product of cellular metabolism is carbon dioxide. Carbon dioxide diffuses from the tissues into the capillary blood, where much of it is reversibly hydrated to form carbonic acid. It is then transported to the lungs by the venous blood, diffuses from the pulmonary capillary blood into the alveoli, and is exhaled into the atmosphere. It is evident, then, that the exchange of oxygen and carbon dioxide at the alveolo-capillary interface is essential to meet the metabolic demands of the body and to prevent the development of life-threatening acidosis.

Respiratory failure may be defined as a significant impairment in the capacity of the respiratory system to perform gas exchange and is recognized by the presence of arterial hypoxemia and/or hypercapnia. On the basis of the duration of impaired gas exchange, respiratory failure may be classified as either acute or chronic. Chronic respiratory failure, which most commonly results from chronic obstructive pulmonary disease (COPD), is accompanied by physiologic adaptations that return systemic oxygen delivery and blood pH toward normal. For this reason, the terms acute and chronic also imply differences in clinical manifestations and in the urgency of therapy. Patients with chronic respiratory failure may, of course, experience an intercurrent illness that leads to acute decompenation (acute on chronic respiratory failure).

This chapter focuses on the evaluation and management of the patient with acute respiratory failure. This abrupt impairment of gas exchange represents a threat to the life of the patient and must be rapidly diagnosed and aggressively and effectively treated. We begin with a brief overview of the mechanisms of abnormal gas exchange. This topic is discussed in detail in Chapter 87.

MECHANISMS OF ABNORMAL GAS EXCHANGE

The effectiveness of the lungs in transferring both oxygen and carbon dioxide is determined by three factors: (1) the rate at which fresh air is supplied to the alveoli (alveolar ventilation); (2) the degree to which ventilation and perfusion are matched in each of the gas-exchanging units of the lungs; and (3) the extent to which oxygen and carbon dioxide equilibrate between the alveolar gas and the pulmonary capillary blood. A disturbance in any of these processes could, therefore, be expected to result in arterial hypoxemia and hypercapnia. Except in the setting of extensive parenchymal and pulmonary capillary destruction (e.g., severe interstitial fibrosis), equilibration of oxygen and carbon dioxide across the alveolocapillary interface is virtually always complete. Diffusion impairment is, therefore, rarely a cause of hypoxemia in patients with respiratory failure and probably never results in hypercapnia. This leaves two major mechanisms of abnormal pulmonary gas exchange: ventilation-perfusion imbalance and alveolar hypventilation. The partial pressure of oxygen and carbon dioxide in the arterial blood (Pao2, Pco2) are also influenced by the fractional concentration of oxygen (P02) in the inspired gas and by the partial pressure of oxygen (P02) and carbon dioxide (Pco2) of the venous blood entering the lungs. These factors are not discussed further in this chapter.

Ventilation-Perfusion Imbalance

The P02 and Pco2 of the gas contained in each alveolus, and therefore of the capillary blood leaving it, are determined primarily by the ventilation-perfusion ratio (V/Q) of that alveolus.1 This concept is illustrated by the oxygen–carbon dioxide diagram shown in Figure 76–1. As the ratio between ventilation and perfusion decreases, the P02 of the end-

CHAPTER 76

Approach to the Patient with Acute Respiratory Failure

John W. Kreit, MD • Robert M. Rogers, MD

The respiratory system, which consists of the lungs, chest wall, and respiratory muscles, performs the vital function of gas exchange. Oxygen is transported through the upper airways to the alveoli, diffuses across the alveolo-capillary membrane, and enters the capillary blood. It then combines with hemoglobin and is transported by the arterial blood to the tissues. In the mitochondria, oxygen is essential for the production of adenosine triphosphate, which provides the energy required for all metabolic processes. The major by-Shoemaker et al. Textbook of Critical Care. 1995.
capillary blood falls and the Pco₂ rises. The opposite occurs as V/Q increases. In the normal lung, ventilation and perfusion are closely matched so that a narrow and symmetric distribution of ratios exists around a value of approximately 1.0. Figure 76-2 shows the distribution of V/Q in a young, healthy man. Any disorder that affects the airways, parenchyma, or vasculature of the lungs, however, will cause an imbalance between ventilation and perfusion, and this will produce abnormally high and low V/Q. The extent to which gas exchange is impaired depends on both the values of the V/Q and the shape of their distribution. It is important to recognize, however, that arterial hypoxemia and hypercapnia will result only from regions of the lungs with low V/Q. High V/Q regions increase the amount of “wasted ventilation” (see later discussion) but do not adversely affect the arterial blood gas tensions.

