prior to inspiration and volume delivery is not affected by changes in lung compliance or airway resistance. CMV indicates that all breaths are mandatory, but may be patient or machine (i.e., time) triggered to inspiration. If the ventilator is set up to allow for patient triggered or machine-triggered, volume-targeted mandatory breaths, the mode is commonly referred to as *assist-control (A/C) volume ventilation* (aka patient-triggered or time-triggered CMV). If only machine-triggered, volume-targeted breaths are allowed, the ventilator is in the *control mode* (aka time-triggered CMV).

Volume Control-Intermittent Mandatory Ventilation (VC-IMV)

IMV and synchronized intermittent mandatory ventilation (SIMV) may be used to provide partial or full ventilatory support. VC indicates the control variable is volume; during mandatory breaths, volume delivery remains constant. IMV indicates that patients may breathe spontaneously between mandatory breaths. As originally introduced, IMV only allowed for time-triggered mandatory breaths. SIMV is the most common form of IMV in which the mandatory breaths may be time or patient triggered. SIMV also allows patients to breathe spontaneously between mandatory breaths and the mandatory breaths are "synchronized" to the end of the patient's exhalation.

Pressure Control-Continuous Mandatory Ventilation (PC-CMV)

Pressure control (PC) indicates that the control variable is pressure and inspiratory pressure is preset as either a constant value or proportional to the patient's inspiratory effort. CMV indicates that all breaths are mandatory. Breaths may be machine or patient triggered. A commonly used form of this mode delivers a predetermined minimum mandatory rate and allows the patient to trigger the ventilator at a higher rate (i.e., assist-control mode); inspiration is pressure limited and time cycled.

Pressure Control-Intermittent Mandatory Ventilation (PC-IMV)

PC indicates that the control variable is pressure while IMV indicates that the patient may breathe spontaneously in between mandatory breaths.

Pressure Control-Continuous Spontaneous Ventilation (PC-CSV)

PC indicates that the control variable is pressure while CSV indicates all breaths are spontaneous. A commonly used form of this mode is referred to as *pressure-support ventilation* (PSV) in which each breath is patient triggered, inspiratory pressure is preset, and inspiration is flow cycled to expiration.

Qualifying subscripts are then added to further describe the ventilatory pattern targeting scheme (e.g., set-point [s], dual [d], adaptive [a], etc.).[24] The suggested taxonomy thus becomes complex and somewhat difficult for clinicians to apply. To further complicate initial ventilator setup, manufacturers use a dizzying array of different terms to describe the modes available on their ventilators. For example, the Covidien Puritan Bennett 840 lists the following modes: bilevel, pressure control assist-control, pressure control synchronized intermittent mandatory ventilation, pressure support, proportional assist ventilation plus, spontaneous, tube compensation, volume control assist-control, volume control plus assist-control, volume control plus synchronized intermittent mandatory ventilation, and volume ventilation plus synchronized intermittent mandatory ventilation. Two other common critical care ventilators, the Dräger Evita X and HAMILTON Medical G5, have similar, but not the same, naming taxonomies for the modes available on those machines.

Despite the large number of modes available on current critical care ventilators, most patients in the ICU will do quite well using volume or pressure ventilation with set point targeting in the assist-control mode (aka VC-CMVs or PC-CMVs). PSV or SIMV with pressure support can also be effectively applied to patients. Positive end-expiratory pressure (PEEP) or continuous positive airway pressure (CPAP) may be added to these common modes. Choice of ventilator mode will be further discussed in Chapter 6, Ventilator Initiation.

The respiratory care clinician must also choose other important ventilator settings including tidal volume (or pressure limit), respiratory rate, trigger method and

sensitivity, inspiratory flow rate (or inspiratory time), and adjustable inspiratory flow pattern (with VC ventilation) or rise time and flow termination criteria (with pressure support ventilation). Oxygen concentration (F_{IO_2}), and PEEP/CPAP level must also be selected. Tidal volume should be selected based on the patient's condition and clinical goals. Large tidal volumes may result in high airway pressures, which may cause ventilator-induced lung injury. Generally speaking, the initial tidal volume should be such that plateau pressure ($P_{plateau}$) $\leq$ 30 cm H_2O. ARDS patients have reduced lung compliance and initial tidal volume may be set at 8 mL/kg and then gradually reduced to 6 mL/kg over the next 1 to 3 hours to maintain $P_{plateau} \leq$ 30 cm H_2O.[25] Patients with neuromuscular disease, on the other hand, may have normal lung compliance and initial tidal volume may be set in the range of 8 to 10 mL/kg.[26] Smaller tidal volumes in these patients may promote the development of atelectasis and some centers titrate tidal volume to higher levels as long as the $P_{plateau}$ remains $\leq$ 30 cm H_2O.

