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## **Respiratory Failure**

Mara E. Nitu and Howard Eigen  
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# Respiratory Failure

Mara E. Nitu, MD,\*  
Howard Eigen, MD†

Author Disclosure  
Drs Nitu and Eigen have disclosed no financial relationships relevant to this article. This commentary does not contain a discussion of an unapproved/investigative use of a commercial product/device.

**Objectives** After completing this article, readers should be able to:

1. Recognize the clinical definition of respiratory failure.
2. List the clinical causes of respiratory failure.
3. Review the underlying pathophysiologic mechanisms of respiratory failure.
4. Describe the physical and laboratory signs of respiratory failure.
5. Discuss the various methods of managing respiratory failure.

## Definitions

Acute respiratory failure describes any impairment in oxygenation or ventilation in which the arterial oxygen tension falls below 60 mm Hg (acute hypoxemia), the carbon dioxide tension rises above 50 mm Hg (acute hypercarbia, hypercapnia) and the pH drops below 7.35, or both. For patients who have underlying chronic respiratory failure, acute hypercarbia can be diagnosed by an increase in  $PCO_2$  by 20 mm Hg from baseline. From a functional standpoint, respiratory failure is defined as the inability of the respiratory system to meet the metabolic needs of the tissues.

## Incidence

The incidence of respiratory failure in pediatrics is inversely related to age. Two thirds of the cases of respiratory failure in children occur in the first postnatal year, and one half are seen in the neonatal period.

The higher incidence of respiratory failure in infants has several developmental explanations. First, the airway is small and, with its narrowest point in the subglottic area, the infant's cone-shaped larynx is a likely site for obstruction. Second, the thoracic cage in infants is soft, with the ribs positioned horizontally, a mechanical disadvantage for chest expansion. Third, due to marginal energy stores in infants, the diaphragm fatigues easily.

Fourth, the immature nervous system often triggers bradypnea/apnea. Finally, the infant's lower airways are small and compliant and easily prone to obstruction.

## Abbreviations

<b>AC:</b>	assist control
<b>ARDS:</b>	acute respiratory distress syndrome
<b>BiPAP:</b>	bilevel positive airway pressure
<b>CPAP:</b>	continuous positive airway pressure
<b>ECMO:</b>	extracorporeal membrane oxygenation
<b>GCS:</b>	Glasgow Coma Scale
<b>HFV:</b>	high-frequency ventilation
<b>LMA:</b>	laryngeal mask airway
<b>iNO:</b>	inhaled nitric oxide
<b>PFT:</b>	pulmonary function testing
<b>RSV:</b>	respiratory syncytial virus
<b>SIMV-PS:</b>	synchronized intermittent mechanical ventilation with pressure support
<b>VILI:</b>	ventilator-induced lung injury
<b>V/Q:</b>	ventilation/perfusion

## Causes

A multitude of conditions can lead to respiratory failure (Table 1). Based on the location of the primary derangement, conditions can be classified as lung disorders, mechanical impairment of ventilation, airway-narrowing disorders, failure of the central nervous system to control respiration, and failure to meet the increased oxygen needs of the tissues. For teaching purposes, the various pathophysiologic mechanisms that lead to respiratory failure can be separated into failure of oxygenation (hypoxia) and failure of ventilation (hypercarbia).

$PaO_2$  is decreased in respiratory failure due to either an imbalance of ventilation and perfusion (V/Q matching) (most frequent) or impairment of oxygen diffusion at the level of the alveolar-capillary membrane (rare). To aid in understanding the concept of V/Q matching, ventilation and perfusion can be compared to two gears working together. If one gear spins

\*Medical Director, PICU/Riley Hospital for Children and of Lifeline Transport Team, Indianapolis, Ind.

†Former member, Editorial Board.

## Table 1. Causes of Respiratory Failure

### Disorders Primarily Involving the Lung

- Pneumonia
- Bronchiolitis
- Asthma
- Cystic fibrosis

### Mechanical Impairment of Ventilation

- Neuromuscular disease (myopathies, Guillain-Barré syndrome)
- Chest wall trauma (flail chest)
- Large pleural effusion
- Restrictive lung disorders with involvement of the respiratory muscles

### Airway-narrowing Disorders

- Foreign body
- Laryngeal web
- Vascular ring

### Failure of the Central Nervous System to Control Respiration

- Trauma
- Infections
- Ingestions
- Genetically determined conditions (eg, congenital hypoventilation syndrome)
- Tumors

### Failure to Meet Increased Oxygen Needs of the Tissue

- Septic shock

more slowly than the other, malfunction occurs (Fig. 1). Using this model, if ventilation becomes zero relative to perfusion, intrapulmonary shunt occurs and deoxygenated blood mixes with the rest of the oxygenated blood.