Ventilation-perfusion imbalance interferes with oxygen transfer in the following way: Areas of the lung with low V/Q contribute blood with an abnormally low PO₂ to the pulmonary venous and systemic arterial blood. Coexisting lung regions with high V/Q contribute blood with a high PO₂. However, these high and low V/Q regions, even if equal in number, do not counterbalance each other for two reasons. First, low V/Q areas typically receive more blood flow than high V/Q areas and therefore make a proportionately larger contribution to the arterial blood. Second, because of the nonlinear shape of the oxygen-hemoglobin dissociation curve, the higher PO₂ of blood leaving high V/Q regions does not translate into a proportionate increase in hemoglobin saturation and oxygen content and therefore provides little extra oxygen to the arterial blood. This concept is illustrated in Figure 76-3.

As shown by the oxygen-carbon dioxide diagram in Figure 76-1, when no ventilation reaches perfused alveoli (V/Q = 0), mixed venous blood passes unchanged through the lung. This is a right-to-left intrapulmonary shunt. This extreme form of ventilation-perfusion imbalance causes hypoxemia simply by the addition of venous blood to the arterial circulation.

Although it is well recognized that ventilation-perfusion inequality and shunt impair oxygen transfer and produce arterial hypoxemia, it is less well appreciated that they also interfere with the removal of carbon dioxide. This occurs because regions of the lungs with low V/Q contribute blood with an elevated Pco₂ to the arterial circulation (see Fig. 76-1). The shift of ventilation from low to high V/Q regions simultaneously produces an increase in alveolar dead space (see later discussion). Ventilation-perfusion imbalance usually does not lead to hypercapnia because chemoreceptors increase minute ventilation to maintain the Pco₂ in the normal range. Hypercapnia will occur, however, if an increase in ventilation is limited by respiratory depression, neuromuscular disease, or excessive work of breathing (e.g., end-stage lung disease).

The severity of ventilation-perfusion imbalance may be assessed by several different measurements. All are based

Figure 76-2. The distributions of ventilation and blood flow in a young, healthy man. Both distributions are narrow, symmetric on a log scale, and positioned about a V/Q ratio of approximately 1.0. (From Wagner PD: Continuous distributions of ventilation-perfusion ratios in normal subjects breathing air and 100% O₂. J Clin Invest 1974; 54:54.)
Figure 76-3. The mechanism by which \( V/Q \) imbalance produces arterial hypoxemia. If a low \( V/Q \) lung unit contributes blood with a \( P_O_2 \) of 30 mm Hg (Point A) and if a high \( V/Q \) lung unit provides an equal quantity of blood with \( P_O_2 \) of 100 mm Hg (Point B), the final \( P_O_2 \) will not be the average of the two values (i.e., 65 mm Hg). Rather, the resultant \( P_O_2 \) (Point C) is determined by the average of the oxygen contents (16.5 cc \( O_2/100 \) cc) or of the hemoglobin saturations (78%). Therefore, the final \( P_O_2 \) is 42 mm Hg.

on the composition of "ideal" alveolar gas, which represents mixed alveolar gas in the absence of any ventilation-perfusion imbalance. The ideal alveolar \( P_O_2 \) (PAO2) is calculated from a modification of the alveolar gas equation:

\[
PAO_2 = (P_b - PH_2O) \frac{FI_O_2 - P_CO_2}{R}
\]

[Equation 1]

where \( P_b \) is the barometric pressure, \( PH_2O \) is the partial pressure of water in the alveoli (47 mm Hg at body temperature), and \( R \) is the respiratory quotient (assumed to be 0.8). The \( P_CO_2 \) of ideal alveolar gas is assumed to be equal to the \( P_CO_2 \).

One commonly used measure of ventilation-perfusion imbalance is the difference between the PAO2 and the PO2 of arterial blood (PA – aO2). This value varies directly with the number and severity of low \( V/Q \) lung units and with the fraction of the cardiac output (CO) that passes through unventilated regions (shunt fraction).