Respiratory rate in combination with tidal volume will determine minute ventilation and P_{aCO_2}. An approximate minute ventilation goal to achieve full ventilatory support for most adult patients is about 100 mL/kg IBW.[26] For patient-triggered breaths, sensitivity must be set at a level where patient triggering requires minimal patient effort without autocycling. Inspiratory flow, tidal volume (or pressure), and respiratory rate will determine inspiratory and expiratory time and I:E ratio. Inspiratory flows should be sufficient to meet or exceed patients' inspiratory demand and expiratory time should be sufficient to avoid the development of autoPEEP. Care should be taken to ensure patient comfort, minimize the WOB, and avoid patient–ventilator asynchrony. Inspiratory flow pattern may have an impact on inspiratory time as well as peak and mean airway pressures and distribution of the inspired gas. Oxygen concentration generally is set at the lowest level required to correct hypoxemia and avoid oxygen toxicity. PEEP/CPAP is often added to prevent end-expiratory alveolar collapse and improve $\dot{V}/\dot{Q}$ and arterial oxygenation while allowing for reduction in F_{IO_2}. Each of these initial ventilator settings will be discussed in detail in Chapter 6, Ventilator Initiation.

Once the decision has been made to institute mechanical ventilatory support, the respiratory care clinician must adjust the level of support provided to achieve adequate alveolar ventilation, maintain acid-base homeostasis, and insure adequate tissue oxygenation. Ventilator settings should be selected that reduce the patient's WOB, ensure patient comfort, and avoid patient–ventilator breathing asynchrony. Patient safety must be ensured, and avoidance of the complications and hazards of mechanical ventilation, wherever possible, must occur. Last but not least, patient management should promote liberation of the patient from the ventilator as soon as reasonably prudent.

In summary, the four primary indications for mechanical ventilation are apnea, acute ventilatory failure, impending ventilatory failure, and severe oxygenation problems. Acute respiratory failure is the most common diagnosis requiring mechanical ventilation. Other common diagnoses include acute exacerbation of COPD, coma, and neuromuscular disease. Clinical manifestations of respiratory failure include respiratory distress, dyspnea, accessory muscle use, retractions, and tachypnea. Rapid shallow breathing is a common finding in patients with respiratory failure. Tachycardia and other arrhythmias are signs of cardiac distress. Bradycardia is an ominous finding. Initially patients may be anxious and restless followed by confusion, somnolence, and coma. Bedside pulmonary function measures associated with ventilatory failure and the need to initiate mechanical ventilation include elevated respiratory rate, reduced tidal volume, rapid shallow breathing index $\geq$ 105, vital capacity $<$ 15 to 20 mL per kg or 1.0 L, and maximum inspiratory pressure $>$ –30 mmHg. Acute ventilatory failure is defined as a sudden rise in arterial P_{aCO_2} with a corresponding decrease in pH. Severe oxygenation problems are best identified by evaluation of arterial blood oxygenation versus F_{IO_2}. P/F ratios provide a convenient estimate of the effectiveness of gas transfer across the lung.

Key Points

- The primary function of the mechanical ventilator is to augment or replace normal ventilation.
- Respiratory failure is the inability of the heart and lungs to maintain adequate tissue oxygenation and/or carbon dioxide removal; hypoxemic respiratory failure (aka lung failure) is a problem with oxygenation while hypercapneic ventilatory failure (aka pump failure) is a problem with ventilation resulting in an abnormal increase in P_{aCO_2}.
- Mechanical ventilation may be required when spontaneous breathing is insufficient or absent.
- Respiratory failure is the most common reason for initiating mechanical ventilatory support.
- Acute ventilatory failure (aka acute hypercapnic respiratory failure) is a sudden rise in P_{aCO_2} with a corresponding decrease in pH.
- The major components of ventilation are tidal volume, respiratory rate, and minute ventilation.
- Alveolar ventilation is determined by tidal volume, respiratory rate, and physiologic dead space.
- Ventilatory capacity refers to the amount of air that can be moved into and out of the lungs by the ventilatory pump.
- Ventilatory requirements (aka ventilatory demand) is the volume of ventilation required to achieve adequate oxygenation and carbon dioxide removal.
- Ventilatory capacity may be reduced due to absent or decreased respiratory drive, increased work of