Oxygen delivery to tissues is a complex process that includes oxygenation at the level of the alveoli of hemoglobin and transport and delivery of the oxygen at the cellular level. Depending on the malfunctioning link that leads to low oxygen delivery, hypoxia can be classified as anoxic, anemic, stagnant, and cytochemical. Anoxic hypoxia occurs when the underlying disturbance exists at the gas exchange (respiratory) level. Anoxic hypoxia can be oxygen-sensitive, with clinical improvement occurring with increased inspired oxygen. When anoxic hypoxia is the result of a shunt (intrapulmonary or intracardiac), increasing the inspired oxygen does not lead to clinical improvement. Anemic hypoxia occurs when oxygen-carrying capacity is impaired, as with anemia (low hemoglobin) or insufficient functional hemoglobin (hemoglo-

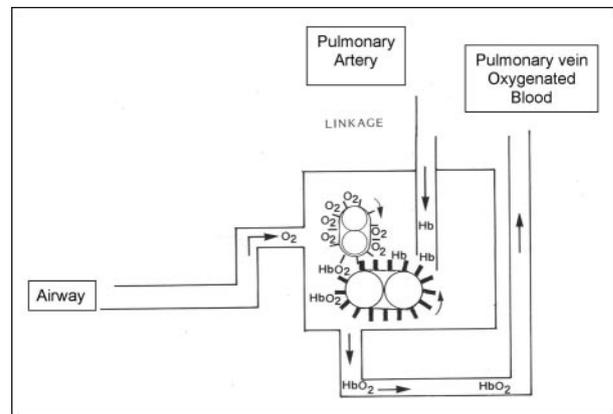


Figure 1. Mechanical view of ventilation/perfusion (V/Q) matching.

binopathies). Oxygen delivery is further dependent on adequate blood flow. Stagnant hypoxia results when total blood flow is decreased (eg, heart failure) or maldistributed (eg, septic shock). At the capillary level, oxygen dissociates from oxyhemoglobin and diffuses into the surrounding area, where it is used by tissues. When this process malfunctions because of either exogenous or endogenous factors, cytochemical hypoxia occurs. An example of exogenous cytochemical hypoxia is toxin ingestion (eg, cyanide) that blocks oxygen use at the mitochondrial level.

Appropriate ventilation is determined by minute ventilation, a product of respiratory rate and alveolar tidal volume. Ventilatory failure occurs in conditions that decrease tidal volume (shallow breathing) or respiratory rate (bradypnea), thereby decreasing carbon dioxide removal. In reality, failure to oxygenate and ventilate usually blends in respiratory failure.

## Clinical Manifestations

### Case 1

A 4-month-old, previously healthy baby is seen in December for fever, a 4-day history of nasal congestion, and progressive difficulty breathing. Vital signs are: heart rate of 169 beats/min, respiratory rate of 56 breaths/min, blood pressure of 126/56 mm Hg, and oxygen saturation on room air of 92%. The infant is crying but can be consoled. Physical examination reveals intercostal and subcostal retractions, tachypnea, bilateral wheezing, and coarse breath sounds. Capillary refill is brisk and the extremities are warm. A chest radiograph shows peribronchial cuffing and slight hyperinflation suggestive of viral pneumonitis. A swab for respiratory syncytial virus (RSV) is reported as positive. Supplemental oxygen is initiated, viral bronchioli-

tis is diagnosed, and the infant is admitted for monitoring. A few hours later, he becomes very agitated, flushed, and inconsolable. His heart rate is 189 beats/min, respiratory rate is 86 beats/min, and oxygen saturation is 92% on 3 L of oxygen administered by nasal cannula. His work of breathing is significantly increased, as demonstrated by nasal flaring, grunting, head bobbing, and significant retractions. The infant is transferred to the intensive care unit for intubation and mechanical ventilation. Arterial blood gas before intubation shows a pH of 7.16 and  $PCO_2$  of 70 mm Hg. He is intubated and mechanically ventilated for 4 days.

In this case, lower airway obstruction led to poor ventilation and respiratory failure. This case also illustrates the clinical manifestations of acute hypercapnia: flushing, agitation, and tachycardia (Table 2).

It is important to note that RSV might cause respiratory failure by two different mechanisms: lower airway involvement (bronchiolitis), as in this case, and RSV-caused central apnea. The latter mechanism is seen more frequently in young infants than in older children.