Another measure of the contribution of low \( V/Q \) lung units and shunt to the arterial blood is the venous admixture. For this calculation, we assume that the difference between the oxygen content of "ideal" pulmonary capillary blood (no ventilation-perfusion imbalance) and arterial blood is due solely to the addition of mixed venous blood to the arterial circulation. The venous admixture (Qva) is expressed as a fraction of total CO:

\[
\frac{Qva}{Qt} = \frac{(CIO_2 - CAO_2)}{(CIO_2 - CVO_2)}
\]

[Equation 2]

where \( CIO_2, CAO_2 \), and \( CVO_2 \) are the oxygen content of ideal capillary blood (calculated using the alveolar gas equation), arterial blood, and mixed venous blood, respectively. When the \( FI_O_2 \) is increased to 1.0, the contribution of low \( V/Q \) lung units is removed, and \( Qva/Qt \) measures the shunt fraction (Qs/Qt).

The volume of inspired air that reaches areas of the lungs with either high \( V/Q \) or no perfusion at all does not contribute optimally to gas exchange. This is referred to as wasted ventilation or physiologic dead space and provides a measure of the number and severity of high \( V/Q \) lung units. The physiologic dead space (VDS) is calculated by assuming that the difference between the \( P_CO_2 \) of ideal alveolar gas (estimated by the \( P_CO_2 \)) and the \( P_CO_2 \) of mixed exhaled gas (PACO2) is due to the addition of inspired air that does not participate in gas exchange. Expressed as a fraction of the tidal volume (VT), VDS is calculated from the Bohr equation:

\[
\frac{V_{DS}}{VT} = \frac{PACO_2 - PACO_2}{Paco_2}
\]

[Equation 3]

The VDS reflects both the volume of the conducting airways (anatomic dead space) and the amount of wasted ventilation to high \( V/Q \) lung units (alveolar dead space). Anatomic dead space can be estimated as 1 mL per pound of (ideal) body weight. The dead space ventilation (VDS) is the total volume of air entering the lungs each minute that does not contribute to gas exchange.

Unfortunately, the clinical usefulness of these three measurements is limited by the fact that all are influenced by factors other than the amount of ventilation-perfusion imbalance and shunt.1-2 Venous admixture and VDS/VT are affected by changes in both minute ventilation and cardiac output. In addition, venous admixture varies inversely with the \( FI_O_2 \) unless a large shunt fraction is present. The PA – aO2 is by far the easiest of the measurements to perform and is unaffected by changes in minute ventilation. These advantages have made the PA – aO2 the most commonly
used method for assessing the severity of ventilation-perfusion imbalance. The major limitation of this measurement is that it varies unpredictably as the FIO2 is changed. This occurs because, in the presence of ventilation-perfusion imbalance, the PAO2 rises relatively slowly with initial increases in FIO2 but increases rapidly when high concentrations of oxygen are reached. As shown in Figure 76-4, the greater the imbalance between ventilation and perfusion, the higher the FIO2 that is required to produce a significant increase in the PAO2. Because the PAO2 varies directly with oxygen concentration, the PA-aO2 initially increases by an amount dependent on the extent of ventilation-perfusion imbalance and then falls as the FIO2 is progressively increased. This is illustrated in Figure 76-5. The PA-aO2 also increases with age (as the PAO2 falls). In a young patient breathing room air, the PA-aO2 should be less than 10 but may increase to as much as 20 in an elderly patient.  

Alveolar Hypoventilation

The alveolar ventilation (VA) is the volume of air entering the lungs each minute that actually participates in gas exchange. It is, therefore, the difference between the minute ventilation (VE) and VDS:

\[ VA = VE - VDS \]  

[Equation 4]

The Paco2 is determined by the VA and by the rate of carbon dioxide production (VCO2):

\[ Paco2 = K \frac{VCO2}{VA} \]  

[Equation 5]

or

\[ Paco2 = K \frac{VCO2}{VE - VDS} \]  

[Equation 6]

where K is a constant.

By definition, alveolar hypoventilation is present whenever the Paco2 rises above normal. As illustrated by equation 6, if carbon dioxide production is constant, an increase in the Paco2 must be associated with either a decrease in VE or an increase in VDS (without a compensatory rise in VE). As predicted by the alveolar gas equation, an increase in the Paco2 will, in turn, result in a fall in the PAO2. If the rise in Paco2 is due to a fall in VE, the PA-aO2 will remain constant. When alveolar hypoventilation is associated with an increase in alveolar dead space, however, low ventilation-perfusion lung units must have also increased. The PAO2 falls by more than the amount predicted by the alveolar gas equation, and the PA-aO2 increases.

