patient's stay in the intensive care unit (ICU), and reduces complications and the mortality rate.[2-7]

Compared with patients receiving only conventional medical therapy (e.g., bronchodilators, anti-inflammatory agents, supplemental O_2, antibiotics), patients receiving NIV have shown significant improvement in vital signs, pH and blood gas values, respiratory rate, and breathlessness within the first hour of application.[3,6,7,20] These results have been compelling enough that NIV is considered a standard of care for the treatment of COPD exacerbation in selected patients.[3,6,7,19-21] Indeed, a recent European Respiratory Society/American Thoracic Society clinical practice guidelines for the use of NIV for ARF recommended bilevel NIV as a viable intervention to treat ARF leading to acute or acute-on-chronic respiratory acidosis (i.e., pH <7.35) because of COPD exacerbation.[21] Additionally, these guidelines recommend that a trial of bilevel NIV should be considered in these COPD patients who require endotracheal intubation and mechanical ventilation unless immediate deterioration is imminent[21] (Key Point 19.1).

Key Point 19.1 Clinical evidence supports the use of NIV as the standard of care for patients with moderate-to-severe exacerbations of COPD who meet selection criteria.

Asthma

The efficacy of NIV in the treatment of severe asthma is inconclusive at this time. The European Respiratory Society/American Thoracic Society guideline for the use of NIV for the treatment of acute respiratory failure did not provide specific criteria for the selection of asthma patients to receive NIV due to lack of evidence.[21] Several RCTs have shown that patients with status asthmaticus complicated by CO_2 retention demonstrate positive outcomes when treated with a trial of NIV. The benefits observed in one study included improved gas exchange, decreased P_aCO_2, and rapid improvement in vital signs within the first 2 hours of NIV treatment.[22] Results from another study found that NIV reduced the need for endotracheal intubation and the associated complications and resulted in fewer hospital admissions for the patients studied.[23] In another RCT involving subjects with severe airway obstruction and respiratory distress, subjects receiving NIV were compared with those who received conventional therapy with supplemental oxygen. The subjects receiving NIV tended to show a decreased requirement for inhaled bronchodilator compared with subjects receiving conventional medical therapy and supplemental oxygen.[24]

Given the need for additional studies to better define the efficacy of NIV in the treatment of patients experiencing severe asthma episodes, caution should be exercised when using NIV for patients who do not need immediate invasive mechanical ventilation or do not have substantial impairment of gas exchange. Patients with severe asthma should be carefully monitored because these patients can deteriorate rapidly and develop severe airway obstruction, which can be difficult to treat even with invasive mechanical ventilation.[25]

Hypoxemic Respiratory Failure

There is conflicting evidence of the efficacy of NIV in the treatment of hypoxemic respiratory failure, probably because of the wide variety of non-COPD parenchymal processes that can cause hypoxemic respiratory failure. Several examples include pneumonia, acute respiratory distress syndrome, trauma, and cardiogenic pulmonary edema. These conditions usually result in severe impairment of gas exchange characterized by refractory hypoxemia, an arterial partial pressure of O_2 to fractional inspired O_2 concentration (P_aO_2/F_IO_2) ratio less than 200, and a respiratory rate greater than 35 breaths/min. In several clinical studies, patients who received conventional medical care for hypoxemic ARF were compared with patients who received NIV plus the usual medical care.[26] In these studies, NIV significantly improved gas exchange, reduced the need for intubation, and reduced the mortality rate in these patients. NIV can be as effective at improving oxygenation within the first hour as invasive ventilation and is associated with fewer complications and a shorter ICU stay.[27] In contrast, other researchers have found no significant improvement in patients' overall condition with NIV unless the patients were also hypercapnic.[28] Although many studies have shown promising results with the use of NIV in hypoxemic respiratory failure, the different causes of hypoxemic respiratory failure make it difficult to apply all of these findings to individual patients.

Community-Acquired Pneumonia

Of the various causes of hypoxemic respiratory failure treated with NIV, pneumonia appears to be one of the most challenging and least consistent for successful outcomes. In a study of patients with COPD and ARF, 38% of the unsuccessful attempts with NIV were associated with the presence of pneumonia.[29] On the other hand, the intubation rate, ICU stay, and mortality rate were reduced when NIV was used to treat patients with severe **community-acquired pneumonia** (CAP).[22,25] In the case of CAP, most of the favorable results were from the subgroup of COPD patients who had pneumonia. In a study by Jolliet and colleagues, 22 of the 24 non-COPD patients with severe CAP and ARF who received NIV showed initial improvement in oxygenation and a reduced respiratory rate. However, despite the improvement, nearly two-thirds of the patients eventually required intubation and mechanical ventilation. [30] Those patients who continued to receive NIV had shorter ICU and hospital stays. Because of the mixed results produced in studies, the current suggestion is that patients with COPD and pneumonia receive an initial trial of NIV. However, caution should be used when non-COPD patients with pneumonia are treated with NIV.

Cardiogenic Pulmonary Edema

Bilevel NIV and mask CPAP has been shown to be effective in the treatment of **acute cardiogenic pulmonary edema** (ACPE).[16,21,31] When patients with ACPE do not respond to conventional pharmacological and O_2 therapy, the use of NIV and mask CPAP with O_2 may expand fluid-filled alveoli, resulting in the following:

- Increased oxygenation
- Increased functional residual capacity (FRC)
- Improved lung compliance
- Reduced work of breathing (WOB)
- Reduced need for invasive ventilation

Several studies have reported similar success in treating ACPE with NIV by mask using PSV plus PEEP.[32-34] In these studies, rapid improvement in gas exchange and pH were noted, along with reduced intubation rates. Patients who were already hypercapnic responded best. A comparison of NIV and CPAP in the

treatment of ACPE showed that although patients treated with NIV demonstrated more rapid improvements in P_aCO_2 and pH, the mortality and intubation rates were not significantly different.[35] It is worth mentioning that although NIV and CPAP are equally effective in treating respiratory failure associated with ACPE, patients with ACPE are treated initially with CPAP. If the patient remains hypercapnic and dyspneic with CPAP, a trial of NIV may be indicated[36] (Key Point 19.2).

Key Point 19.2 Patients with ACPE are treated initially with CPAP. If the patient remains hypercapnic and dyspneic with CPAP, a trial of NIV is indicated.

Chronic Care Setting

In chronic respiratory failure, NIV is considered to be a supportive therapy rather than a lifesaving treatment. Most of the clinical disorders that require this level of support are characterized by chronic hypoventilation, nocturnal desaturation, respiratory muscle fatigue, and poor sleep quality. As the disease process progresses, daytime gas exchange worsens and patients often show classic symptoms of chronic hypoventilation (Box 19.2).

Nocturnal use of NIV (4–6 hours) can have certain clinical benefits for patients with chronic hypoventilation disorders (see Box 19.1). The most significant of these are improvement of symptoms associated with chronic hypoventilation and an improved quality of life. Although the physiological mechanism underlying these benefits is not well understood, investigators have hypothesized that NIV benefits these patients in one or all of the following ways[38-40]:

- It provides intermittent rest for the respiratory muscles, resulting in less muscle fatigue and more efficiency of function.
- It reduces the frequency and severity of sleep-disordered breathing, leading to longer sleep and better sleep quality.
- It eliminates nocturnal hypoventilation, making the respiratory centers more responsive to increases in CO_2 and leading to improvement in daytime ventilation.
- It may eliminate auto-PEEP, which would reduce WOB required to trigger a breath during NIV.

Restrictive Thoracic Disorders

Restrictive thoracic disorders include chest wall deformities and neuromuscular conditions that result in progressive muscle weakness, hypoventilation, and eventually respiratory failure. Patients with neuromuscular disorders were the first group of patients studied to be successfully converted from invasive ventilation (tracheostomy) to NIV (mouthpiece interface).[37] These patients required continuous support; however, NIV can also benefit patients who require ventilatory support only at night or intermittently during the day. In the short-term use group, daytime gas exchange and respiratory muscle strength improve and symptoms of hypoventilation are alleviated.[38-40] Nocturnal use of NIV also eliminates OSA and O_2 desaturation at night, which are common in patients who use negative pressure ventilatory support.[41]

Quality of life appears to improve for patients with neuromuscular disorders who use NIV. A high degree of satisfaction, along with improved mental well-being and psychosocial function, has been noted for patients with restrictive thoracic disorders.[42] Long-term follow-up of these patients has shown significantly shortened hospital stays and an overall increased survival time compared with patients who did not receive ventilatory support.[43] For these reasons, the consensus is that NIV is the ventilator mode of choice for chronic respiratory failure caused by restrictive thoracic disorders in patients who can protect their airway[44,45] (Key Point 19.3).

Key Point 19.3 NIV is the ventilator mode of choice for chronic respiratory failure caused by restrictive thoracic disorders in patients who can protect their airways.

BOX 19.2 Symptoms of Chronic Hypoventilation

- Fatigue
- Morning headache
- Daytime hypersomnolence
- Cognitive dysfunction
- Dyspnea

Chronic Stable Chronic Obstructive Pulmonary Disease

Evidence of the efficacy of long-term nocturnal NIV is limited and often contradictory in severe stable COPD. Early studies of patients with severe stable COPD focused on the use of intermittent negative pressure ventilation to rest the muscles of respiration.[46,47] Some investigators reported potential benefits, but most patients could not tolerate the devices used, and the benefits were only temporary. In addition, negative pressure ventilation actually collapsed upper airway structures during sleep and induced OSA.

A number of studies have since been performed on patients with severe stable COPD who used nocturnal NIV. Results from these studies included reduced daytime P_aCO_2, reduced nocturnal O_2 desaturation and hypoventilation, improved sleep quality, and improved quality of life.[47-50] Other studies have found minimal or no benefit with nocturnal NIV in these patients.[51,52] The discrepancy in these findings could be the result of differing patient selection, methods, or ventilator settings. Closer examination of baseline characteristics of the study participants reveals an important finding: the greatest benefits from NIV were seen in individuals who had more severe CO_2 retention and more episodes of nocturnal desaturation.

A recent clinical practice guideline published by the American Thoracic Society (ATS) suggested on the basis of evidence to date that patients diagnosed with chronic stable COPD with hypercapnia may benefit and should be considered for nocturnal NIV.[50] The guideline also suggested that barriers to implementation will require attention from physicians, as well as payors and other stakeholders.

Cystic Fibrosis

The role of NIV in the treatment of advanced cystic fibrosis has not been precisely defined. In general, NIV increases V_T, reduces diaphragmatic activity, and improves oxygenation in some

patients with cystic fibrosis who have acute exacerbations.[53] Intermittent use of NIV could help support these patients for several months while they await lung transplantation.[54-56]

Nocturnal Hypoventilation

Several other disorders associated with **nocturnal hypoventilation** include central sleep apnea, obesity hypoventilation syndrome, and OSA combined with COPD or congestive heart failure. These disorders may also lead to daytime CO_2 retention. If nocturnal hypoventilation is severe, symptoms will be severe and will manifest during the daytime (see Box 19.2). Without intervention, these symptoms can then progress to overt respiratory failure.

The therapy of choice for OSA is CPAP. However, if these patients continue to hypoventilate despite CPAP therapy, NIV may improve daytime gas exchange and symptoms associated with chronic hypoventilation.[57] Likewise, patients with central hypoventilation or obesity hypoventilation syndrome who do not respond to first-line therapies (e.g., O_2, respiratory stimulants, weight loss, supplemental O_2, CPAP) should be considered for treatment with NIV (Key Point 19.4).

***Key Point* 19.4** Patients with OSA are typically treated initially with CPAP therapy. NIV is indicated if these patients continue to experience hypoventilation and nocturnal desaturation.

OTHER INDICATIONS FOR NONINVASIVE VENTILATION

Facilitation of Weaning From Invasive Ventilation

Reducing the number of days that a patient receives invasive mechanical ventilation reduces the risk for infection and other complications, lowers the mortality rate, and reduces health care costs.[58-60] Many respiratory care departments in acute care facilities have devised weaning protocols for discontinuing ventilation and extubating patients as soon as possible. However, many weaning protocols depend on patient tolerance of daily spontaneous breathing trials to determine the likelihood of successful extubation. (See Chapter 20 for information on weaning and spontaneous breathing trials.) After extubation, the excessive WOB that spontaneous breathing places on the respiratory muscles can lead to fatigue and ultimately reintubation.