### Case 2

A 9-year-old child who has a history of Down syndrome, mitochondrial myopathy, and tracheostomy is admitted because of a 3-week history of decreased activity and increased somnolence. His respiratory rate is 35 beats/min with very shallow effort. Arterial blood gas reveals: pH, 7.33;  $PCO_2$ , 62 mm Hg;  $PO_2$ , 54 mm Hg; and  $HCO_3^-$ , 28 mEq/L on room air (0.21  $F_{iO_2}$ ). Complete blood count reveals polycythemia with a hemoglobin of 15 g/dL (150 g/L) and hematocrit of 48% (0.48). The patient receives 100% oxygen, and subsequent arterial blood gas determination documents pH, 7.23;  $PCO_2$ , 80 mm Hg;  $PO_2$ , 118 mm Hg; and  $HCO_3^-$ , 32 mEq/L. Chest radiograph reveals mild cardiomegaly and increased pulmonary markings suggestive of chronic lung disease (Fig. 2). Echocardiography shows mild pulmonary hypertension and right ventricular hypertrophy. The patient is placed on home mechanical ventilation to treat chronic respiratory failure.

Increased work of breathing is the usual primary man-

Table 2. Signs and Symptoms of Hypoxia and Hypercapnia

Hypoxia	Hypercapnia
<p><b>Mild</b></p> <ul style="list-style-type: none"> <li>• None or decreased efficiency only</li> </ul> <p><b>Moderate</b></p> <ul style="list-style-type: none"> <li>• Mood changes: euphoria or depression</li> <li>• Decreased efficiency</li> <li>• Impaired judgment</li> <li>• Headache</li> <li>• Hypertension</li> <li>• Exertional dyspnea</li> <li>• Cyanosis</li> <li>• Hyperpnea, variable</li> <li>• Tachycardia</li> <li>• Polycythemia (chronic <math>CO_2</math> retention)</li> </ul> <p><b>Severe</b></p> <ul style="list-style-type: none"> <li>• Hypertension or hypotension</li> <li>• Dimness of vision</li> <li>• Somnolence, stupor, coma</li> </ul>	<p><b><math>P_{CO_2}</math> Above Baseline (in mm Hg)</b></p> <ul style="list-style-type: none"> <li>+5: Hot hands</li> <li>+10: Rapid bounding pulse, small pupils</li> <li>+15: Engorged fundal veins, confusion or drowsiness, muscular twitching</li> <li>+30: Depressed tendon reflexes, depressed extensor plantar responses, and coma</li> <li>+40: Papilledema</li> </ul>

ifestation of respiratory failure. Patients who have underlying myopathy lack the ability to mount this important compensatory mechanism for impending respiratory failure, and their physical findings may be misleading. As for this patient, such individuals present with tachypnea and very shallow breathing without retractions.

The first blood gas result for this child is typical of chronic respiratory failure: chronic carbon dioxide retention (increased  $PCO_2$ ) leading to metabolic compensation (increased serum bicarbonate concentration, increased base excess), with the pH reflecting only mild acidosis. The second blood gas pattern exemplifies how administering 100% oxygen to patients who have chronic respiratory failure may lead to higher carbon dioxide retention. For patients who have chronic respiratory failure, the respiratory center is stimulated primarily by hypoxia. By improving oxygenation, the hypoxic drive of the respiratory center is blunted, and alveolar ventilation decreases, leading to a higher carbon dioxide concentration (acute respiratory failure on top of the existing chronic respiratory failure).

Other important findings in this patient include polycythemia, pulmonary hypertension, and cor pulmonale, which represent possible but rare complications of chronic hypoxemia.



Figure 2. Chest radiograph revealing mild cardiomegaly and increased pulmonary markings.

### History and Physical Examination

The initial assessment of the patient in respiratory failure should focus on determining the urgency of medical intervention. Several clinical clues help discern who requires intubation and mechanical ventilation. In the hands of an experienced physician, this decision usually is reached within the first few minutes of the clinical encounter. The most helpful indicators are vital signs, work of breathing, and level of consciousness. The patient who exhibits very rapid respirations, significant retractions, head bobbing, nasal flaring, and grunting requires aggressive and urgent respiratory support. As the patient becomes increasingly fatigued, he or she has more shallow respirations, leading to lack of responsiveness and hypoxemia despite a high  $\text{FiO}_2$ . Such ominous signs of respiratory failure or impending cardiorespiratory arrest should prompt emergent airway control and ventilatory support. Patients presenting with severe hemodynamic compromise, mottled extremities, and very low blood pressure that have caused a markedly decreased response to painful stimuli (impending cardiac arrest) also require emergent airway control, breathing, and circulatory support. Central nervous system disorders leading to decreased responsiveness also mandate emergent airway control and breathing support.

If emergent intervention is not necessary, a more comprehensive history can be obtained and should focus on determining probable causes of the respiratory failure: previous fever and illness contacts, possible foreign body aspiration, and previous chronic lung disease (cystic

fibrosis, asthma, prematurity). Causes of central hypoventilation (drug ingestion, head trauma, and seizures) also should be queried.