CLASSIFICATION OF RESPIRATORY FAILURE

On the basis of the underlying mechanism of abnormal gas exchange, respiratory failure may be divided into three types (Table 76-1). Type 1, or oxygenation failure, is characterized by an abnormally low PAO2 and a normal or low Paco2. It may be caused by any disorder that produces ventilation-perfusion imbalance or a right-to-left intrapulmonary shunt. The abnormally high and low V/Q result in a fall in the Paco2 and an increase in the PA-aO2, venous admixture, and VDS/VT. Minute ventilation increases to compensate for the elevated alveolar dead space, and therefore the Paco2 remains normal or falls. Type 1 respiratory

<table>
<thead>
<tr>
<th>Type</th>
<th>PAO2</th>
<th>Paco2</th>
<th>PA-aO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Oxygenation failure</td>
<td>↓</td>
<td>NL ↓</td>
<td>↑</td>
</tr>
<tr>
<td>2: Ventilation failure</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>3: Combined failure</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
</tbody>
</table>

Abbreviations: PAO2 = arterial partial pressure of oxygen; Paco2 = arterial partial pressure of carbon dioxide; PA-aO2 = alveolar-arterial difference in partial pressure of oxygen.
TABLE 76–2. Causes of Type 1 (Oxygenation) Failure

<table>
<thead>
<tr>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult respiratory distress syndrome</td>
</tr>
<tr>
<td>Asthma</td>
</tr>
<tr>
<td>Atelectasis</td>
</tr>
<tr>
<td>Cardiogenic pulmonary edema</td>
</tr>
<tr>
<td>Chronic obstructive pulmonary disease (including bronchiectasis and cystic fibrosis)</td>
</tr>
<tr>
<td>Interstitial fibrosis</td>
</tr>
<tr>
<td>Pneumonia (infectious or chemical)</td>
</tr>
<tr>
<td>Pneumothorax</td>
</tr>
<tr>
<td>Pulmonary embolism</td>
</tr>
<tr>
<td>Pulmonary hypertension</td>
</tr>
</tbody>
</table>

failure can be caused by any disorder that affects the airways, parenchyma, or vasculature of the lung. The most common causes are listed in Table 76–2.

Type 2, or ventilation failure, occurs when a primary fall in V̇E results in alveolar hypoventilation. The resulting rise in the Paco₂ is accompanied by a decrease in the PaO₂ as predicted by the alveolar gas equation, and therefore the PA – aO₂ does not increase. Type 2 respiratory failure can be caused by any disorder that decreases central respiratory drive, interferes with the transmission of signals from the central nervous system, or impedes the ability of the respiratory muscles to expand the lungs and chest wall. A partial list is provided in Table 76–3.

Type 3, or combined oxygenation-ventilation failure, occurs when V̇E cannot be increased sufficiently to maintain a normal Paco₂ in the presence of marked ventilation-perfusion imbalance. Type 3 respiratory failure is, therefore, characterized by a low PaO₂ an elevated Paco₂, and an increased PA – aO₂ venous admixture, and V̇Ḋ/V̇t. In theory, any disorder causing type 1 can also cause type 3 respiratory failure. In fact, however, only a few of these disorders commonly result in carbon dioxide retention. These are listed in Table 76–4.

DIAGNOSIS

The diagnosis of respiratory failure is based on the presence of hypoxemia and/or hypercapnia and, therefore, relies primarily on arterial blood gas analysis. Although the exact values are somewhat arbitrary, respiratory failure is typically defined as a PaO₂ less than 60 mm Hg (breathing room air) and/or a Paco₂ greater than 46 mm Hg. Hypercapnia in the setting of acute respiratory failure will be accompanied by an uncompensated respiratory acidosis.

In recent years, oximetry has become increasingly available and popular as a means of noninvasively measuring arterial hemoglobin saturation (SaO₂). Inaccurate readings may be obtained, however, when the SaO₂ is low and in the presence of jaundice, dark skin pigmentation, and elevated levels of carboxyhemoglobin. In addition, oximetry provides no information about the PaCO₂. Significant hypercapnia and acidosis may be present without an abnormally low hemoglobin saturation, especially if supplemental oxygen is being administered. Oximetry should, therefore, never be used as a substitute for arterial blood gas measurement in the initial assessment of the patient suspected of having respiratory failure. Oximetry may be used to follow the SaO₂ provided that periodic validation is obtained via blood gas analysis.