NIV provides a viable weaning alternative for patients who demonstrate respiratory muscle fatigue post extubation. It has been suggested that NIV reduces the WOB and maintains adequate gas exchange as effectively as invasive ventilation.[61] NIV can also shorten the duration of invasive ventilation.[62,63] In one study of a group of patients for whom 3 days of spontaneous breathing trials failed, NIV was shown to reduce the spontaneous WOB, maintain adequate gas exchange, and reduce ICU and hospital stays.[64] NIV has also been shown to reduce the likelihood that patients will need a tracheotomy.[62] Most patients who appear to benefit from NIV during weaning from invasive ventilation suffer from chronic illness (e.g., COPD). Therefore, it is questionable whether the benefits of NIV would apply to patients with other disease processes. Nonetheless, the evidence is strong enough to warrant consideration of NIV in patients for whom spontaneous breathing trials fail and who meet appropriate NIV selection criteria.

"Do Not Intubate" Patients

Patients with terminal or advanced disease who develop ARF are not viewed as good candidates for endotracheal intubation and mechanical ventilation. NIV may be a viable alternative therapy for these patients, although its use with this group of patients remains controversial. Previous studies involving primarily end-stage COPD patients in whom endotracheal intubation was contraindicated found that most of these patients were successfully supported with NIV and eventually weaned from ventilatory support.[65,66] Many of these patients would not have survived the acute process had they not been placed on NIV. Patients with acute pulmonary edema may also benefit from support with NIV. However, survival was not improved in patients with ARF arising from other causes such as pneumonia or cancer.[67]

The argument for using NIV in patients who have "do not intubate" status is that NIV may relieve severe dyspnea, reduce sedation requirement, and preserve patient comfort. It may also reverse the acute process in disorders such as COPD or pulmonary edema and allow these patients to live longer.[68] The argument against using NIV in these patients is that it can prolong the dying process, add to patient discomfort, and consume valuable resources.[69] When NIV is used in these cases, the patient and family members should be informed that NIV is a form of life support that can be uncomfortable but that may be removed at any time.[19]

PATIENT SELECTION CRITERIA

Success of NIV and avoidance of major complications depend on appropriate selection of patients in both acute and chronic care settings. Evidence gained from the use of NIV in various patient populations and clinical settings has led to the development of guidelines that promote the highest chance of success (Table 19.1).

TABLE 19.1 Indications, Symptoms, and Selection Criteria for Noninvasive Ventilation in Acute Respiratory Failure in Adults

Indications	Symptoms	Physiological Criteria
Acute exacerbation of COPD Acute asthma Hypoxemic respiratory failure Community-acquired pneumonia Cardiogenic pulmonary edema Immunocompromised patients Postoperative patients Postextubation (weaning) "Do not intubate"	Moderate to severe dyspnea Respiratory rate >24 breaths/min Accessory muscle use Paradoxical breathing	P_aCO_2 >45 mm Hg, pH <7.35 *or* P_aO_2/F_IO_2 <200

COPD, Chronic obstructive pulmonary disease; F_IO_2, fractional inspired oxygen concentration; P_aCO_2, arterial carbon dioxide partial pressure; P_aO_2, arterial oxygen partial pressure.

BOX 19.3 Exclusion Criteria for Noninvasive Ventilation

1. Respiratory arrest or the need for immediate intubation
2. Hemodynamic instability
3. Inability to protect the airway (impaired cough or swallowing)
4. Excessive secretions
5. Agitated and confused patients
6. Facial deformities or conditions that prevent mask from fitting
7. Uncooperative or unmotivated patients
8. Brain injury with unstable respiratory drive

Acute Care Setting

In the acute care setting, the selection process must be based on the patient's diagnosis, clinical characteristics, and risk for failure. The assessment process may be viewed as a two-step process. The first step involves establishing the need for ventilatory assistance according to clinical and blood gas criteria. The consensus of studies is that patients who need ventilatory assistance show signs and symptoms of distress, including tachypnea (respiratory rate greater than 24 breaths/min), use of accessory muscles, and paradoxical breathing.[44] Blood gas criteria should reveal a moderate to severe respiratory failure (i.e., a pH <7.35 and P_aCO_2 >45 mm Hg *or* a P_aO_2/F_IO_2 <200). It is also important to know when NIV is not appropriate. For example, NIV may be unnecessary for patients with mild respiratory distress. NIV may also not be appropriate for a patient who has already deteriorated to severe respiratory failure because it may delay lifesaving intubation and ventilation.

Once the need for ventilatory support is established, the second step is to exclude patients at increased risk for failure and complications (Box 19.3). Such patients include individuals with respiratory arrest, hemodynamic instability, or other major organ involvement; patients with excessive secretions; and patients unable to protect their airway because of impaired cough or swallowing ability. Patients with any of these disorders are at highest risk for aspiration. Finally, agitated and confused patients or those with facial burns or deformities that preclude a good mask fit are excluded.

A final consideration in the selection of patients with ARF is the potential reversibility of the disease process. It has been clearly established that NIV is effective in the treatment of acute exacerbations of COPD. Supportive ventilatory assistance allows time for conventional therapies (e.g., bronchodilators, O_2, antibiotics) to reverse the acute process so that intubation may be avoided. Other causes of ARF may not be treated as successfully as COPD, but a trial of NIV may be warranted if the patient meets the selection criteria. All patients should be monitored closely so that intubation, if necessary, is not unduly delayed (Key Point 19.5).

***Key Point* 19.5** The reversibility of the disease process must be considered before NIV is initiated.

Chronic Care Setting

Establishing the need for intermittent ventilatory assistance in patients with chronic respiratory failure begins with the recognition of typical symptoms of nocturnal hypoventilation and poor sleep quality. These most commonly include the following:

- Excessive fatigue
- Morning headache
- Daytime hypersomnolence
- Cognitive dysfunction
- Dyspnea

Objective criteria, such as blood gases, depend on the rate of progression of the disease process. For patients with restrictive thoracic or central hypoventilation disorders, institution of NIV is recommended when P_aCO_2 is 45 mm Hg or higher or when sustained nocturnal desaturation occurs, as evidenced by an O_2 saturation by pulse oximeter (S_pO_2) under 88% for longer than 5 consecutive minutes.[44] NIV may also be indicated if a patient with restrictive thoracic disease is symptomatic and has severe pulmonary dysfunction (vital capacity [VC] <50% of the predicted level), even if CO_2 retention is absent.[44] Patients with nocturnal hypoventilation or OSA may require only nocturnal CPAP for splinting the airway open to overcome hypoventilation. However, NIV should be initiated if patients with moderate to severe OSA do not respond to CPAP therapy. Patients who recover from episodes of ARF or who are hospitalized repeatedly for exacerbations of their condition should also be considered for noninvasive ventilatory assistance (Key Point 19.6).

***Key Point* 19.6** NIV should be considered for patients with severe stable COPD who are symptomatic despite optimal treatment. NIV should also be considered for COPD patients who demonstrate evidence of OSA and are unresponsive to CPAP therapy.

The conflicting findings of studies regarding the use of NIV for severe stable COPD have limited the development of evidence-based selection guidelines. Studies have demonstrated that COPD patients with severe hypercapnia are likely to benefit from NIV.[49,70] A consensus of medical experts recommended the use of nocturnal NIV in symptomatic yet medically stable patients with COPD whose daytime P_aCO_2 is 55 mm Hg or higher.[44] The term *medically stable* in this instance means that the patient is being optimally treated, and OSA and CPAP therapy have been considered and ruled out.[44] The consensus statement also recommended a trial of NIV for COPD patients receiving long-term O_2 administration (2 L/min or more) if the P_aCO_2 is 50 to 54 mm Hg and the patient demonstrates evidence of frequent hypopnea episodes and sustained nocturnal desaturation. A history of frequent hospitalizations for acute exacerbations also helps justify the use of NIV in COPD patients.

As for any patient requiring NIV, the ability to protect the airway is crucial. This is especially important for patients with chronic respiratory failure because most of these individuals live at home or in an extended care setting and may not be monitored closely. Patients with neuromuscular disorders may present an even greater challenge as their disease progresses and they begin to lose oropharyngeal muscle strength and the ability to generate an effective cough. Cough-assisting devices or airway clearance techniques may help these individuals remove secretions and maintain a patent airway.

Patient motivation must also be considered with NIV in the chronic care setting. Few, if any, therapeutic results are realized if the patient does not comply with the prescribed therapy.[71] This

TABLE 19.2 Indications, Symptoms, and Selection Criteria for Noninvasive Ventilation in Chronic Disorders

Indication	Symptoms	Physiological Criteria
Restrictive thoracic disorders Muscular dystrophy Multiple sclerosis Amyotrophic lateral sclerosis Kyphoscoliosis Postpolio syndrome Stable spinal cord injuries	Fatigue Dyspnea Morning headache Hypersomnolence Cognitive dysfunction	P_aCO_2 ≥45 mm Hg Nocturnal S_pO_2 ≤88% for 5 consecutive minutes MIP <60 cm H_2O FVC <50% predicted
Severe stable COPD	Following optimal therapy with bronchodilators, O_2, and other therapy, COPD patients must demonstrate: Fatigue Dyspnea Morning headache Hypersomnolence	P_aCO_2 >55 mm Hg P_aCO_2 50–54 mm Hg + S_pO_2 <88% for 5 consecutive min P_aCO_2 50–54 mm Hg + recurrent hospitalizations for hypercapnic respiratory failure (>2 hospitalizations in a 12-mo period)
Nocturnal hypoventilation Obstructive sleep apnea Obesity hypoventilation Idiopathic hypoventilation	Fatigue Morning headache Hypersomnolence	Polysomnographic evidence of OSA not responsive to CPAP

COPD, Chronic obstructive pulmonary disease; *CPAP,* continuous airway pressure; *FVC,* forced vital capacity; *MIP,* maximum inspiratory pressure; *OSA,* obstructive sleep apnea; P_aCO_2, partial pressure of arterial carbon dioxide; S_pO_2, pulse oximetry saturation.

latter point emphasizes the importance of selecting patients who are symptomatic and motivated by the desire for relief of those symptoms. Table 19.2 summarizes the symptoms and selection criteria for chronic respiratory failure disorders.

EQUIPMENT SELECTION FOR NONINVASIVE VENTILATION

The equipment required for NIV generally includes ventilators, humidifiers, and interfaces or masks.

Types of Ventilators

Successful application of NIV has been achieved using portable homecare ventilators, adult acute care ventilators, and portable pressure support (pressure-targeted) ventilators. The choice of ventilator should be based on the level of support required and the advantages and disadvantages of the appropriate machines.[72]

Pressure-Targeted Ventilators

Portable **pressure-targeted ventilators** (PTVs) are also known as bilevel CPAP ventilators, pressure support ventilators, or bilevel pressure ventilators. These ventilators are microprocessor-controlled, electrically powered units that use a blower to regulate gas flow into the patient circuit to maintain the preset pressure levels at the patient connection. PTVs have a single-circuit gas delivery system that uses an intentional leak port for patient exhalation instead of a true exhalation valve; this allows the continuous flow of gas through the small leak port to help maintain pressure levels and flush exhaled gases from the circuit.

PTVs are pressure-limited, flow- and time-triggered, flow- and time-cycled ventilators. These devices are designed to increase minute ventilation and improve gas-exchange capabilities using the delivery of an **inspiratory positive airway pressure** (IPAP) and an **expiratory positive airway pressure** (EPAP). The calibrated pressure range for IPAP typically is 2 to 30 cm H_2O; the range for EPAP typically is 2 to 20 cm H_2O.[72]

Manufacturers of PTVs use variable mode nomenclature, which is often confusing, but most of these units offer the following modes of ventilatory support:

- CPAP (spontaneous)
- PSV (IPAP/EPAP)
- Spontaneous/timed (S/T)

In the CPAP mode the patient breathes spontaneously at a set baseline pressure. The patient controls both the rate and depth of breathing. Flow sensors and pressure transducers respond to the patient's inspiratory and expiratory effort and increase or decrease flow through the circuit to maintain a stable level of pressure.