breathing resulting in ventilatory muscle fatigue, neuromuscular disease, and impaired lung function.
- Ventilatory requirements may increase due to hypoxia, increased metabolic rate, metabolic acidosis, or increased physiologic dead space.
- When ventilatory requirements exceed ventilatory capacity, mechanical ventilatory support may be necessary.
- Respiratory drive may be reduced or absent in the presence of severe hypoxemia, severe hypercapnia, cardiac arrest, neurologic disease, head trauma, near-drowning, poisoning, severe electrical shock, drug overdose (e.g., narcotics, barbiturates, and tranquilizers), general anesthesia, alkalosis, electrolyte disorders, severe hypothyroidism, and certain other disease states and conditions.
- Ventilatory capacity may be reduced due to upper airway obstruction; lower airway bronchospasm, mucosal edema, or secretions; reductions in lung or thoracic compliance; alveolar filling or collapse; interstitial pulmonary fibrosis; or increased physiologic dead space.
- Increased ventilatory workload may result in ventilatory muscle fatigue, reduced ventilatory capacity, and the development of acute ventilatory failure.
- Causes of increased ventilatory workload include decreased lung compliance, decreased thoracic compliance, increased airway resistance, and increased level of ventilation required.
- Causes of ventilatory muscle weakness or dysfunction include amyotrophic lateral sclerosis, botulism, critical illness myopathy and polyneuropathy, muscular dystrophy, Guillain-Barré syndrome, multiple sclerosis, malnutrition, myasthenia gravis, poliomyelitis, tetanus, and tick paralysis.
- Neuromuscular-blocking agents block nerve transmission at the myoneural junction (aka neuromuscular junction) and cause ventilatory muscle paralysis.
- Arterial carbon dioxide tension ($Paco_2$) is inversely proportional to alveolar ventilation ($\dot{V}A$) and directly proportional to carbon dioxide production ($\dot{V}CO_2$).
- Clinically, the single best index of alveolar ventilation is measurement of $Paco_2$.
- Clinical manifestations of acute respiratory failure include tachycardia, tachypnea, diaphoresis, anxiety, respiratory distress, accessory muscle use, and intercostal retractions. Manifestations of severe respiratory failure may include markedly increased respiratory rate, rapid shallow breathing, slowed or irregular breathing, periods of apnea, asynchronous chest wall to diaphragm movement, confusion, somnolence, and coma.
- Goals of mechanical ventilation include providing adequate alveolar ventilation and oxygenation, restoring and maintaining acid-base homeostasis, reducing the work of breathing, ensuring patient safety and comfort, minimizing harmful side effects and complications, and promoting liberation of the patient from the ventilator.
- The primary indications for institution of mechanical ventilation are apnea, acute ventilatory failure, impending ventilatory failure, and severe oxygenation problems.
- Apnea is the complete cessation of breathing and failure to provide mechanical ventilatory support in the presence of prolonged apnea will lead to cardiac arrest and brain death in minutes.
- Acute ventilatory failure in which an acute increase in $Paco_2$ results in a pH $\leq$ 7.25 provides an indication for mechanical ventilation.
- Impending ventilatory failure refers to situations where ventilatory failure is likely to occur in the immediate future.
- Refractory hypoxemia refers to an oxygenation problem that does not respond conventional oxygen therapy.
- Patients with refractory hypoxemia may require the use of PEEP or CPAP.
- Complications of mechanical ventilation include barotrauma, ventilator-associated lung injury, airway injury, infection, ventilator-associated pneumonia, pulmonary embolus, hypotension, and stress ulcers (gastrointestinal bleeding).
- Contraindications to mechanical ventilation include pneumothorax without chest tubes, absence of clear indications, rapid resolution of apnea or ventilatory failure, futility of intervention, or when mechanical ventilation is against the patient's wishes.
- The decision to initiate mechanical ventilatory support should be based on a thorough patient assessment, sound clinical judgment, and an understanding of the indications, contraindications, complications, and hazards of mechanical ventilation.
- Decisions regarding initial ventilator setup include use of invasive or noninvasive ventilation, use of full or partial ventilatory support, choice of mode, and selection of initial ventilator settings.

References

1. Selvakumar N, Casserly B, Rounds S. Essentials in critical care medicine. In: Benjamin IJ, Griggs RC, Wings EJ, Figgs JG (eds.). *Andreoli and Carpenter's Cecil Essentials of Medicine*, 9th ed. Philadelphia, PA: Elsevier-Saunders; 2016: 259–265.
2. Aboussovan LS. Respiratory failure and the need for ventilator support. In: Kacmarek RM, Stoller JK, Heuer AJ (eds.). *Egan's Fundamentals of Respiratory Care*, 11th ed. St. Louis, MO: Elsevier; 2017: 972–986.
3. Cairo JM. Establishing the need for mechanical ventilation. In: Cairo JM (ed.). *Pilbeam's Mechanical Ventilation: Physiological and Clinical Applications*. 6th ed. St. Louis, MO: Elsevier; 2016: 43–57.
4. Feller-Kopman DJ, Schwartzstein RM. The evaluation, diagnosis, and treatment of the adult patient with acute hypercapnia respiratory failure. In: Stoller JK, Finlay G (eds.). *UpToDate*; July 20, 2017.
5. Maloney JP. Acute ventilatory failure. In: Hanley ME, Welsh CH (eds.). *Current Diagnosis and Treatment in Pulmonary Medicine*. Columbus, OH: McGraw Hill Education; 2003. Access Medicine. Available at http://accessmedicine.mhmedical.com. Accessed April 11, 2017.