Arterial blood gas measurements will be obtained, of course, only if the diagnosis of respiratory failure is suspected on clinical grounds. Patients with acute respiratory failure will have manifestations of the underlying disease and may also have symptoms and signs of hypoxemia and/or hypercapnia. Hypoxemia may be accompanied by tachypnea, tachycardia, and hypertension. Cerebral hypoxia produces changes in mentation that can range from mild confusion (with a characteristic loss of recent memory) to delirium. Cyanosis of the nail beds may be evident. Hypercapnia exerts its major effect on the central nervous system. Patients typically progress through the stages of lethargy, stupor, and finally coma as the Paco₂ rises. At high Paco₂ levels, brain stem depression leads to slowing of the respiratory rate and finally to apnea. Although hypoxemia and hypercapnia may be associated with many clinical manifestations, these symptoms and signs may not occur until long after gas exchange is markedly and dangerously impaired. For example, significant increases in heart rate, respiratory rate, and blood pressure may not occur until the arterial hemoglobin saturation falls below 70% to 80%. Cyanosis will occur only when the concentration of deoxygenated hemoglobin in the capillary blood exceeds 5 g/dL. Even under optimal conditions, therefore, cyanosis will be present only when the PaO₂ falls to approximately 45 mm Hg. In fact, cyanosis is often detected only at much lower levels. This is especially true in the presence of anemia. In addition, the clinical manifestations associated with hypoxemia and hypercapnia are nonspecific and may occur in the absence of respiratory failure. Physicians must then remain vigilant for even subtle symptoms and signs of respiratory insufficiency and have a very low threshold for obtaining arterial blood gas measurements.

TABLE 76–3. Causes of Type 2 (Ventilation) Failure

<table>
<thead>
<tr>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disorders Affecting Central Respiratory Drive</td>
</tr>
<tr>
<td>Brain stem infarction or hemorrhage</td>
</tr>
<tr>
<td>Brain stem compression from supratentorial mass</td>
</tr>
<tr>
<td>Drug overdose (e.g., narcotics, benzodiazepines, tricyclics)</td>
</tr>
<tr>
<td>Disorders Affecting Signal Transmission to the Respiratory Muscles</td>
</tr>
<tr>
<td>Amyotrophic lateral sclerosis</td>
</tr>
<tr>
<td>Guillain-Barré syndrome</td>
</tr>
<tr>
<td>Multiple sclerosis</td>
</tr>
<tr>
<td>Myasthenia gravis</td>
</tr>
<tr>
<td>Spinal cord injury</td>
</tr>
<tr>
<td>Disorders of the Respiratory Muscles or Chest Wall</td>
</tr>
<tr>
<td>Muscular dystrophy</td>
</tr>
<tr>
<td>Polymyositis/dermatomyositis</td>
</tr>
<tr>
<td>Flail chest</td>
</tr>
</tbody>
</table>

EVALUATION

Once the diagnosis of respiratory failure is made, a search must be made for its cause. This evaluation is based on arterial blood gas measurements and the history, physical examination, and chest x-ray films.

Arterial Blood Gas Analysis

As shown in Table 76–1, measurement of the PaO₂ and Paco₂ and calculation of the PA – aO₂ can be used to place patients with respiratory failure into one of three categories.
Once this classification has been made, the diagnostic possibilities become more limited (see Tables 76–2 to 76–4).

**History**

The medical history must include information about both pulmonary and extrapulmonary symptoms and signs. The presence or absence of cough, sputum production, hemoptysis, pleuritic or nonpleuritic chest pain, fever, paroxysmal nocturnal dyspnea, orthopnea, weakness, and sensory disturbances must be noted. The duration of symptoms, any events or circumstances associated with the onset of symptoms (e.g., surgery, trauma, drug or alcohol ingestion), and the presence of prior pulmonary or extrapulmonary disease must also be determined.

**Physical Examination**

The physical examination must be thorough, but particular attention should be directed toward the respiratory, cardiovascular, and neuromuscular systems. The pulmonary examination must detect the presence of stridor, wheezing, rales, rhonchi, bronchial breath sounds, a pleural rub, a prolonged expiratory time, diminished or absent breath sounds, and dullness or hyperresonance to percussion. The cardiovascular examination must include an assessment of jugular venous pressure and a careful search for cardiac murmurs and an S3 gallop. The neurologic examination must detect altered mentation, sensory loss, and weakness of both the skeletal muscles and the diaphragm. The presence of paradoxical inward movement of the anterior abdominal wall during inspiration is very suggestive of paralysis or weakness of the diaphragm and is a key, but often overlooked, physical finding.