With the PSV (bilevel) mode, the difference between two pressure levels (IPAP and EPAP) determines the level of pressure support for each assisted breath. A change to the set IPAP occurs only in response to the patient's inspiratory effort. When the patient reaches a predetermined flow threshold, the breath is terminated and the patient exhales to the set EPAP level. There is no set rate; the patient must initiate each breath.

In the S/T mode (older models may use the term *A/C*), the clinician sets the IPAP and EPAP, a respiratory rate, and an inspiratory time (e.g., IPAP%). The patient may initiate breaths that are supported to the IPAP level, as in the PSV mode, but if the patient fails to make an inspiratory effort within a set interval, the machine triggers inspiration to the set IPAP level. IPAP then cycles to EPAP based on the IPAP% period. In all modes, the patient's delivered V_T depends on the gradient between the IPAP level and the EPAP, the inspiratory time, patient inspiratory effort, and the patient's lung characteristics (airway resistance and lung compliance) (Key Point 19.7).

Key Point 19.7 In all modes of bilevel positive pressure ventilation, the patient's delivered V_T depends on the gradient between the IPAP and EPAP, the inspiratory time, and the patient's inspiratory effort and lung characteristics.

Average volume-assured pressure support (AVAPS) is a relatively new technology available on the Philips Respironics Healthcare V60 ventilator (Eindhoven, The Netherlands) (Fig. 19.2). AVAPS devices automatically adapt pressure support to match a patient's ventilatory needs by delivering an average V_T (V_T range = 200–1500 mL) based on the patient's condition. AVAPS may be useful in the treatment of patients with COPD, neuromuscular diseases, obesity hypoventilation, and chronic hypoventilation.

AVAPS devices operate with several modes of ventilation, including CPAP, S/T, spontaneous, timed, and PCV. The Respironics V60 ventilator continually calculates and compensates for the total leak rate (i.e., intentional and unintentional patient leak). The clinician enters the known intentional leak value specific to the mask–patient interface and the circuit's exhalation port so that the ventilator can accurately calculate and display the patient leak using an Auto-Trak sensitivity system.[72] The Auto-Trak+ option allows the clinician to further adjust thresholds that manage trigger and cycling and the level of Auto-Trak sensitivity. The manufacturer's suggested setting for initiating AVAPS include a target V_T of 8 mL/kg, ideal body weight (IBW), maximum IPAP of 25 cm H_2O (depending on the patient's pathology), minimum EPAP of +4 cm H_2O, respiratory rate 2 to 3 beats/min below resting respiratory rate, and an inspiratory time of 1.5 seconds.[72]

A PTV's ability to deliver flow in response to patient demand is equivalent and often superior to that of ICU adult ventilators and portable homecare ventilators. Flow sensors in the PTV system continuously monitor and adjust flow (variable up to 180 L/min) based on the set pressure, the patient's inspiratory and expiratory efforts, and the difference between the intentional leak in the leak port and unintentional leaks that might occur around the patient-ventilator interface. The PTV's ability to compensate for leaks makes it easier for the patient to flow-trigger the unit into inspiration and to reach the inspiratory flow threshold necessary to terminate each pressure-supported breath.

Fig. 19.2 Philips Respironics Healthcare V60 ventilator. (Courtesy Philips Respironics, Eindhoven, The Netherlands.)

Most units now have adjustable inspiratory and expiratory sensitivity controls that improve synchronization between the patient and ventilator. PTVs also allow adjustment of the amount of time required to reach the IPAP (i.e., rise-time control). Use of the rise-time control may enhance patient comfort, reduce WOB, and improve patient–ventilator synchrony. Two other features of portable PTVs that can enhance patient comfort are the **ramp** and **delay-time controls**. Ramp allows positive pressure to increase gradually over a set interval (delay time). The ramp rate generally can be set in increments of 1, 2, or 3 cm H_2O, and the delay time can be set in 5-minute increments between 5 and 30 minutes. The ramp and delay-time controls are more likely to be used in homecare or chronic care NIV.

Portable PTVs have certain limitations that may restrict their use in ARF. For example, O_2 delivery is not standard on most portable PTVs. When supplemental O_2 is required, it must be bled into the system via the mask or into the circuit near the machine outlet. Therefore, the F_IO_2 can vary and is affected by four factors:

1. O_2 flow rate
2. Type of leak port in the system
3. Site where O_2 is bled into the circuit
4. IPAP and EPAP

Higher O_2 flow rates result in higher O_2 concentrations. Lower IPAP and EPAP levels also yield higher O_2 concentrations.[73,74] In addition, F_IO_2 is affected by the type of leak port and the site where O_2 is added to the circuit. If the leak port is located in the circuit, higher F_IO_2 values are obtained if the O_2 is bled into the patient's mask. If the leak port is located in the mask, higher F_IO_2 values are obtained if the O_2 is bled into the circuit at the machine outlet.[75] (The lowest levels of O_2 are obtained when the leak port is in the mask and O_2 is bled into the mask.) Because the O_2 concentration delivered is the result of a complex interaction between these variables, a ventilator with an O_2 blender should be used for patients who require a high or precise F_IO_2.

Rebreathing of CO_2 is a concern with any PTV that uses a single-circuit gas delivery system because exhalation occurs through the intentional leak port and depends on the continuous flow of gas in the circuit. If gas flow is inadequate, exhaled gases may not be adequately flushed from the system, resulting in the patient rebreathing exhaled CO_2. The flow of gas through the leak port depends on the EPAP setting and the patient's inspiratory-to-expiratory ratio. At low EPAP settings (<4 cm H_2O) and with fast respiratory rates, flow may not be adequate to flush CO_2 from the circuit. Studies have shown that use of an EPAP of 4 cm H_2O or higher improves continuous flow of gas through the system and minimizes CO_2 rebreathing.[76,77] Some have considered adding an isolation-type exhalation valve to the circuit to eliminate CO_2 rebreathing, but these valves tend to increase expiratory airway resistance significantly and increase WOB.

Pressure support ventilators initially were designed for use in the home or in noncritical areas of patient care. Their simple design and ease of operation make them ideal for home or subacute care. However, most of these units have few monitoring

Key Point 19.8 To prevent CO_2 rebreathing, the EPAP level should be set at 4 cm H_2O or higher so that adequate gas flows can flush CO_2 from the breathing circuit.

capabilities or alarms. With the increased use of NIV to treat ARF and to avoid intubation, PTVs have been developed with alarms that can detect large leaks, patient disconnection, and mechanical failure. Monitoring capabilities have improved such that the respiratory rate and V_T are measured and displayed. Pressure support ventilators, such as the BiPAP Vision (Phillips Respironics), provide graphic waveforms, which allow the practitioner to monitor for patient–ventilator asynchrony and make necessary adjustments (Key Point 19.8).

Portable Homecare Ventilators

Portable homecare ventilators were originally designed for invasive ventilation in the home or extended care facility for patients who required long-term assisted ventilation. The advantages of these electrically powered, microprocessor-controlled ventilators included compact size and the use of three power sources: A/C current, internal D/C battery, and external D/C battery. They were capable of providing patient- or time-triggered, pressure-limited, and volume- or pressure-cycled ventilation. Unlike adult critical care ventilators, early portable ventilators had no graphic displays and basic audible and visual alarms, which included low battery, power loss, low pressure, high pressure, power switchover, apnea, and microprocessor malfunction. PEEP could be obtained by attaching an external threshold resistor to the patient circuit exhalation valve. These units were not equipped with internal blenders, and therefore precise O_2 concentrations are not possible. As with portable PTVs, O_2 had be bled into the system through an adaptor from a separate O_2 source. Older portable volume ventilators, if used for NIV, are more likely to be used in patients with chronic respiratory failure resulting from neuromuscular disorders. These patients require higher ventilating pressures that cannot be obtained with portable PTVs.

With the increased use of NIV, portable homecare ventilators have undergone a radical change in design and function. They now include different modes, alarms, and graphic capabilities similar to those of acute care ventilators and portable PTVs. Early portable ventilators were strictly volume ventilators; newer ventilators (e.g., LTV2 Ventilator [Vyaire Medical, Irvine, Calif.] [Fig. 19.3]) now have both volume- and pressure-targeted modes of ventilation, flow triggering, and PEEP capabilities (see Fig. 19.3).[69] These ventilators are more responsive to patient flow needs and can be used for either invasive ventilation or NIV. Thus, they are ideal for achieving a seamless transition from the extended care facility to the home.

Adult Acute Care Ventilators

Ventilators used in adult critical care units offer additional ventilatory support options and alarms, a precise F_IO_2, and more monitoring features than portable PTVs. These extra features may be advantageous for patients in ARF who require close monitoring and supervision during NIV. Although the pressure support mode is most commonly used to administer NIV, volume- or pressure-controlled modes combined with PEEP can also be administered via mask interface.

Fig. 19.3 The LTV2 ventilator. (The LTV2™ ventilator series image and Vyaire Medical are © 2023 Vyaire Medical, Inc.; Used with permission.)

The most significant disadvantage of using acute care ventilators is the inability of some machines to compensate for leaks. Leaks at the patient interface interfere with triggering and cycling functions of the ventilator and result in patient–ventilator asynchrony and increased WOB. In the pressure support ventilation mode, air leaks cause gas flow to increase during delivery of the breath, making the cycle threshold difficult to achieve. This may prolong the inspiratory phase or cause the patient to exhale actively against the flow in an effort to terminate the breath. Most ICU ventilators have a flow-cycled mechanism that can be adjusted to terminate the breath sooner if air leaks increase the inspiratory time. The increased flow in the circuit may also cause some ventilators to autotrigger into inspiration or impair the patient's ability to flow-trigger the machine into inspiration (trigger asynchrony), resulting in increased muscle activity on inspiration.

When significant leaks are present around the interface, the patient may be more comfortable in a pressure-targeted, time-cycled mode, such as pressure-controlled continuous mandatory ventilation. In this mode, a rate and inspiratory time can be set according to the patient's rate and inspiratory time during spontaneous breathing. Cycling to exhalation then is a function of time rather than flow, which may improve synchronization with the ventilator and reduce patient respiratory effort.[78]

Although studies have demonstrated no significant differences in gas exchange between volume- and pressure-targeted modes,[78,79] volume control modes are seldom used to deliver NIV in the acute care setting. This is most likely because of the leakage around the interface, which may cause a loss of volume delivery to the patient, resulting in hypoventilation. V_T can be increased to compensate for leaks, but ventilating pressures often increase as well. Volume control modes are more likely to be used in the chronic care setting for patients with neuromuscular disorders who have been taught to "stack" breaths to achieve larger V_T to enhance coughing and secretion clearance.[80]

Because of the increased use of NIV in the acute care setting, many ventilator manufacturers have incorporated specific noninvasive modes of ventilation into their acute care ventilators. These noninvasive modes allow for leak compensation in a manner similar to that of portable PTVs. Difficulties with triggering and cycling have improved, but considerable variation in the efficiency of this leak compensation exists between acute care ventilators.[81,82] As the amount of leakage increases, many of these ventilators require adjustments of trigger sensitivity and cycling function to maintain patient–ventilator synchrony.

Humidification During Noninvasive Ventilation

Excessive drying of nasal mucosa from the administration of nasal CPAP or NIV has been associated with nasal congestion and increased nasal resistance, which can cause patient discomfort and noncompliance.[83] Use of a heated humidifier during administration of nasal CPAP can significantly reduce drying of the nasal mucosa and lead to improved patient comfort and compliance during NIV.[84,85] Passover-type heated humidifiers are often used because heated bubble humidifiers and heat-moisture exchangers can increase airway resistance in the ventilator circuit and interfere with patient triggering (Key Point 19.9).[86]

***Key Point* 19.9** Passover heated humidifiers should be used to treat or prevent nasal congestion and improve patient comfort. Bubble humidifiers and heat-moisture exchangers increase airway resistance and will increase inspiratory WOB.