Vital signs are extremely helpful in determining the severity of respiratory failure. In the otherwise healthy child, tachypnea is one of the earliest compensatory mechanisms for inadequate ventilation. The patient who presents with severe tachypnea and increased work of breathing (intercostal and substernal retractions) warrants immediate intervention and close monitoring. Bradypnea usually is an ominous sign reflecting failure of compensatory mechanisms and requires emergent intervention. Patients who have underlying neuromuscular disease may be unable to mount the usual signs of respiratory distress because they often lack the ability to increase the respiratory rate or produce retractions; rather, they present with shallow and ineffective respirations.

Continuous monitoring of pulse oximetry has become an important tool for respiratory assessment and monitoring. Pulse oximetry is a noninvasive method widely used to assess oxygen saturation. It employs light absorption characteristic of oxyhemoglobin to estimate oxygen saturation of hemoglobin. A pulse oximetry saturation of 90% is associated with a  $\text{PaO}_2$  of 60 mm Hg, based on the sigmoid shape of the oxyhemoglobin dissociation curve.

Pulse oximetry has several limitations. Because it measures saturation and not oxygen content or oxygen delivery, moderately low oxygen saturations in a patient who has anemia may be clinically significant. Anemia may lead to tissue hypoxia, despite a normal  $\text{PaO}_2$ , as exemplified by the following equations:

- $\text{O}_2$  Content = hemoglobin (Hgb) in grams  $\times$  1.34 mL of  $\text{O}_2$  per gram  $\times$  %  $\text{O}_2$  saturation
- Normal =  $15 \text{ g} \times 1.34 \times 100\% = 20 \text{ mL of O}_2$
- Low  $\text{PaO}_2$  (60 mm Hg) (normal Hgb) =  $15 \times 1.34 \times 90\% = 18.1 \text{ mL of O}_2$
- Anemia ( $\text{Po}_2 = 100 \text{ mm Hg}$ ) =  $8 \times 1.34 \times 100\% = 10.7 \text{ mL of O}_2$

$\text{SaO}_2$  can increase artificially when carboxyhemoglobin concentrations are high (eg, smoke inhalation), decrease artificially in the presence of intravenous dyes such as methylene blue, or increase or decrease artificially in the presence of high methemoglobin concentrations. Pulse oximetry is unreliable for patients who have decreased tissue perfusion (shock, hypovolemia, or hypothermia) due to poor signal detection. The pulse rate registered on the oximeter should match the patient's heart rate.

Monitoring oxygen saturation alone in patients who have respiratory failure might be misleading because a patient receiving supplemental oxygen can maintain good oxygenation despite retaining carbon dioxide.

Cyanosis rarely is a helpful sign in the assessment of respiratory failure because it occurs late in the course of respiratory failure. Patients who have anemia develop cyanosis only at much lower levels of  $\text{PaO}_2$  because cyanosis is related to the absolute amount of reduced hemoglobin. Also, conditions associated with poor perfusion, such as septic shock or cardiac failure, may mimic cyanosis.

Heart rate usually parallels the work of breathing. Tachycardia typically is a compensatory mechanism for maintaining adequate oxygen delivery in the face of hypoxemia. Bradycardia develops because of severe hypoxemia and is a sign of impending cardiorespiratory arrest.

Blood pressure usually is high when a patient is anxious. Low blood pressure is an ominous sign, suggesting decompensated shock, and should trigger the initiation of aggressive hemodynamic and respiratory support.

Physical examination of the respiratory system starts with assessment of the work of breathing. Close monitoring and frequent reassessments in an intensive monitoring setting are paramount. Again, patients who have neuromuscular disease present with shallow, ineffective respirations. Decreased work of breathing with more

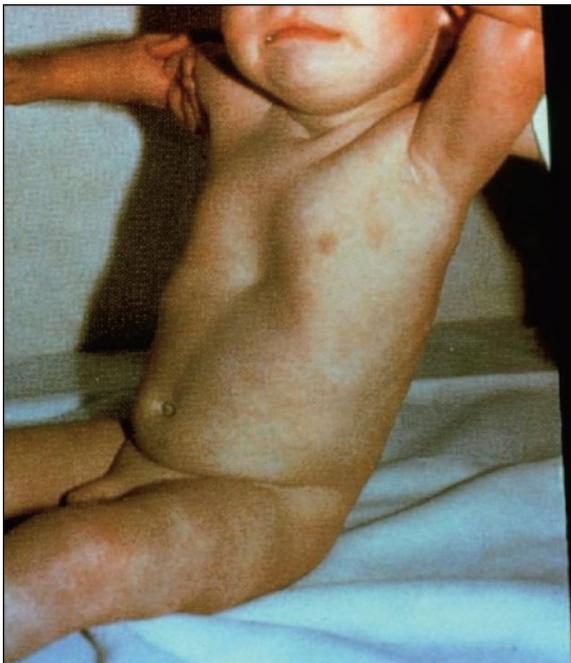


Figure 3. Intercostal and substernal retractions.