**Chest X-Ray Examination**

The chest x-ray examination is useful for further narrowing the differential diagnosis or for solidifying or confirming a presumptive diagnosis based on the history and physical examination. The presence of interstitial or airspace disease, bullae, atelectasis, pleural effusion, pneumothorax, chest wall deformity, and high or low lung volumes provides important information about the underlying disease process. It should be noted that some causes of respiratory failure may be associated with a normal-appearing chest x-ray film. These include pulmonary embolism, asthma, upper airway obstruction, and most disorders producing respiratory center depression or weakness of the respiratory muscles.

On the basis of the information provided by arterial blood gas analysis and the history, physical, and chest x-ray examination, a specific diagnosis can often be made. For example, the previously healthy patient with several days of fever, chills, productive cough, and dyspnea who has bronchial breath sounds on physical examination and a focal area of airspace disease on chest x-ray films has pneumonia. The patient who experiences the acute onset of dyspnea, hemoptysis, and a pleural rub several days after surgery must be strongly suspected of having a pulmonary embolus. In the patient with a history of coronary artery disease who experiences substernal chest pain and dyspnea, has rales and an S3 gallop on examination, and has interstitial densities on chest x-ray examination, myocardial infarction with congestive heart failure is the most likely diagnosis. The patient with a history of suicide attempts who presents with a markedly depressed mental status, shallow and slow respirations, an otherwise normal examination, and a normal chest x-ray film should be suspected of having drug-induced respiratory depression.

**MANAGEMENT**

The management of every patient with respiratory failure, regardless of the cause, has four essential components: (1) establish a patent airway; (2) maintain sufficient ventilation; (3) ensure adequate oxygen delivery to the tissues; and (4) treat the underlying cause of respiratory failure.

**Airway Management**

All patients with respiratory failure must be assessed for the presence of upper airway obstruction. Signs of partial obstruction are inspiratory snoring or stridor accompanied by a diminished tidal volume. Complete obstruction is indicated by lack of airflow in the presence of sustained and often vigorous inspiratory efforts. Patients may have upper airway obstruction as the primary cause of respiratory failure (e.g., food or foreign body aspiration, laryngeal edema) or as a secondary event. For example, hypoventilation from central nervous system depression or neuromuscular disease may be exacerbated by airway obstruction at the level of the oropharynx as a result of loss of muscle tone. Secondary airway obstruction can often be relieved by lifting the mandible or by inserting an oropharyngeal airway. In all cases of upper airway obstruction, however, translaryngeal intubation or tracheostomy must be performed if airway patency cannot be rapidly established. Additional indications for endotracheal intubation are listed in Table 76–5 and include loss of laryngeal reflexes that prevent aspiration, inability to clear pulmonary secretions adequately, and inadequate oxygenation or ventilation (see following discussion).

**Ventilation**

As previously discussed, hypercapnia signifies the presence of alveolar hypoventilation. This may result from either a fall in V̇e or an inadequate ventilatory response to an increase in low V̇E/Q lung units and alveolar dead space. An abrupt rise in the Paco2 will, in turn, lead to an acute respiratory acidosis. Mechanical ventilation is used to treat acute, severe hypoventilation. Traditionally, this has required endotracheal intubation. Recently, however, several studies have suggested that noninvasive mechanical ventilation using a nasal or full facemask is an effective alternative in a small number of patients.11, 12, 12a Mechanical ventilation, including noninvasive ventilatory assistance, is discussed in detail in Chapters 97 to 104. In this chapter, we discuss only a few general but very important aspects of mechanical ventilatory support.

Guidelines for the institution of mechanical ventilation are shown in Table 76–6. As a general rule, mechanical ventilation should be initiated when hypercapnia results in an arterial pH less than or equal to 7.25. Note that hypercapnia by itself is not an indication for mechanical ventilation.