Patient Interfaces

The effectiveness of NIV is greatly influenced by the interface chosen to deliver positive pressure to the airway. A variety of interfaces are available, including nasal masks, oronasal masks, total face masks, helmets, nasal pillows, and mouthpieces with lip seals. All interfaces have advantages and disadvantages (Table 19.3). Therefore, the clinician must choose one that optimizes patient comfort and compliance with NIV.

Nasal Interfaces

Nasal masks are widely used for both CPAP and NIV (Fig. 19.4). Although nasal masks are available in many sizes and shapes from a number of manufacturers, the basic design is a small translucent, triangular device with a plastic shell and a cushion of soft, supple material that helps provide a seal around the patient's nose.[87] The mask is secured to the patient's head and face by a harness composed of hook-and-loop fastening straps or a soft polyester head cap.

A nasal mask may offer several advantages over a full-face mask. It is much easier to fit and secure to the patient's face, and it may be more tolerable than a face mask to patients who feel claustrophobic. Because the nasal mask covers only the patient's nose, it allows the patient to cough and clear secretions, speak, and possibly eat. Nasal masks have considerably less mechanical dead space than full-face masks and therefore reduce the potential for rebreathing CO_2.

The two most common disadvantages of the nasal mask are air leaks and skin irritation. Leaks occur to some degree in all patients receiving NIV with any mask. Nasal masks are more prone to leakage, especially in patients who are primarily mouth-breathers. For these patients, a chin-strap may help hold the mouth closed

TABLE 19.3 Advantages and Disadvantages of the Various Interfaces Used in Noninvasive Ventilation

Interface	Advantages	Disadvantages
Nasal masks	Easy to fit and secure to patient's face Less feeling of claustrophobia Low risk for aspiration Patient can cough and clear secretions Maintains ability to speak and eat Less mechanical dead space	Mouth leaks Eye irritation Facial skin irritation Ulceration over nose bridge Oral dryness Nasal congestion Increased resistance through nasal passages
Full-face masks (oronasal masks)	Reduces air leakage through the mouth Less airway resistance	Increased risk for aspiration Increased risk for asphyxia Increased dead space Claustrophobia Difficult to secure and fit Facial skin irritation Ulceration over nose bridge Must remove mask to eat, speak, or expectorate secretions
Nasal pillows or seals	Same as nasal mask	Pressure sores around nares Nasal air leaking
Mouthpieces	Facilitate communication Less feeling of claustrophobia Low risk for aspiration Patient can cough and clear secretions Low risk for CO_2 rebreathing No headgear requirements	Hypersalivation Possible orthodontic deformity

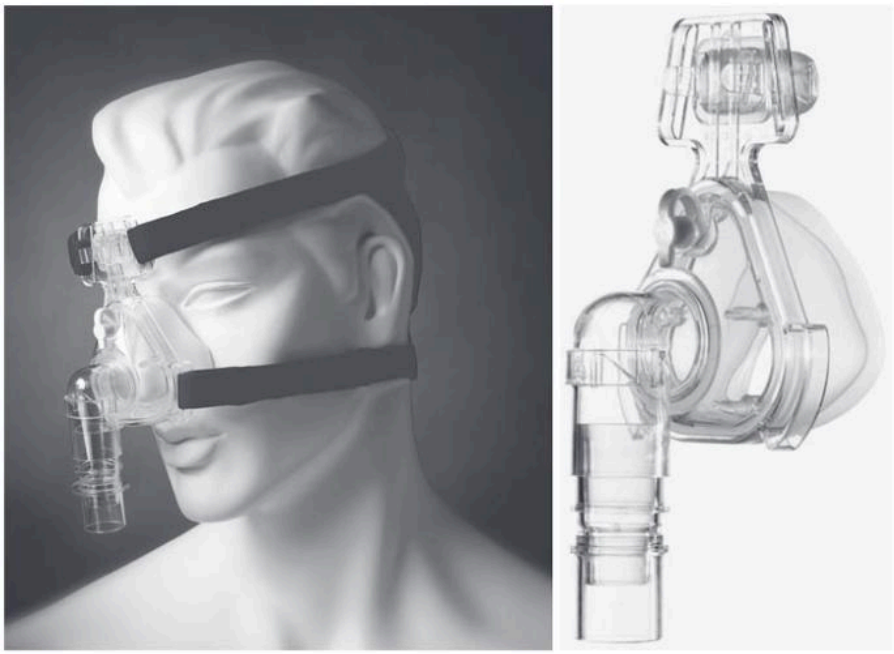

Fig. 19.4 Disposable nasal mask and headgear. (Courtesy Philips Respironics, Eindhoven, The Netherlands.)

during administration of NIV. Air leaks around the nasal mask often result in eye irritation. The strap tension required to maintain a snug fit between the nasal mask and the face often creates intolerable skin pressure, especially over the bridge of the nose. If the headgear straps are too tight, leakage may worsen, as does the pressure exerted over the nose. This can lead to redness and irritation of the skin and the potential for ulceration. Clinicians must ensure the tension on the headgear straps is not excessive. The clinician should be able to slip at least one finger between the straps and the patient's face.

Leaks and discomfort commonly occur because the mask is too large for the patient. Most manufacturers now provide mask-specific sizing gauges to aid sizing (Fig. 19.5). For nasal masks, the smallest mask that comes closest to the following contact points should be used:

- The point just above the junction of the nasal bone and cartilage (nasal bridge)
- The skin on the sides of both nares
- The area just below the lowest point of the nose, above the upper lip

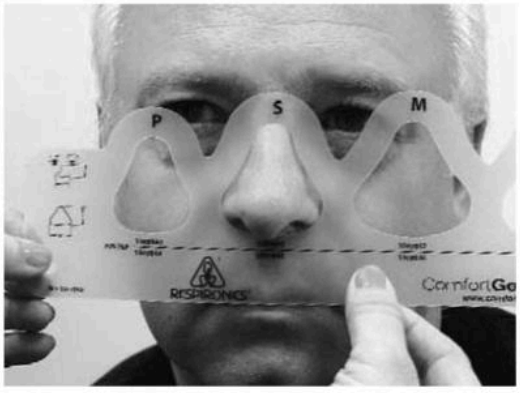

Fig. 19.5 A fitting gauge is used to ensure correct fitting of nasal mask. (Courtesy Philips Respironics, Eindhoven, The Netherlands.)

Several manufacturers have modified the standard nasal mask to minimize leakage and to enhance patient comfort for chronic use of NIV. One such modification is a mask with gel-filled cushions that seal better and with less pressure exerted over the nose (Fig. 19.6). Other modifications include the use of forehead spacers or an extra-thin plastic flap around the cushion of the mask to permit better sealing of the mask with less pressure and discomfort.

A recently introduced minimask incorporates a small lightweight cushion that sits on the tip of the nose, eliminating both the pressure over the bridge of the nose and air leakage into the eyes (Fig. 19.7). For patients who cannot tolerate any of the commercially available masks, a custom-molded mask may be contoured to the patient's face enhancing comfort and reducing air leaks.

Patients who cannot tolerate nasal masks may use nasal pillows or nasal-sealing cushions. These consist of soft rubber or silicone pledgets that fit directly into the patient's nares (or seal the opening) and are held in place by a plastic shell attached to adjustable headgear (Fig. 19.8).

Full (Oronasal) and Total Face Mask and Helmet

The oronasal mask, or full-face mask, covers the nose and the mouth and may be used in NIV for patients who cannot tolerate nasal masks because of large air leaks through the patient's mouth (Fig. 19.9). This mask has become popular for the treatment of patients with ARF because acutely dyspneic patients tend to breathe more through the mouth as dyspnea increases.

Several concerns arise with the use of the full-face mask. Two important concerns are the potential for aspiration if vomiting occurs and the risk for asphyxia if the ventilator malfunctions. Commercially available masks are now equipped with quick-release mechanisms for simple removal and entrainment valves

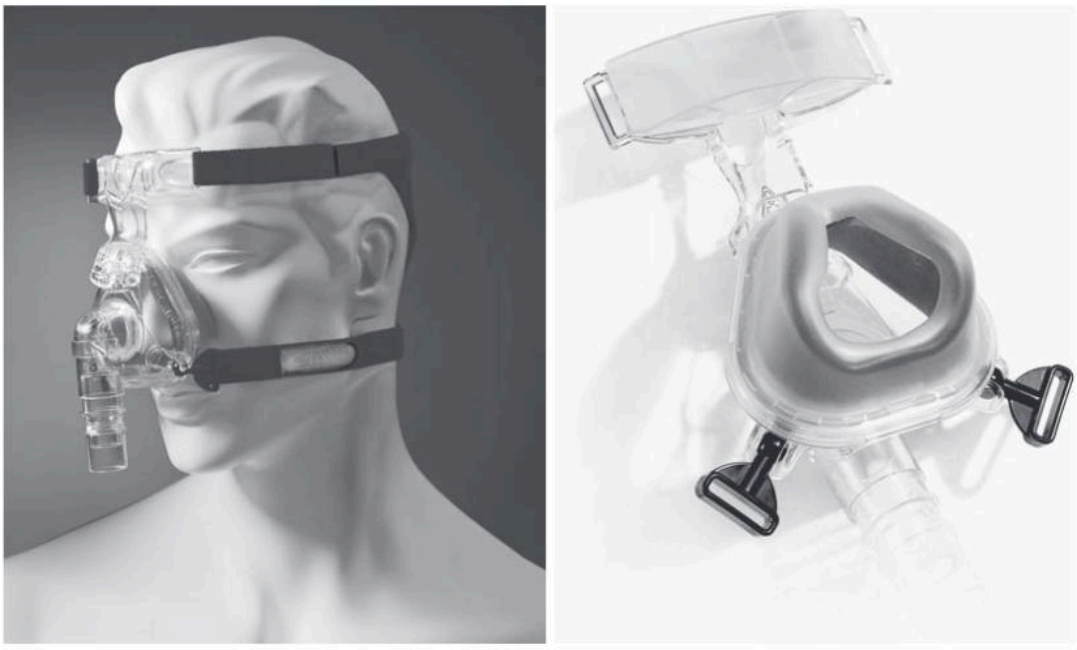

Fig. 19.6 Gel-filled nasal masks. (Courtesy Philips Respironics, The Netherlands.)

Fig. 19.7 Nasal minimask and headgear. (Courtesy Philips Respironics, The Netherlands.)

Fig. 19.8 Nasal pillows and headgear. (Courtesy Covidien-Nellcor Puritan-Bennett, Boulder, Colo.)

that open to allow breathing of room air if the ventilator malfunctions. A typical adult full-face mask has an average dead space volume of 250 mL.[88] The presence of dead space raises the concern of possible CO_2 rebreathing. In addition, the full-face mask does not allow the patient to eat or communicate well or to cough and expectorate secretions without removing the mask. Patients may also have a greater tendency to feel claustrophobic with this type of mask. As with the nasal mask, proper size and fit help ensure patient safety, comfort, and compliance with the therapy. Using a sizing gauge for oronasal masks, the clinician should choose the smallest-size mask that comes closest to the following contact points:

- The area just outside the sides of the mouth
- The area just below the lower lip
- The bridge of the nose (Fig. 19.10)

Fig. 19.9 Full-face mask or oronasal mask. (From ResMed, Poway, Calif.)

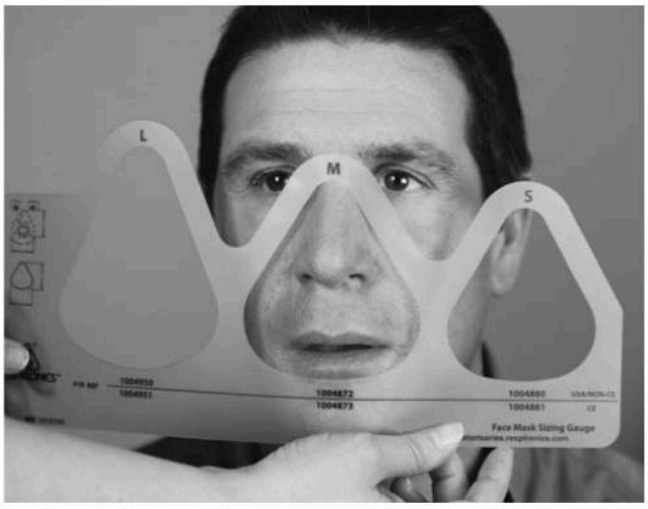

Fig. 19.10 Sizing gauge used to determine proper size of full-face mask. (Courtesy Philips Respironics, Eindhoven, The Netherlands.)