6. Hall JB, McShane. Ventilatory failure. In: *Critical Care Medicine: Respiratory Failure and Mechanical Ventilation, Merck Manual Professional Version*. Kenilworth, NJ; 2017. Available at https://www.merckmanuals.com/professional/critical-care-medicine/respiratory-failure-and-mechanical-ventilation/ventilatory-failure. Accessed April 11, 2017.
7. Piraino T. Monitoring the patient in the intensive care unit. In: Kacmarek RM, Stoller JK, Heuer AJ (eds). *Egan's Fundamentals of Respiratory Care*, 11th ed. St. Louis, MO: Elsevier; 2017: 1154–1189.
8. Johnson DC. Control of ventilation. In: Flaherty KR, Manaker S, Finlay G (eds). *UpToDate*; August 1, 2017.
9. Stoller JK. Management of exacerbations of chronic obstructive pulmonary disease. In: Barnes PJ, Hollingsworth H (eds.). *UpToDate*; 2016.
10. Jankowich MD. Obstructive lung disease. In: Benjamin IJ, Griggs RC, Wings EJ, Figgs JG (eds.). *Andreoli and Carpenter's Cecil Essentials of Medicine*, 9th ed. Philadelphia, PA: Elsevier-Saunders; 2016: 207–221.
11. Global Initiative for Chronic Obstructive Lung Disease (GOLD). GOLD 2017 global strategy for the diagnosis, management and prevention of COPD. January 2017. Available at http://goldcopd.org/gold-2017-global-strategy-diagnosis-management-prevention-copd/. Accessed April 11, 2017.
12. Fanta CH. Management of acute exacerbations of asthma in adults. In: Bochner BS, Hockberger RS, Hollingsworth H (eds.). *UpToDate*; 2017.
13. Hyzy RC. Physiologic and pathophysiologic consequences of mechanical ventilation. In: Parsons PE, Finlay G (eds.). *UpToDate*; 2017.
14. Emmett M, Palmer BF. Simple and mixed acid-base disorders. In: Sterns RH, Forman JP (eds.). *UpToDate*; 2016.
15. Emmett M, Szerlip H. Approach to the adult with metabolic acidosis. In: Sterns RH, Forman JP (eds.). *UpToDate*; 2016.
16. Courey AJ, Hyzy RC,. Overview of mechanical ventilation. In: Parsons PE, Finlay G (eds.). *UpToDate*; 2016.
17. Kacmarek RM. Physiology of ventilatory support. In: Kacmarek RM, Stoller JK, Heuer AJ, (eds). *Egan's Fundamentals of Respiratory Care*, 11th ed. St. Louis, MO. Elsevier; 2017: 1016–1057.
18. Sarani B. Inpatient management of traumatic rib fractures. In: Bulger EM, Friedburg JS, Collings KA (eds.). *UpToDate*; 2017.
19. Camargo CA, Krishnan JA. Invasive ventilation in adults with acute exacerbations of asthma. In: Manaker S, Hollingsworth H (eds.). *UpToDate*; 2016.
20. Vriesendorp FJ. Guillain-Barré syndrome in adults: clinical features and diagnosis. In: Shefner JM, Targoff IN, Dashe JF (eds.). *UpToDate*; 2017.
21. Schwartz DR, Malhotra A, Kacmarek RM. Prone ventilation for adult patients with acute respiratory distress syndrome. In: Parsons PE, Finlay G (eds.). *UpToDate*; 2017.
22. Kacmerek RM. Initiating and adjusting invasive ventilatory support. In: Kacmarek RM, Stoller JK, Heuer AJ (eds.). *Egan's Fundamentals of Respiratory Care*, 11th ed. St. Louis, MO. Elsevier; 2017:1078–1110.
23. Lacomis D. Neuromuscular weakness related to critical illness. In: Shefner JM, Dashe JF (eds.). *UpToDate*; 2017.
24. Chatburn Rl, El-Khatib M, Mireles-Cabodevila E. A taxonomy for mechanical ventilation: 10 fundamental maxims. *Respir Care*. 2014;59(11):1747–1763.
25. Siegel MD, Hyzy RC. Mechanical ventilation of adults in acute respiratory distress syndrome. In: Parsons PE, Finlay G (eds.). *UpToDate*; 2016.
26. Hou P, Baez AA. Mechanical ventilation of adults in the emergency department. In: Walls RM, Grayzel J (eds.). *UpToDate*; 2016.