<table>
<thead>
<tr>
<th>TABLE 76–5. Indications for Endotracheal Intubation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper airway obstruction</td>
</tr>
<tr>
<td>Impaired secretion clearance</td>
</tr>
<tr>
<td>Requirement for mechanical ventilation</td>
</tr>
</tbody>
</table>
Many patients with chronic ventilation failure have a relatively normal pH as a result of metabolic compensation. It is the acidosis, not the hypercapnia, that must be corrected. This guideline is, however, not meant to be strictly applied. For example, intubation and mechanical ventilation might be appropriately delayed if a patient with an arterial pH of less than 7.25 has ventilation failure from a process that is potentially rapidly reversible (e.g., narcotic overdose, some cases of asthma). On the other hand, patients with evidence of worsening ventilation failure or impending failure of the respiratory muscles should be electively intubated rather than waiting until intubation becomes an emergency procedure. Patients with progressive hypercapnia, marked tachypnea, or signs of diaphragmatic fatigue should, therefore, be intubated and mechanically ventilated long before the arterial pH reaches 7.25. Elective intubation and ventilation have been advocated for patients with neuromuscular disease when the vital capacity falls below 15 mL/kg or when the maximum inspiratory and expiratory pressure decreases to ±30 cm H₂O.¹³,¹⁴

Several modes of mechanical support are available on modern ventilators. When selecting a mode of ventilation for a patient with acute respiratory failure, several principles should be kept in mind. First, the ventilator should relieve most of the patient’s work of breathing and allow the respiratory muscles to rest. This can be best accomplished by selecting the assist-control mode or the synchronized intermittent mandatory ventilation (SIMV) mode with the set respiratory rate close to the patient’s spontaneous rate. SIMV with a low set rate should not be used in the initial management of acute respiratory failure because it may not significantly reduce the work of breathing and may perpetuate or even worsen respiratory muscle fatigue.¹⁵

Second, the mode of ventilation selected should guarantee the patient a minimum safe or back-up minute ventilation. Once again, the assist-control and SIMV modes meet this requirement. Pressure-set modes of ventilation do not and should be used only with great caution in patients with acute respiratory failure. During pressure support ventilation, for example, the tidal volume delivered with each mechanical breath depends not only on the set pressure but also on the patient’s inspiratory effort and on the compliance and resistance of the respiratory system. In addition, all pressure-supported mechanical breaths must be triggered by the inspiratory efforts of the patient. Therefore, the tidal volume, VE and, most importantly, the PAco₂ and pH may vary significantly over time even on the same ventilator settings. Pressure control ventilation may be beneficial in some patients with ARDS that is refractory to conventional ventilatory management.¹⁶,¹⁰⁶ Again, because the tidal volume is variable and not set, the VE and PAco₂ must be closely monitored when this mode of ventilation is used.

In addition to the mode of ventilation, the clinician must also select the tidal volume, respiratory rate, and FiO₂ to be provided by the ventilator. Tidal volume should be based on body size and should be in the range of 8 to 12 mL/kg (ideal body weight). As previously mentioned, the set respiratory rate should produce a VE that will meet most of the patient’s ventilatory requirements. An initial rate of 10 to 16 breaths per minute is typically required. Intubated patients with oxygenation failure should initially receive an FiO₂ of 1.0. This will either rapidly correct the hypoxemia or allow for the early institution of therapy with positive end-expiratory pressure (see later discussion). Changes in these initial ventilator settings should be based on serial blood gas analysis.

### Oxygenation

One of the cornerstones in the management of acute respiratory failure must be to provide sufficient oxygen to the tissues of the body. Although arterial hypoxemia must be corrected, it is important to realize that the PaO₂, inasmuch as it determines the SaO₂, is only one determinant of the amount of oxygen delivered to the tissues. Oxygen delivery (DO₂) is also dependent on the concentration of hemoglobin (Hb) and the CO.

\[
DO₂ = 1.34 \times Hb \times \frac{SaO₂}{100} \times CO \times 10
\]

[Equation 7]

Tissue oxygen delivery can, therefore, be improved not only by increasing the SaO₂ but also by correcting anemia and increasing the CO.

In the patient with arterial hypoxemia, sufficient supplemental oxygen should be provided to increase the PaO₂ to approximately 60 to 70 mm Hg. Because of the shape of the oxygen-hemoglobin dissociation curve (see Fig. 76-3), at a PaO₂ below 60 mm Hg, relatively small increases will result in a significant improvement in SaO₂ and DO₂. As the PaO₂ is increased further, however, there is little additional increase in SaO₂.