Other alternatives for patients who cannot tolerate nasal or oronasal masks may be the total face mask or helmet. The total face mask consists of a clear, lightweight, plastic faceplate surrounded by a soft inflatable cushion that seals the perimeter of the face and does not obstruct vision (Fig. 19.11). When the mask is connected to a ventilating system, air circulates throughout the entire mask, providing for more comfortable breathing. The incidence of pressure sores is lower because the mask seals the entire face.

The concerns discussed for the full-face mask (aspiration, asphyxiation, and rebreathing) also apply to the total face mask. Like the full-face mask, the total face mask is equipped with a quick-release feature and entrainment valve for room air breathing in case of ventilator malfunction.

The helmet is a transparent cylinder of polyvinyl chloride that fits over the patient's entire head. A metallic ring enclosed within a soft silicone collar seats the cylinder at the patient's neck and shoulders and is further secured by straps under each armpit

Fig. 19.11 Total face mask. (Courtesy Philips Respironics, Eindhoven, The Netherlands.)

(Fig. 19.12). Two hoses attach to the cylinder to allow for gas entering and leaving the hood. Although this device is not currently approved for use in the United States, it has been used successfully in other countries for the treatment of ARF.[89,90]

The helmet has several advantages compared with the full-face mask: less resistance to gas flow, less need for patient cooperation, less interference with speech or coughing, and less skin breakdown. The primary concern with the use of the helmet is potential for CO_2

Fig. 19.12 NIV helmet. (Courtesy StarMed Spa, Biomedical CE, Mirondola, Italy.)

Fig. 19.13 Mouthpiece and seal used to administer continuous positive airway pressure.

rebreathing as a result of the large volume of the cylinder.[89,91] Studies comparing the use of the helmet with the full-face mask have also shown that the helmet is less efficient in decreasing the inspiratory WOB and increases patient–ventilator asynchrony.[91,92]

Oral Interfaces

Mouthpieces and lip seals have been used to provide NIV for many years in patients with chronic respiratory failure (Fig. 19.13). Mouthpieces provide an effective means of ventilation for patients with neuromuscular disorders and may provide an alternative for patients who cannot control mouth leakage during nasal ventilation. Mouthpieces have the advantages of facilitating communication, secretion clearance, and oral intake, and they minimize the problem of CO_2 rebreathing.

Mouthpieces do not usually require the use of headgear or straps. They can often be held in place with the hands or held in the mouth with an orthodontic appliance, especially during daytime hours. Patients with neuromuscular disorders who are confined to a wheelchair often secure their mouthpiece to a gooseneck clamp attached to the chair. It is important to recognize that nasal air leakage is a concern when using mouthpieces and may compromise NIV efficacy. Nose clips may help alleviate this problem. If the mouthpiece is used nocturnally, lip seals can be added over the mouthpiece to prevent leakage during sleep. Also, custom-fitted mouthpieces can prevent leakage and add to the comfort and efficacy of NIV.

SETUP AND PREPARATION FOR NONINVASIVE VENTILATION

After selecting the ventilator and interface or interfaces, the respiratory therapist is responsible for initiating NIV (Box 19.4). Effective ventilation absolutely requires patient cooperation and tolerance; therefore the respiratory therapist must gain the patient's trust and compliance. Carefully explaining the process and repeating the explanations as the process continues can significantly improve patient compliance. The purpose of the interface, goals of the therapy, expected results, and possible complications should be explained clearly using terms the patient can understand.

BOX 19.4 Steps for Initiating Noninvasive Ventilation

1. Place patient in an upright or sitting position. Carefully explain the NIV procedure, including goals and possible complications.
2. Using a sizing gauge, make sure a mask that is the proper size and fit is chosen.
3. Attach the interface and circuit to ventilator. Turn on the ventilator and adjust it initially to low-pressure settings.
4. Hold or allow the patient to hold the mask gently to the face until the patient becomes comfortable with it. Encourage the patient in proper breathing technique.
5. Monitor oxygen (O_2) saturation; adjust the fractional inspired O_2 (F_IO_2) to maintain O_2 saturation above 90%.
6. Secure the mask to the patient. Do not make the straps too tight.
7. Titrate the inspiratory positive airway pressure (IPAP) and expiratory positive airway pressure (EPAP) to achieve patient comfort, adequate exhaled tidal volume, and synchrony with the ventilator. Monitor the peak airway pressure delivered.
8. Check for leaks and adjust the straps if necessary.
9. Monitor respiratory rate, heart rate, level of dyspnea, O_2 saturation, minute ventilation, and exhaled tidal volume.
10. Obtain blood gas values within 1 hour.

The respiratory therapist may want to have several types and sizes of interfaces at the patient's bedside. If a mask is chosen, a fitting gauge can aid in ensuring the proper size and fit. After selecting the appropriate interface, the respiratory therapist turns on the ventilator, attaches the interface to the circuit, and sets initial low-pressure settings. Most often, these include an EPAP pressure of 4 to 5 cm H_2O and an IPAP pressure of 8 to 10 cm H_2O.[6] At this point, the alarms are silenced and the patient is allowed to hold the mask to the face before the headgear is secured.

During the setup, the respiratory therapist should reassure the patient and coach the person in the proper breathing pattern. A different interface or mask size may be necessary if excessive leakage or discomfort occurs. Once the patient is comfortable and his or her breathing has become synchronized with the ventilator, the headgear straps are adjusted to ensure a snug, secure fit. The straps should not be too tight because this increases leakage from the mask (as mentioned previously, if the interface has been properly secured, the respiratory therapist should be able to slip at least one finger under the straps). Once ventilation has been established and the patient's comfort is ensured, the respiratory therapist can further assess the patient and the effectiveness of the patient-ventilator system.

MONITORING AND ADJUSTMENT OF NONINVASIVE VENTILATION

Several studies have identified potential indicators of success for patients on NIV in both the acute and chronic care setting

BOX 19.5 Predictors of Success With Noninvasive Ventilation

- Higher level of consciousness
- Younger age
- Less severe illness; no comorbidities
- Less severe gas exchange abnormalities (pH 7.10–7.35; arterial partial pressure of carbon dioxide [P_aCO_2] <92 mm Hg)
- Minimal air leakage around the interface
- Intact dentition
- Synchronous breathing efforts with ventilator
- Lower quantity of secretions
- Absence of pneumonia
- Positive initial response to NIV within 1 to 2 hours
  - Correction of pH
  - Decreased respiratory rate
  - Reduced P_aCO_2

(Box 19.5).[93-95] In the acute care setting, NIV is more likely to be successful in patients who are alert and cooperative, can protect the airway, and have not yet developed severe acid–base or gas exchange abnormalities than it is in patients who are limited in any of these. The patient's initial response to NIV may be the most significant indicator of success or failure. For this reason, close bedside monitoring of the patient's vital signs and respiratory status begins as soon as NIV is instituted and continues until the patient's respiratory status has stabilized (Case Study 19.1).

Patient tolerance and comfort with the system are important to ensuring the effectiveness of NIV at alleviating respiratory distress. Clinically, improvement in patient comfort is indicated by a decrease in respiratory rate, reduced inspiratory muscle activity, and synchronization with the ventilator. If these indicators are absent, the respiratory therapist must take steps to ensure the patient's comfort, such as refitting or changing the mask to reduce air leakage, encouraging and coaching the patient in the proper breathing pattern, or adjusting ventilator settings (Key Point 19.10).

***Key Point* 19.10** Improvement in patient comfort is indicated by a decreased respiratory rate, decreased inspiratory muscle activity, and synchronization with the ventilator.

Case Study 19.1

Patient Selection for Noninvasive Ventilation

A 72-year-old woman with a history of COPD is receiving NIV for ventilatory failure secondary to postoperative pneumonia. The patient is wearing a full-face mask but is having difficulty swallowing and coughing. She appears weak and has become more agitated and confused in the past hour. The respiratory rate is 24 breaths/min, and the S_pO_2 is 92%. O_2 is being bled into the patient's mask at the rate of 5 L/min. What action should be taken at this time?

Case Study 19.2

Monitoring and Adjusting Noninvasive Ventilation

A 71-year-old, 176-lb (80-kg) man is admitted to the ICU for an acute exacerbation of COPD. On admission he was tachypneic and dyspneic, as evidenced by a respiratory rate of 30 beats/min and the use of accessory muscles of respiration. Arterial blood gas values with nasal O_2 at 2 L/m were as follows: pH = 7.31, P_aCO_2 = 56 mm Hg, P_aO_2 = 49 mm Hg. The attending physician ordered NIV in an attempt to normalize the pH. The respiratory therapist initiates NIV with a full-face mask at the following settings: A/C mode; respiratory rate *(f)* = 12 breaths/min; IPAP = 10 cm H_2O; EPAP = 4 cm H_2O; and O_2 at 3 L/min bled into the circuit at the machine outlet.

After 1 hour on NIV, the patient complains of some dyspnea and discomfort and has a respiratory rate of 26 breaths/min. The average exhaled tidal volume is approximately 310 mL. The full-face mask appears to fit well, and no significant leaks are detected. Arterial blood gases at this time are pH = 7.32, P_aCO_2 = 53 mm Hg, P_aO_2 = 59 mm Hg, and S_aO_2 = 90%. What changes, if any, should be made in the current settings to make the patient more comfortable and help normalize pH?

Insufficient IPAP levels often result in sustained or increased respiratory rates caused by inadequate V_T delivery. Patient–ventilator synchrony may be improved by adjusting rise time, inspiratory sensitivity, and expiratory flow cycling percentage (if available) and by carefully increasing EPAP to offset possible intrinsic PEEP. If EPAP is increased, IPAP may also need to be increased to maintain the same gradient between IPAP and EPAP and thus ensure adequate V_T delivery. Low doses of sedative may also be necessary to assist patient compliance (Case Study 19.2).

Oxygenation and heart rate are monitored continuously with pulse oximetry. The F_IO_2 is adjusted to maintain S_pO_2 at 90% to 92%. Shortly after initiation of NIV (1–2 hours), the adequacy of ventilatory support is determined by arterial blood gas (ABG) measurements. Patients showing an improved pH and P_aCO_2 are more likely to avoid intubation.[94,95] However, the P_aCO_2 may take longer to decrease in some patients, particularly those with chronic hypercapnia. This should not cause alarm as long as the patient is showing clinical improvement in oxygenation and a decrease in respiratory distress.

A patient in ARF is closely observed in an acute care setting (ICU, emergency department) so that if NIV is unsuccessful, other means of support are readily available. Attempts at NIV are terminated in favor of invasive measures if the pH and P_aCO_2 continue to worsen or show no improvement and are accompanied by respiratory distress, worsening level of consciousness, hemodynamic instability, or worsening oxygenation. Other measures of support may be necessary if the patient cannot tolerate any of the types or sizes of interfaces or is unable to clear secretions and protect the airway (Box 19.6).