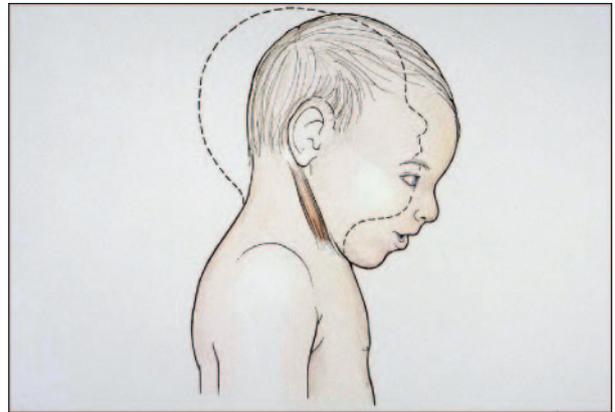


Figure 4. Head bobbing.

superficial respirations along with worsening mental status are ominous signs and signal severe respiratory failure and impending arrest.

Clinical findings suggestive of increased work of breathing include nasal flaring, intercostal and substernal retractions (Fig. 3), head bobbing (Fig. 4), respiratory pauses, grunting, and thoracoabdominal asynchrony (Fig. 5).

During inspection of the chest wall, the shape of the thoracic cage and spine should be noted. Asymmetric chest movements or tracheal deviation raise the question of a unilateral pathologic process such as severe pleural effusion or pneumothorax.

Auscultation of the chest assesses the adequacy of air exchange, symmetry of breath sounds, and presence of abnormal breath sounds such as wheezing or crackles. Very decreased breath sounds signal severe reduction in air exchange. Stridor usually is an inspiratory sound that suggests narrowing of the upper airway in conditions such as croup or laryngomalacia. Wheezing typically is an expiratory sound, associated with prolonged expiration,

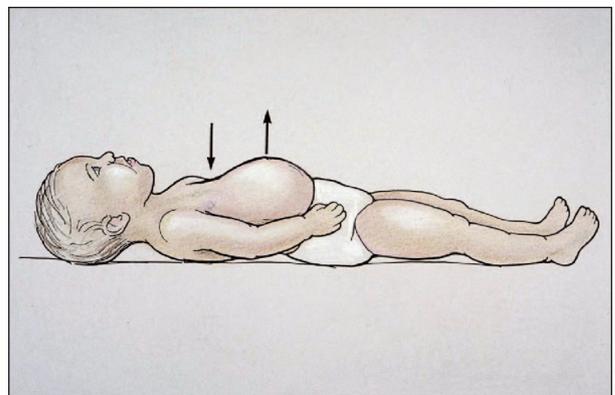


Figure 5. Thoracoabdominal asynchrony.

**Table 3. Normal Arterial Blood Gas Values**

pH: 7.4 (7.38 to 7.42)  
 Po<sub>2</sub>: 80 to 100 mm Hg  
 Pco<sub>2</sub>: 35 to 45 mm Hg  
 O<sub>2</sub> Saturation: 95% on room air  
 HCO<sub>3</sub>: 22 to 26 mEq/L  
 Base Excess: -2 to +2 mEq/L

and indicative of lower airway disorders such as asthma, bronchiolitis, or bronchomalacia. Asymmetric wheezing should raise the suspicion of a foreign body aspiration or a mass obstructing the airway. Crackles indicate an alveolar process such as pneumonia.

Examination of the heart for abnormal heart sounds may offer clues to possible congenital or acquired heart disease. Measurement of blood pressure in all four extremities along with palpation of brachial and femoral pulses helps to rule out aortic coarctation.

Assessment of muscle strength and gait is important for diagnosing several illnesses that may lead to chronic respiratory failure. Muscle strength is decreased in myopathies such as Duchene muscular dystrophy and some mitochondrial diseases. In infancy, delayed motor milestones often provide the first clues to a severe myopathy. Lack of attaining head control at an appropriate age may suggest spinal muscular atrophy. Loss of motor milestones also raises the suspicion of a myopathy. Acute ascending paralysis may suggest Guillain-Barré syndrome, and acute generalized muscle weakness may suggest botulism as causes of respiratory failure.

Changes in mental status, either agitation or somnolence, can be signs of respiratory failure. Agitation may be due to hypoxemia, and somnolence may be due to hypercarbia (Table 2). Assessment using the Glasgow Coma Scale (GCS) is important. A decreased GCS score indicates impaired neurologic function, which may be caused by any of three mechanisms: direct neurologic insult (meningitis, traumatic brain injury), hypoxemia and hypercarbia due to respiratory failure or poor perfusion, and poor oxygen delivery in shock. Altered mental status leads to an inability to control the airway and secretions (depressed respiratory drive, depressed gag reflex). A GCS score below 8 is

an indication for airway control by intubation and mechanical ventilation.