The initial concentration of oxygen chosen should be based on the underlying mechanism of impaired gas exchange. Diseases associated with the mismatching of ventilation and perfusion (e.g., asthma, COPD) produce hypoxemia that is usually responsive to relatively low levels of supplemental oxygen. Depending on the initial PaO₂, patients with these conditions can usually be treated with oxygen concentrations ranging from 0.24 to 0.40 using a Venturi or aerosol mask or with oxygen flow rates of 1 to 4 L/min via a nasal cannula. It is well known that some patients with COPD experience hypercapnia and respiratory acidosis when given supplemental oxygen. For many years, this was believed to be due to loss of the hypoxi
respiratory drive with consequent fall in \( V_e \). It has recently been shown, however, that hypercapnia in this setting is due primarily to worsening ventilation-perfusion imbalance.\(^{17, 18}\) Regardless of its mechanism, fear of this complication often results in inadequate oxygen administration to patients with acute respiratory failure. Several important points must be emphasized. First, oxygen-induced hypercapnia occurs almost exclusively in patients with severe airflow obstruction and chronic carbon dioxide retention.\(^{17, 18}\) Second, the rise in \( P_{aCO_2} \) is minimized by administering just enough oxygen to eliminate arterial hypoxemia.\(^{17, 18}\) In this group of patients, then, it is best to start with lower levels of supplemental oxygen (\( FIO_2 \) of 0.28 or 1 or 2 \( L/min \)). Third, although controlled oxygen administration may cause worsening hypercapnia, the development of significant respiratory acidosis is uncommon\(^{19}\) and in our experience is often due to sedation- or narcotic-induced central respiratory depression. Finally, it is essential to remember that hypoxemia must be corrected even if the \( P_{aCO_2} \) rises. If necessary, hypercapnia and acute respiratory acidosis can be managed with mechanical ventilation.

Hypoxemia caused primarily by intrapulmonary shunting will improve but only partially correct, even with the administration of high concentrations of oxygen. Therefore, patients with pneumonia, cardiogenic pulmonary edema, ARDS, and other diseases producing extensive alveolar filling should initially receive the highest possible concentration of oxygen. In nonintubated patients, this can be achieved by using a non-rebreather mask or a high-flow aerosol mask. The all-too-common practice of beginning with low fractional concentrations of oxygen and "working upward" as repeated blood gas measurements show a persistently low \( P_{aO_2} \) may delay the correction of life-threatening tissue hypoxia for several hours.

Not uncommonly, patients with a large intrapulmonary shunt have hypoxemia that is not corrected even by the highest \( FIO_2 \) achievable with a facemask. In a few patients, hypoxemia may be corrected by the administration of continuous positive airway pressure via a facemask.\(^{20}\) In most cases, however, refractory hypoxemia is managed by endotracheal intubation and mechanical ventilation. Intubation allows the delivery of higher concentrations of oxygen to the alveoli, and mechanical ventilation reduces oxygen consumption by decreasing patient work of breathing. Patients with ARDS will usually also require the addition of PEEP. In this group of patients, PEEP has been shown to increase the \( P_{aO_2} \) by opening atelectatic alveoli and by redistributing lung water from the alveoli to the interstitium.\(^{21, 22}\) Unfortunately, PEEP often produces a decrease in CO primarily through its effect on venous return. It may, therefore, increase the \( P_{aO_2} \) and \( S_aO_2 \) and yet cause a fall in \( D_O_2 \) to the tissues. For this reason, serial measurements of \( D_O_2 \), not just \( P_{aO_2} \), are essential when PEEP is used in patients with acute respiratory failure.

**Therapy of the Underlying Disease**

Once a stable airway and adequate ventilation and oxygenation have been established, therapy can be focused on the cause of acute respiratory failure. The management of specific disorders is beyond the scope of this chapter but is discussed in detail in subsequent chapters in this section.

**CONCLUSION**

Acute respiratory failure represents a sudden, severe disturbance in the exchange of oxygen and carbon dioxide between the environment and the cells of the body. It is, therefore, a medical emergency and a very real threat to the life of the patient. A large number of diseases may lead to acute respiratory failure, and many have specific therapies. However, the diagnosis, evaluation, and initial management of this disorder are the same regardless of the underlying cause. The approach to the patient with acute respiratory failure must be thorough and systematic and based on an understanding of the mechanisms of normal and abnormal gas exchange.

**References**

22. Chaudhary BA, Burki NK: Ear oximetry in clinical practice.