Some patients require NIV on a long-term, intermittent basis (e.g., as for OSA). The focus of monitoring in these patients is to alleviate the signs and symptoms associated with chronic hypoventilation and impaired sleep, such as fatigue, daytime somnolence, morning headache, and dyspnea. In some cases, signs and

BOX 19.6 Criteria for Terminating NIV and Switching to Invasive Mechanical Ventilation

1. Worsening pH and arterial partial pressure of carbon dioxide (P_aCO_2)
2. Tachypnea (>30 breaths/min)
3. Hemodynamic instability
4. Pulse oximeter O_2 saturation (S_pO_2) less than 90%
5. Decreased level of consciousness
6. Inability to clear secretions
7. Inability to tolerate interface

Case Study 19.3

Common Complications of Noninvasive Ventilation

A 68-year-old man with severe stable COPD and OSA has been receiving NIV via nasal mask for approximately 3 months. Follow-up ABG analysis and continuous nocturnal oximetry do not show any significant improvement in gas exchange or the frequency of sleep-related events. When questioned about his use of the NIV system, the patient admits he uses the system only for about 2 hours because of uncomfortable nasal dryness and sinus pain. The respiratory therapist examines the patient's NIV equipment and notes that it includes an unheated pass-over humidifier and that the nasal mask appears to fit well without significant leakage. What can be done to increase the patient's comfort and tolerance with the NIV system?

symptoms of **cor pulmonale** associated with chronic hypoxemia may also be present, such as distended neck veins, enlarged liver, and peripheral edema. Alleviation of these signs and symptoms may take several days or weeks and depend mainly on the patient's comfort, tolerance, and compliance with the NIV system. Efforts are made to maximize patient comfort by choosing a well-fitting and comfortable interface and headgear and by initiating short trials of NIV and slowly increasing the patient's time on the system. Once a patient can tolerate the NIV system for 4 to 6 hours per 24 hours, signs and symptoms are likely to improve.

Objective evidence (e.g., continuous nocturnal oximetry, ABGs) may reveal an improvement in gas exchange and a decrease in or complete cessation of the number of sleep-related respiratory events. If no improvement is seen after about 4 to 6 weeks, the clinician should attempt to determine the reasons for failure. These may include lack of motivation and compliance because of discomfort, advanced age, the existence of comorbidities and cognitive defects, or the need for additional therapeutic efforts[72] (Case Study 19.3).

AEROSOL DELIVERY IN NONINVASIVE VENTILATION

The administration of aerosolized bronchodilators is often necessary for patients receiving NIV, especially those with obstructive airway disease. Patients may be removed from the ventilator and given aerosolized medications via nebulizer or pressurized metered-dose inhaler (pMDI) with a spacer in the traditional manner, but this may cause rapid deterioration of the patient's condition.

BOX 19.7 Factors Affecting Aerosol Delivery During Noninvasive Ventilation

1. Type of aerosol generator (SVN vs. VMN vs. MDI)
2. Position of the leak port
3. Synchronization of MDI actuation with inspiration
4. IPAP and EPAP levels
5. Presence or absence of a humidifier in the circuit

Medications (e.g., bronchodilators) can be administered in line with the NIV using a small-volume nebulizer (SVN), a vibrating mesh nebulizer (VMN), or pMDI with a spacer. A number of studies have shown that each device can be an effective means of delivering medications to patients, but clinicians should be aware of the factors that affect the efficiency of aerosol delivery (Box 19.7). These factors include the type of circuit and ventilator settings used, the position of the aerosol generator in relation to the leak port, and the type of aerosol generators and interface used during the treatment.[96-100]

Ventilator settings affect delivery and response to bronchodilators during NIV, with higher peak inspiratory pressure associated with greater deposition as opposed to an increase in expiratory pressure, which leads to a decrease in aerosol delivery. Previous studies had shown that the efficiency of aerosol delivery was similar for either a nebulizer or an MDI when the leak port is located in the circuit and the aerosol device is placed between the leak port and mask[98] (Fig. 19.14). If the leak port is located in the mask, aerosol delivery from a pMDI is more efficient than from a nebulizer provided the MDI is actuated at the beginning of inspiration. When NIV is delivered through a conventional ventilator circuit and mask with no leak, aerosol methods used with continuous mechanical ventilation apply.

It is also worth noting that studies indicate that the percentage of drug delivery is lower with SVN compared with pMDI or VMN and that the amount of drug delivered with the vibrating mesh nebulizer is greater than with either an SVN or a pMDI.[97-100]

Aerosol delivery to the lower airways is less effective when administered through a humidified circuit during invasive ventilation. It is reasonable to suggest that the use of a humidified circuit with NIV would likely give similar results, although this effect has not been studied with NIV.

Nasal masks or full-face masks present additional problems during aerosol delivery. Air leaks in the mask or circuit cause continuous flow in the circuit to increase, which may potentially increase aerosol loss. The volume of the mask itself increases the potential for a larger portion of the aerosol dose to deposit on the face or in the eyes of the patient. For this reason, aerosol therapy is not recommended when a total face mask or helmet is being used to administer NIV.[101]

COMPLICATIONS OF NONINVASIVE VENTILATION

NIV is considered much safer than invasive mechanical ventilation. Complications with NIV are usually related to mask

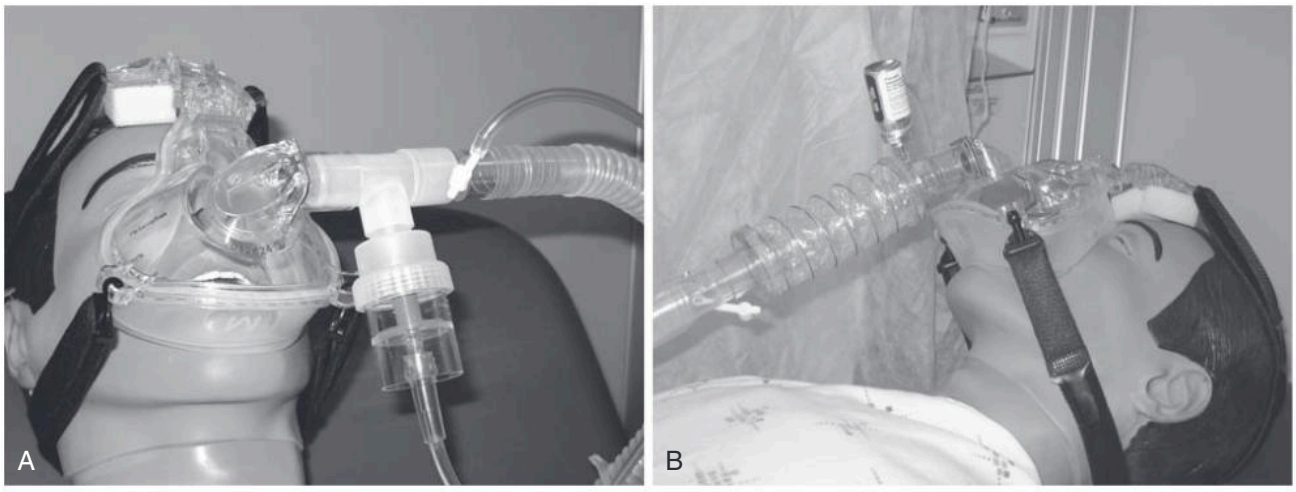

Fig. 19.14 (A) Position of small-volume nebulizer between leak port in the circuit and the noninvasive ventilation (NIV) mask. (B) Position of metered-dose inhaler spacer between leak port in the circuit and the NIV mask.

discomfort, air pressures, or gas flows. Serious complications can occur, such as aspiration pneumonia, pneumothorax, and hypotension, but they are unlikely if patient selection guidelines are closely followed. If the NIV is to be successful, the respiratory therapist must be knowledgeable about all potential complications and take the proper course of action to prevent or minimize their occurrence.

Mask discomfort is the most common complication of NIV. Air leaks around the mask often result in eye irritation. In addition, the strap pressure required to maintain an airtight fit often creates excessive pressure over the bridge of the nose and cheek area. Pressure sores may develop, leading to skin breakdown and ulceration of the nasal bridge. To correct this problem, the respiratory therapist first checks the mask for proper size and fit, making sure that the mask is not too large and that headgear tension has been minimized as much as possible. Forehead spacers or wound-care dressing or both may alleviate pressure on the nasal bridge and protect the skin. A change to a different style of mask or headgear system or a complete change of interface may be required in some cases. Nasal gel masks, bubble-type masks, and masks with added plastic flaps are designed to facilitate a better seal with lower headgear strap tensions.

Nasal pillows or nasal seals can also be used to relieve pressure on the nasal bridge, but they can become uncomfortable because of pressure on the nares. If this occurs, alternating between interface styles may help, especially when NIV is to be used long term.

Another common complaint from patients who use nasal masks is nasal and oral dryness or nasal congestion from high flows through the mask and air leakage through the mouth. Adding or increasing humidification or irrigating the nasal passages with saline may prove helpful. If congestion persists, topical nasal decongestants or steroids can be used. A chinstrap may help with oral dryness because of air leakage through the mouth for patients who have nasal masks. These straps keep the patient's mouth closed and minimize leakage, thus reducing the airflow to the mask. If chinstraps are not effective at reducing leakage through the mouth, a change to an oronasal mask may be better because it covers both the nose and mouth. However, oronasal masks are subject to the same skin contact problems as nasal masks and may also increase claustrophobic reactions.

Oral interfaces (mouthpieces and lip seals) are associated with minor complications, such as oral discomfort, hypersalivation, and leakage of air from the nose. Most of these problems diminish with fitting adjustments and patient adaptation. If leakage is sufficient to compromise the efficacy of NIV, nose clips may alleviate the problem. Patients who prefer mouthpieces for NIV probably will invest in a custom-made mouthpiece. These may prove to be more tolerable for chronic long-term use of NIV.

Regardless of the interface used, gastric insufflation is a common occurrence in about 50% of all patients using NIV; however, it is rarely intolerable. Gastric insufflation is more likely to occur in patients using volume ventilation.[102] In such cases, gas in the stomach is probably the result of the higher pressure needed for V_T delivery. For the most part, gas insufflation does not cause major problems and usually diminishes in time or with the administration of **simethicone agents**.

A serious potential complication of NIV is aspiration pneumonia, which is most likely to occur if vomitus is retained in the mask when an oronasal mask is used. Some clinicians recommend that a nasogastric tube be used with an oronasal mask, particularly in patients with excessive gastric distention, nausea, and vomiting.[1] As mentioned previously, aspiration is best prevented through careful selection of patients who are able to cough and protect the airway.

Other major complications of NIV include mucus plugging, hypoxemia, hypotension, and respiratory arrest. Mucus plugging is more likely to occur if the patient is dehydrated or has difficulty expectorating secretions or if humidification is inadequate. High O_2 flow rates (up to 40 L/min) have been associated with life-threatening airway obstruction caused by **inspissated secretions**.[103] The risk for mucus plugging can be minimized if patients are kept well hydrated and appropriate adjunct therapies are applied to assist with secretion removal. Patients with neuromuscular disorders who have impaired cough mechanisms may benefit from cough-assistive techniques. Inline aerosolized bronchodilators and heated humidity may also aid secretion removal in most patients.

Hypoxemia is more likely to occur in patients with hypoxemic respiratory failure who require high O_2 concentrations. Most portable PTVs cannot achieve consistent F_IO_2 levels above 50% unless O_2 is bled into the system at abnormally high flow rates, which may interfere with patient synchrony and alter the pressure and flow delivery from the ventilator. Mucus plugging, agitation, and failure to keep the mask on the patient's face also have been linked to hypoxemia. The appearance of any of these contributing factors may be an indication to change to invasive mechanical ventilation.

Hemodynamic complications rarely occur during the administration of NIV or CPAP because low inflation pressures are used with these techniques. Hypotension, when it occurs, is usually seen in patients with low intravascular fluid volume or underlying cardiac disease. Hypotension rarely occurs in patients with COPD but may result if high levels of auto-PEEP develop.

Patients with ACPE may benefit from increased intrathoracic pressures, which reduce venous return and subsequently ventricular preload. However, if ventricular preload declines markedly, organ perfusion may be compromised. Careful selection of initial pressures and close monitoring may reduce the risk for cardiac ischemia in these patients. Table 19.4 summarizes the complications associated with CPAP and NIV.