### Laboratory and Radiographic Evaluation

Both laboratory and radiographic investigations are important tools for assessing and monitoring the response to the management of respiratory failure. However, the necessity for immediate intervention should not be delayed pending the results of the blood gas or chest radiograph.

The arterial blood gas accurately assesses the extent of hypoxemia or hypercarbia (Table 3). The results of blood gas analysis should be correlated with the clinical picture (Table 4). A normal Pco<sub>2</sub> in a patient demonstrating very high work of breathing and severe tachypnea is not reassuring; this finding reflects respiratory failure (patient is maintaining normal Pco<sub>2</sub> by breathing hard and fast, and exhaustion is bound to occur) and demands appropriate intervention. Similarly, normal Pco<sub>2</sub> in a patient who has severe metabolic acidosis and tachypnea is a sign of impending respiratory failure.

The complete blood count may offer clues to the cause of respiratory failure. Anemia can be associated with chronic illness and polycythemia with obstructive sleep apnea.

A chest radiograph is an important tool used to confirm a diagnosis suspected on clinical grounds, such as pneumonia, pulmonary edema, pneumothorax, or pleural effusion.

Pulmonary function testing (PFT) has been a major step forward in the assessment of the functional status of the respiratory system because it accurately measures the volume of air that can be moved and how rapidly the air can flow. PFT provides objective measurements that can be used to characterize the respiratory disease, assess its severity, and document the course of the illness and response to therapy.

**Table 4. Interpretation of Blood Gas Results**

Condition	pH	Pco <sub>2</sub>	Base Excess
Acute respiratory acidosis	↓	↑	↔
Chronic respiratory acidosis with metabolic compensation	slightly ↓	↑	↑
Acute on chronic respiratory acidosis	↓	- ↑	↑
Acute metabolic acidosis with respiratory compensation	↓	↓	↓
Acute hyperventilation	↑	↓	↔

## Management of Respiratory Failure

Unrecognized respiratory failure is the leading cause of cardiopulmonary arrest in children. Therefore, early diagnosis and close monitoring are paramount. Required interventions range from close monitoring and supplemental oxygen to full mechanical ventilatory support. If the rapid initial assessment warrants emergent intervention, preparation for intubation and mechanical ventilation should be undertaken.

Bag-mask ventilation with 100% oxygen is an important initial step to ensure proper ventilation and preoxygenation before the intubation. This step also allows time to gather all the necessary equipment (appropriate size endotracheal tube, large-bore suction, laryngoscope, carbon dioxide detector, and intubation drugs). The key to successful intubation is calm and controlled performance. Depending on the clinical setting, intubation is performed best by medical personnel who have the highest available expertise in performing the procedure (critical care physicians, anesthesiologists, emergency medical services personnel). The patient should be well sedated. Neuromuscular blockade is useful, except in rare situations when a very difficult airway is anticipated (eg, Pierre Robin syndrome, anterior mediastinal mass). In cases of a difficult airway, the use of a laryngeal mask airway (LMA) should be considered very early. Multiple unsuccessful intubation attempts should be avoided.

The LMA is an alternative airway device that can be used for emergent airway support. It consists of an inflatable silicone mask and rubber connecting tube. The device is inserted blindly into the pharynx, forming a low-pressure seal around the laryngeal inlet and permitting gentle positive-pressure ventilation. Use of the LMA allows rapid access and does not require laryngoscopy or muscle relaxants, making it a reasonable option for temporary control of the very difficult airway. However, the LMA does not fully protect against aspiration in the patient who has not been fasting.

If emergent intervention it is not warranted, a wide array of support can be offered. For mild cases, the only required intervention may be supplemental oxygen delivered via nasal canula. When oxygen requirements are high, oxygen can be delivered by a nonrebreather mask (delivers high-flow oxygen at 10 to 15 L/min). Rarely, pediatric patients who have chronic respiratory failure depend on hypoxemia for the respiratory drive, and providing more oxygen may decrease the drive to breathe.

Noninvasive mechanical ventilation can be used in selected patients in the intensive care unit. Patients who could benefit from this intervention usually have good

respiratory drive and increased work of breathing. However, such patients must be monitored closely because noninvasive mechanical ventilation is not designed for those who are developing apnea or whose mental status is altered.

Continuous positive airway pressure (CPAP) or bi-level positive airway pressure (BiPAP) are modes of noninvasive mechanical support. The positive pressure is delivered through a tight-fitting facemask. CPAP provides only a single level of airway pressure maintained throughout the respiratory cycle, thereby helping to prevent alveolar collapse. BiPAP provides an inspiratory positive airway pressure for ventilator assistance and expiratory positive airway pressure to facilitate and maintain lung expansion. The risk of developing pressure sores on the face limits prolonged use of noninvasive mechanical ventilation for 24 hours per day. BiPAP at night can be used at home for patients who have chronic respiratory failure to postpone the need for tracheostomy or home mechanical ventilation or who choose not to use other interventions.

Conventional treatment of acute respiratory failure involves positive-pressure ventilation with supplemental oxygen. Newer generations of mechanical ventilators offer multiple modes and features. Because no clear data exist on the appropriate ventilator mode for a particular condition, managing mechanical ventilation remains part of the art of practicing medicine. Several accepted general concepts of mechanical ventilation contribute to outcome.

First are considerations of the mode of ventilation and the inspiratory flow pattern. In assist control (AC) mode, each breath given is a full tidal volume initiated when the patient takes a small triggering breath. Because AC gives a full breath each time, it is not appropriate for weaning a patient from mechanical ventilation.

At the other end of the spectrum is synchronized intermittent mechanical ventilation with pressure support (SIMV-PS), which delivers a combination of full support breaths and patient-initiated spontaneous breaths that have partial support, so some work is done by the ventilator and some by the patient. The controlled breaths can be limited either by reaching a preset pressure limit (pressure control) or a preset volume limit (volume control).

It is important to facilitate optimal patient-ventilator interaction while keeping the adverse effects of deep sedation to a minimum. In addition, ventilation with elevated oxygen concentrations and airway pressure has been shown to worsen lung injury, known as ventilator-induced lung injury (VILI). Thus, the goal is to mini-

mize lung injury while providing effective ventilation and oxygenation. An  $\text{FiO}_2$  greater than 0.6 used for longer than 6 hours is believed to add oxidative stress to the ventilated lung and contribute to VILI.

In 2000, the Acute Respiratory Distress Syndrome (ARDS) network reported improved outcome in adults treated with low tidal volume ventilation (6 mL/kg) compared with those treated with high tidal volume (12 mL/kg). It is unclear whether 6 mL/kg is superior to 8 mL/kg and whether results of these studies can be extrapolated to pediatric patients. At present, use of the lowest possible pressures and volumes to maintain acceptable ventilation and oxygenation is recommended. Because maintaining appropriate oxygen delivery to the major organs is most important, the volumes and pressures used for mechanical ventilation must be high for some very ill patients.

The instillation of surfactant or inhaled nitric oxide (iNO) can supplement mechanical ventilation in carefully selected patients. Intratracheal instillation of surfactant in preterm infants has significantly improved the outcome of respiratory distress syndrome of prematurity and, therefore, has become the standard of care. The use of surfactant for the treatment of ARDS in the pediatric age group still is controversial and currently the subject of a multicenter trial. iNO is an adjunctive therapy administered to patients who have documented or suspected pulmonary hypertension and significant oxygenation failure.

If adequate gas exchange cannot be achieved with conventional mechanical ventilation, high-frequency ventilation (HFV) is a good therapeutic option. With growing use, HFV no longer represents a nonconventional mode of ventilation. The basic principle of HFV is the delivery of tidal volumes smaller than the dead space with a rate greater than 150 breaths/min. In a way, this “extreme” model of low tidal volume ventilation mitigates the deleterious effect of barotrauma and volutrauma associated with high tidal volume ventilation and high pressure changes. There is little agreement on selection criteria for patients who would benefit from HFV. In general, HFV should be considered in those who require maximum  $\text{FiO}_2$  and high airway pressure (peak pressures higher than 35 mm Hg) to meet adequate oxygenation for longer than a few hours.

When all options have failed to provide adequate gas exchange and hemodynamic support, strong consideration should be given to extracorporeal membrane oxygenation (ECMO). The general indication for ECMO in patients who have respiratory failure is a reversible underlying illness

that has failed conventional ventilator strategies. ECMO is a modified heart-lung machine that provides total gas exchange through an extracorporeal system, allowing the lungs to “rest” and not be subjected to the additional lung injury caused by high-pressure ventilation. Survival after ECMO is determined primarily by the underlying illness. For example, in neonates, meconium aspiration syndrome requiring ECMO carries the best prognosis, with a survival rate of 94%, but pediatric patients undergoing ECMO for viral pneumonia have an average survival rate of approximately 64%. Selecting the patients for whom ECMO is indicated has been controversial, particularly because of ongoing improvements in conventional strategies.