TABLE 19.4 Complications Associated With Mask Continuous Positive Airway Pressure/ Noninvasive Ventilation Therapy

Complications	Corrective Actions
Mask discomfort	Check mask for correct size and fit
Excessive leaks around mask	Minimize headgear tension Use spacers or switch mask style
Pressure sores	Use wound-care dressing over nasal bridge
Nasal/oral dryness or nasal congestion	Add or increase humidification Irrigate nasal passages with saline Apply topical decongestants Use a chinstrap to keep the mouth closed Change to full-face mask
Mouthpiece/lip seal leakage	Use nose clips Use custom-made oral appliances
Aerophagia, gastric distention	Use lowest effective pressures for adequate V_T delivery Use simethicone agents
Aspiration	Adhere to proper selection of patients who can protect their own airway
Mucus plugging	Ensure adequate patient hydration Ensure adequate humidification Avoid excessive oxygen flow rates (>20 L/min) Allow short breaks from NIV to permit directed coughing techniques
Hypotension	Avoid excessively high peak pressures (≤20 cm H_2O)

DISCONTINUING NONINVASIVE VENTILATION

The duration of ventilatory assistance with NIV depends on how quickly the cause of respiratory failure can be reversed. In most patients with ARF, successful weaning from NIV may occur within hours or a few days.[45] Standard weaning techniques have not been established, but the most common approach involves increasing periods off mask ventilation.

Once the patient's condition is stabilized, the mask may be removed for short periods according to the patient tolerance. Supplemental O_2 is administered as needed during these times off the ventilator. The patient is closely monitored for signs of respiratory distress and fatigue.

If signs of respiratory distress occur, the patient is placed back on mask ventilation immediately. Prolonging these periods of ventilator interruption when the patient is experiencing respiratory distress may lead to rapid decompensation and the need for emergency intubation.

In the same manner as spontaneous breathing trials, periods off the ventilator lengthen as the underlying condition improves and the patient shows acceptable vital signs, good gas exchange, and no respiratory distress. (See Chapter 20 for information on spontaneous breathing trials.)

Another approach to NIV weaning is applied in the same manner as weaning from pressure support ventilation during invasive ventilation. IPAP is gradually reduced to a minimum level, allowing the patient to assume more of the WOB. Once the minimum level has been reached, NIV can be discontinued.

Regardless of the weaning method used, the reversibility of the disease process that caused ARF is the most important consideration for successful weaning. Some patients, especially those with chronic hypercapnia and impaired ventilatory function, may continue to use NIV nocturnally after recovering from an acute exacerbation.

PATIENT CARE TEAM CONCERNS

The success of NIV depends on time and commitment from the members of the patient care team. All members of this team must thoroughly understand the indications, benefits, and complications of NIV. As a critical member of this team, the respiratory therapist often must commit considerable time to initiating and monitoring NIV. Studies have shown that more time is required during an initial 8-hour shift to institute NIV than to establish conventional invasive ventilation.[104-106] The extra time is required to fit the patient properly with an interface and to monitor and adjust ventilator settings. Time and patience are also required to remain at the bedside and to instruct patients carefully to obtain their full cooperation. Once the patient's condition has stabilized, this time requirement usually decreases.

SUMMARY

- NIV is an important option for patients requiring mechanical ventilation.
- The three basic methods of applying NIV are negative pressure ventilation, abdominal-displacement ventilation, and positive pressure ventilation.

- The physiological goal of NIV in ARF is to improve gas exchange by resting the respiratory muscles and increasing alveolar ventilation.
- The most significant benefit of using NIV in treating ARF caused by COPD is the avoidance of intubation, which in turn can lead to longer hospital stays, higher mortality, and increased health care costs.
- NIV may improve daytime gas exchange and symptoms associated with chronic hypoventilation for patients who continue to hypoventilate despite CPAP therapy.
- NIV can be used to reduce the WOB and maintain adequate gas exchange in patients who show fatigue after extubation.
- Patients with terminal or advanced disease who develop ARF are not good candidates for endotracheal intubation and mechanical ventilation. NIV may relieve severe dyspnea in these patients and help ensure patient comfort.
- In the acute care setting, the selection process for NIV must be based on the patient's diagnosis, clinical characteristics, and the risk for failure.
- Establishment of the need for intermittent ventilatory assistance in patients with chronic respiratory failure should begin with the recognition of the typical symptoms of nocturnal hypoventilation and poor sleep quality.
- NIV should be initiated if patients with moderate to severe OSA do not respond favorably to CPAP.
- Excessive drying of nasal mucosa is a common complaint of patients receiving nasal CPAP or NIV. Proper humidification can prevent or improve mucosal dehydration.
- The type of interface used to deliver positive pressure to the airway can influence the effectiveness of NIV. Nasal masks have considerably less mechanical dead space than full-face masks, thus reducing the potential for rebreathing CO_2.
- NIV is more likely to be successful in the acute care setting for patients who are alert and cooperative, can protect the airway, and have not yet developed severe acid–base or gas exchange abnormalities.
- Potential complications of NIV include aspiration pneumonia, mucus plugging, hypoxemia, hypotension, and respiratory arrest.

REVIEW QUESTIONS *(see Appendix A for answers.)*

1. NIV has just been initiated on a patient in respiratory distress with an IPAP pressure of 12 cm H_2O and an EPAP pressure of 5 cm H_2O. Which of the following would indicate clinical improvement of the patient's condition?
1. Increased respiratory rate
2. Synchronization with the ventilator
3. Decreased inspiratory muscle activity
4. Decreased S_aO_2

A. 1 and 2 only
B. 2 and 3 only
C. 2, 3, and 4
D. 1, 2, 3, and 4

2. Which of the following patients would *not* be a good candidate for nasal-mask NIV?
A. A patient with a pH of 7.34
B. A patient with stable COPD and OSA
C. A patient with an absent cough reflex
D. A patient who requires nocturnal NIV only

3. A patient has been on nasal-mask NIV for almost 24 hours. The patient is now complaining of nasal congestion and a dry mouth. Which of the following would you recommend?
A. Reduce the inspiratory flow
B. Change to a full-face mask
C. Begin inline aerosol treatments
D. Add a heated humidifier

4. A patient may benefit from the nocturnal application of NIV if which of the following symptoms is present?
1. Morning headache
2. Daytime hypersomnolence
3. Aching and stiff joints
4. Nocturnal desaturation

A. 1 and 2 only
B. 1, 2, and 4
C. 1, 2, 3, and 4
D. 1 and 4 only

5. A patient has been on NIV with a nasal mask for the past hour. The patient is still experiencing significant leaking around the mask. Which of the following would be the most appropriate action to take at this time?
A. Change to a full-face mask
B. Tighten the head straps
C. Intubate and begin invasive mechanical ventilation
D. Add a heated humidifier to the circuit

6. The best way to prevent aspiration during NIV is to:
A. Insert a nasogastric tube before NIV application
B. Use only a nasal mask for application
C. Adhere to proper selection guidelines
D. Use delivery pressures less than 10 cm H_2O

7. Which of the following are reported to be advantages of using a portable pressure-targeted ventilator in the delivery of NIV?
1. Variable flow delivery capabilities
2. Leak compensation
3. Adjustable inspiratory and expiratory sensitivity
4. Sophisticated alarm systems

A. 1 and 2 only
B. 1, 2, and 3
C. 2, 3, and 4
D. 1, 2, 3, and 4

8. Which of the following would result in the lowest F_IO_2 during the administration of NIV when O_2 is bled into the circuit of a portable pressure-targeted ventilator?
A. Bleeding O_2 into the mask when the leak port is located in the mask
B. Bleeding O_2 into the mask when the leak port is located in the circuit
C. Bleeding O_2 into the circuit when the leak port is located in the circuit
D. Bleeding O_2 into the circuit and sealing the leak

9. Which of the following ventilator settings would most likely result in rebreathing of CO_2?
A. EPAP levels >6 cm H_2O
B. EPAP levels <4 cm H_2O
C. IPAP levels >6 cm H_2O
D. CPAP levels >6 cm H_2O

10. The physiological benefits of NIV include which of the following?
A. Decrease in P_aCO_2 levels
B. Decrease in P_aO_2 levels
C. Decrease in HCO_3^- levels
D. Increase in use of accessory muscles

11. A patient is admitted to the coronary ICU for acute cardiogenic pulmonary edema. The physician wants to use noninvasive ventilatory support in the treatment of this patient's condition. Which following modes of ventilatory support would be most appropriate to use at this time?
1. PSV
2. Bilevel NIV
3. CPAP
4. PSV and PEEP
A. 1 and 3 only
B. 2 and 3 only
C. 2, 3, and 4
D. 1, 2, 3, and 4

12. The highest level of evidence now supports the use of NIV as a standard of care in the treatment of:
A. Community-acquired pneumonia
B. Severe but stable COPD
C. Acute asthma
D. Acute exacerbations of COPD

13. A patient has been on NIV for 1 hour in the assist mode only. Ventilator settings include IPAP at 8 cm H_2O and EPAP at 4 cm H_2O. O_2 is being bled into the circuit at 4 L/min. The patient's ABGs after 1 hour reveal pH = 7.34, P_aCO_2 = 62 mm Hg, and P_aO_2 = 62 mm Hg. The patient's respiratory rate is 27 breaths/min and S_pO_2 is 92%. There is minimal leaking around the face mask. What would be the most appropriate ventilator change to make at this time?
A. Increase EPAP level to 8 cm H_2O
B. Decrease EPAP level to 2 cm H_2O
C. Increase IPAP level to 10 cm H_2O
D. Decrease IPAP level to 6 cm H_2O

14. All of the following may increase CO_2 rebreathing during NIV *except:*
A. Use of a full-face mask
B. Low EPAP pressure levels
C. Patient breathing pattern
D. High inspiratory flow rates

15. Clinical benefits of NIV in an acute care setting include which of the following?
1. Lower incidence of ventilator-associated pneumonia
2. Improved patient comfort
3. Reducing staff time in the care of patients with COPD
4. Lower intubation rate
A. 1 and 2 only
B. 2 and 3 only
C. 1, 2, and 4
D. 1, 2, 3, and 4

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CHAPTER 20

Weaning From and Discontinuation of Mechanical Ventilation

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KEY TERMS

- Adaptive support ventilation
- Automatic tube compensation
- Mandatory minute ventilation
- Respiratory alternans
- Weaning

LEARNING OBJECTIVES

On completion of this chapter, the reader will be able to do the following:

1. List the weaning parameters and acceptable values for ventilator discontinuation.
2. Compare the three standard modes of weaning in relation to their success in discontinuing ventilation.
3. Define the closed-loop modes of weaning described in the chapter.
4. Recognize appropriate use of closed-loop modes of weaning based on the description of a clinical setting.
5. Identify assessment criteria for discontinuing a spontaneous breathing trial in a clinical situation.
6. Describe criteria used to determine whether a patient is ready for extubation.
7. Recognize postextubation difficulties from a clinical case description.
8. Recommend appropriate treatment for postextubation difficulties.
9. State the first recommendation for weaning a patient from mechanical ventilation established by the task force formed by the American College of Chest Physicians, the Society of Critical Care Medicine, and the American Association for Respiratory Care.
10. Describe an appropriate treatment for a patient with an irreversible respiratory disorder that requires long-term ventilation.

11. Name the parameter used as the primary index of drive to breathe.
12. Suggest adjustments to ventilator settings during use of a standard weaning mode based on patient assessment.
13. Explain the appropriate procedure for management of a patient for whom a spontaneous breathing trial has failed.
14. Explain the function of long-term care facilities in the management of ventilator-dependent patients.
15. Assess data used to establish the probable cause of failure to wean.

WEANING TECHNIQUES

Patients require mechanical ventilation when their ability to support ventilatory demands is outweighed by a disease process or when the respiratory drive is inadequate to maintain ventilation because of disease or medications (Fig. 20.1).[1,2] Ventilation can be discontinued after the need for mechanical ventilation has been resolved. This is typically a straightforward maneuver for most patients. The ventilator is simply disconnected from the patient, and the endotracheal tube (ET) is removed. About 80% of patients requiring temporary mechanical ventilation do not require a gradual withdrawal process and can be disconnected within a few hours or days of initial support.[3,4] Examples of this type of temporary ventilation include postoperative ventilatory support for recovery from anesthesia, treatment of uncomplicated drug overdose, and exacerbations of asthma.[3] For patients who have undergone invasive mechanical ventilation for less than a week, discontinuation is typically a quick process. However, for some patients, the process can be lengthy and complex.[5]

The term **weaning** is frequently used to describe the gradual reduction of ventilatory support from a patient whose condition is improving.[1,2,4-7] Some practitioners prefer terms such as discontinuation, gradual withdrawal, or liberation.[1] Regardless of the terminology, the process is the same (Key Point 20.1).