Weaning from mechanical ventilation is achieved gradually as the underlying pathologic process resolves. Determining extubation readiness should involve assessment not only of the patient’s pulmonary status but also the overall clinical status. Neurologic considerations are important, including assessment of the patient’s sedation status, ability to protect the airway, and capability of maintaining an appropriate respiratory drive. Cardiovascular considerations include the degree of hemodynamic support and anticipated effect of increased work of breathing on cardiac function. Airway edema and airway abnormalities are important factors that can lead to extubation failure.

## Summary

- An array of conditions can lead to the inability of the respiratory system to meet the metabolic needs of the tissues.
- Unrecognized respiratory failure is the leading cause of cardiorespiratory arrest in pediatrics, making prompt interventions and close monitoring in the critical care setting paramount.
- Clinical interventions vary widely from noninvasive methods to intubation and mechanical ventilation and, as an extreme invasive measure, the use of ECMO.
- Treating respiratory failure is a dynamic field; new strategies are emerging that will add dimensions to this care.

## Suggested Reading

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## PIR Quiz

Quiz also available online at [pedsinreview.aappublications.org](http://pedsinreview.aappublications.org).

5. A 6-year-old boy suffering from lupus nephritis and hepatitis has been treated for hypertensive encephalopathy with high-dose intravenous sodium nitroprusside therapy for the past 10 days. Multiple attempts to change his antihypertensive therapy to other agents have been unsuccessful. Findings on electrocardiography and echocardiography are consistent with left ventricular hypertrophy. He now has developed increased respiratory rate and work of breathing. His venous blood gas shows metabolic acidosis and a hemoglobin-oxygen saturation of 88%. You suspect impaired oxygen use by the tissues. Which of the following conditions is *most* likely to result in such a state?
  - A. Central nervous system depression.
  - B. Cyanide toxicity.
  - C. Decreased cardiac output.
  - D. Methemoglobinemia.
  - E. Pulmonary edema.
  
6. An 8-month-old boy presents to the emergency department for respiratory difficulty of 2 days' duration. He was born at 28 weeks' gestation, and his neonatal course was complicated by the development of hyaline membrane disease, for which he received mechanical ventilation for 4 weeks. He currently receives bronchodilators and furosemide for bronchopulmonary dysplasia. His respiratory rate is 40 breaths/min, with nasal flaring and moderate chest wall retractions. His heart rate is 120 beats/min and blood pressure is 92/60 mm Hg. His arterial blood gas in room air shows: pH, 7.29; P<sub>CO<sub>2</sub></sub>, 60 mm Hg; and P<sub>O<sub>2</sub></sub>, 52 mm Hg. Supplemental oxygen is administered via a nonrebreather face mask. Thirty minutes later, the infant appears somnolent, with decreased respiratory effort. Repeat arterial blood gas shows: pH, 7.20; P<sub>CO<sub>2</sub></sub>, 75 mm Hg; and P<sub>O<sub>2</sub></sub>, 90 mm Hg. Which of the following is the *best* explanation for the worsening of his acidosis?
  - A. Decreased oxygen use by the tissues.
  - B. Decreased stimulation of chemoreceptors.
  - C. Increased impairment of carbon dioxide diffusion.
  - D. Increased intrapulmonary shunt.
  - E. Increased ventilation/perfusion mismatch.
  
7. A 6-year-old girl who has Guillain-Barré syndrome with increasing weakness is being monitored by pulse oximetry to assess the adequacy of her respirations status. After her oxygen saturation declines to 94%, supplemental oxygen (30%) is delivered via a face mask, resulting in an increase in oxygen saturation to 100%. Which of the following is a cause for concern in this setting?
  - A. Adequacy of oxygenation is not reliably assessed by pulse oximetry value.
  - B. Presence of respiratory failure can be unrecognized by pulse oximetry value alone.
  - C. Risk of oxygen toxicity outweighs benefit of increasing oxygen saturation from 94% to 100%.
  - D. She will become oxygen-dependent.
  - E. Supplemental oxygen will suppress her respiratory drive.
  
8. A 14-year-old girl who has myelomeningocele presents with increasing respiratory distress. She has been complaining of fever, cough, and runny nose for the past 2 days. Vital signs are: respiratory rate, 24 breaths/min; heart rate, 100 beats/min; and blood pressure, 140/90 mm Hg. She has moderate intercostal retractions. The expiratory phase is prolonged, with bilateral wheezing. Arterial blood gas while breathing supplemental oxygen shows: pH, 7.23; P<sub>CO<sub>2</sub></sub>, 80 mm Hg; and base excess, 4 mEq/L. Which of the following *best* describes her acid-base status?
  - A. Acute hyperventilation.
  - B. Acute metabolic acidosis with respiratory compensation.
  - C. Acute on chronic respiratory acidosis.
  - D. Acute respiratory acidosis.
  - E. Chronic respiratory acidosis with metabolic compensation.

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