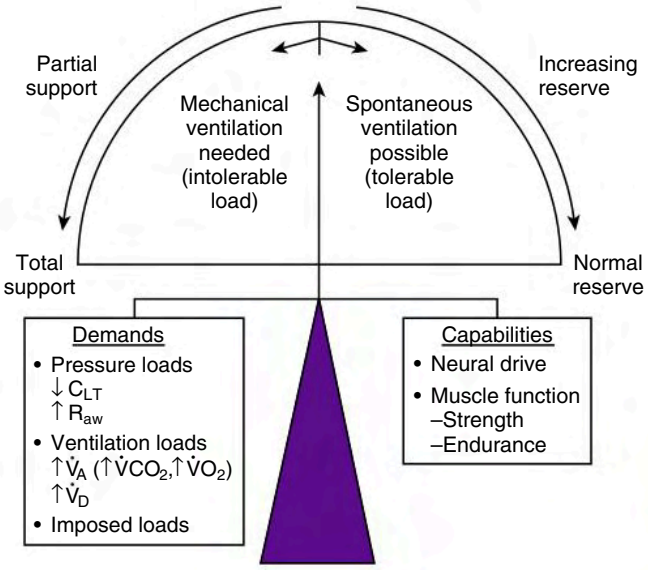

Fig. 20.1 Schematic of the balance between a patient's respiratory capabilities and demands. When demands outweigh capabilities, the balance shifts to the left and a higher level of ventilatory support is needed. As the patient's condition improves, the balance shifts to the right. The clinical challenges are twofold: (1) to recognize when ventilatory assistance is no longer needed and (2) to provide an appropriate level of assistance until that happens. C_{LT}, Compliance of the lungs and thorax; R_{aw}, airway resistance; $\dot{V}_A$, alveolar ventilation; $\dot{V}CO_2$, carbon dioxide production; $\dot{V}_D$, dead space ventilation; $\dot{V}CO_2$, oxygen consumption. (Modified from MacIntyre NR: Psychological factors in weaning from mechanical ventilatory support, *Respir Care* 40:277—281, 1995.)

***Key Point* 20.1** Weaning is frequently used to describe the gradual reduction of ventilatory support from a patient whose condition is improving. Other terms that are used to describe this process include discontinuation, gradual withdrawal, or liberation.

Several facts must be taken into consideration if ventilation is to be discontinued successfully. First, patients may require ventilatory support during weaning. Second, supplemental oxygen (O_2) and positive end-expiratory pressure (PEEP) may be required to support oxygenation. Third, some individuals may require maintenance of the artificial airway even after ventilatory support has been discontinued. Fourth, many patients require more than one of these therapeutic interventions. Although each of the first three components mentioned can be treated separately, they are an integral part of the overall process of ventilator discontinuation (Box 20.1).[6,7]

Ventilatory support should be discontinued and the artificial airway removed as soon as possible to avoid the risks associated with mechanical ventilation, such as ventilator-induced lung injury, ventilator-associated pneumonia (VAP), airway trauma from the ET, and unnecessary sedation. However, it is important to recognize that premature withdrawal of ventilatory support or of the airway can result in ventilatory muscle fatigue, compromised gas exchange, and loss of airway protection.[1] Premature discontinuation is also associated with a higher mortality rate.[8-10]

The decision to wean a patient from the ventilator depends on the patient's level of recovery from the medical problems that imposed the need for mechanical ventilation and the patient's overall clinical condition and psychological state. Therefore the patient's physiological capacity and mental and emotional status must be evaluated before an attempt is made to remove the patient from ventilatory support.

BOX 20.1 Components of Ventilatory Management and Discontinuation

- Positive pressure ventilation (PPV) to support breathing
- Supplemental O_2 and positive end-expiratory pressure (PEEP) to improve oxygenation
- Artificial airway to protect the airway and provide invasive ventilation
- Airway management to maintain clear airways (i.e., suctioning; humidification and warming of inspired air; bronchial hygiene; and aerosolized medications)
- Therapy directed at the primary disease process

This chapter reviews ventilator techniques used during weaning from ventilatory support, in addition to evidence-based recommendations for determining whether a patient meets the criteria for ventilator discontinuation. A discussion of the process of weaning, clinical conditions that may compromise a patient's ability to be weaned, and the introduction to long-term care when a patient cannot be weaned are also presented.

METHODS OF TITRATING VENTILATOR SUPPORT DURING WEANING

Ventilatory support can be reduced as a patient becomes increasingly able to resume part of the work of breathing (WOB). Three approaches have been commonly used to reduce ventilatory support and gradually place more of the WOB on the respiratory muscles: intermittent mandatory ventilation (IMV), pressure support ventilation (PSV), and T-piece weaning. Until the early 1990s, the three methods were considered equally effective.[11] More recent studies have clearly shown that the weaning process was inordinately prolonged with IMV compared with other weaning techniques.[10,12] Despite these findings, a substantial number of physicians continue to use IMV to wean patients from mechanical ventilatory support.[13]

In addition to these traditional methods, more sophisticated forms of closed-loop ventilation have been introduced for weaning patients. These include volume-targeted PSV (e.g., volume support), automode, **mandatory minute ventilation** (MMV), **automatic tube compensation**, and artificial intelligence systems.

Intermittent Mandatory Ventilation

Intermittent mandatory ventilation (IMV) was first introduced in the 1960s as a method to provide ventilation to infants afflicted with idiopathic respiratory distress syndrome. The first IMV systems used to wean adult patients from mechanical ventilation were introduced in the 1970s. Fig. 20.2 shows a diagram of a volume ventilator with an added continuous-flow IMV circuit used for adult patients. A blended gas source is directed into a reservoir bag (3-L anesthetic bag). The IMV circuit connects this reservoir to the ventilator circuit by means of a one-way valve. The one-way valve prevents a positive pressure breath, generated by the machine, from entering the reservoir bag. This system allows a continuous flow of gas from the reservoir bag through the humidifier and the main inspiratory line to the patient. During a positive pressure breath, the high pressure closes the one-way valve, preventing machine air from entering the reservoir bag and allowing the mandatory ventilator breath.

Synchronized intermittent mandatory ventilation (SIMV) was later introduced as a method to synchronize a patient's efforts with the mandatory breaths provided by the ventilator during IMV. The theory underlying IMV/SIMV is that the patient's respiratory muscles would work during spontaneous breathing intervals and rest during mandatory breaths.[14] (NOTE: Modern microprocessor ventilators have incorporated this technology into their devices and the term *IMV* is simply used to describe mechanical ventilators that offer either SIMV or IMV.)

A common weaning practice with IMV is to reduce the mandatory rate progressively, usually in steps of 1 or 2 breaths/min and at a pace that matches the patient's improvement. PSV can be added to unload the spontaneous breaths and reduce the patient's WOB through the ventilator system, circuit, and artificial airway, which in turn can help prevent excessive fatigue (Case Study 20.1). Use of pressure support is especially important when the IMV rate is low (i.e., less than 4–6 breaths/min). The level of PSV used during IMV typically ranges from 5 to 10 cm H_2O; the set pressure usually depends on assessment of the spontaneous

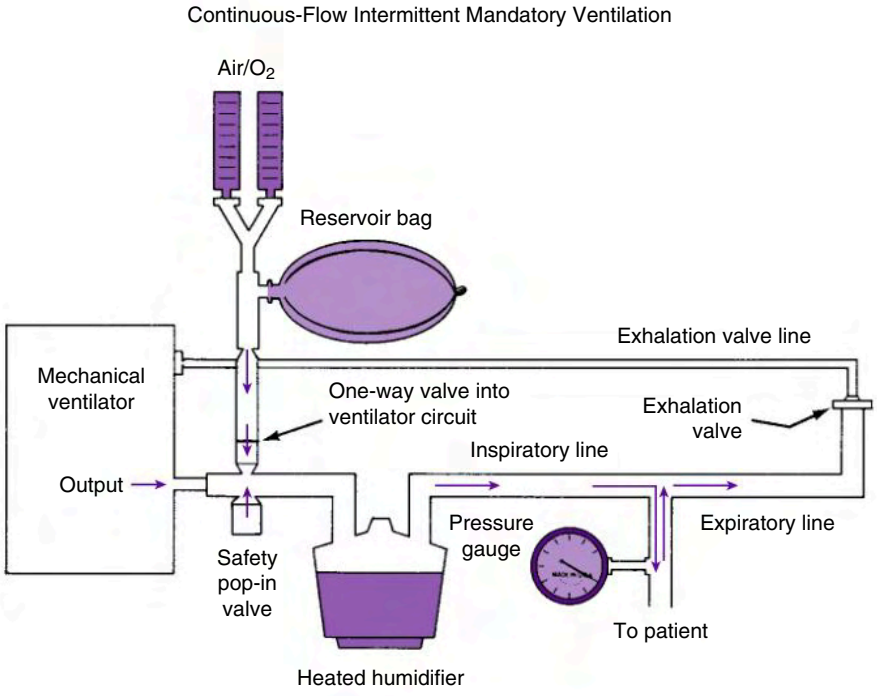

Fig. 20.2 Schematic illustrating the gas flow through a prototype intermittent mandatory ventilation circuit. See text for details.

Case Study 20.1

Evaluation of Weaning Attempt

A patient who appears to be ready for discontinuation of ventilatory support is being weaned with IMV. The following data indicate the patient's progress. No pressure support ventilation or continuous positive airway pressure is used to support spontaneous breaths.

Time	Set V_T (mL)	Spontaneous V_T (mL)	IMV Rate (breaths/min)	Spontaneous Respiratory Rate (breaths/min)
07:00	800	400–500	6	6
12:00	800	400–500	4	12
16:00	800	350–400	2	18
20:00	800	275–325	1	30

IMV, Intermittent mandatory ventilation; V_T, tidal volume.

Do you think the patient is being managed correctly during the weaning process? If not, what would you recommend?

tidal volume (V_T) achieved and the apparent WOB. PEEP of 3 to 5 cm H_2O is also used to help compensate for changes in functional residual capacity (FRC) associated with the use of an ET and the recumbent position.[15,16]

In reality, the respiratory muscles may perform significant work with both mandatory and spontaneous breaths during IMV (Fig. 20.3). Ventilator asynchrony may occur because the patient's respiratory center does not anticipate whether the next breath from the ventilator will be mandatory or spontaneous.[15] When the mandatory rate is reduced to the point where it provides 50% or less of the required minute ventilation ($\dot{V}_E$), the WOB for the patient actually may be as much as when support is withdrawn completely.[16,17] Consequently the patient's spontaneous respiratory rate *(f)* may increase significantly.[10,12] (Additional information on IMV can be found in Chapter 5.)

Pressure Support Ventilation

With PSV, the patient controls the *f,* timing, and depth of each breath; in other words, PSV is patient triggered, pressure limited, and flow cycled. The sophisticated monitoring and alarm systems available with intensive care unit (ICU) ventilators make this nonvolume-oriented approach a safe and effective mode of weaning. Theoretically, PSV allows the clinician to adjust the ventilatory workload for each spontaneous breath to enhance endurance conditioning of the respiratory muscles without causing fatigue.[17,18]

The most practical method of establishing the level of PSV is to base the initial setting on the patient's measured airway resistance. In general, this is a pressure support level of 5 to 15 cm H_2O for patients who meet weaning criteria. Another sound approach involves attempting to reestablish the patient's baseline respiratory rate (15–25 breaths/min) and V_T (300–600 mL/min). An inappropriate pressure support setting can be identified by the presence of respiratory distress, which manifests as tachycardia, hypertension, tachypnea, diaphoresis, paradoxical breathing, **respiratory alternans** (altering use of the diaphragm to breath and the accessory muscles of respiration), and excessive accessory muscle use.

During weaning with PSV, the clinician gradually reduces the level of support as long as an appropriate spontaneous *f* and V_T are maintained and distress is not evident. When pressure support is reduced to about 5 cm H_2O, the pressure level is not high enough to contribute significantly to ventilatory support. However, this level of support is usually sufficient to overcome the work imposed

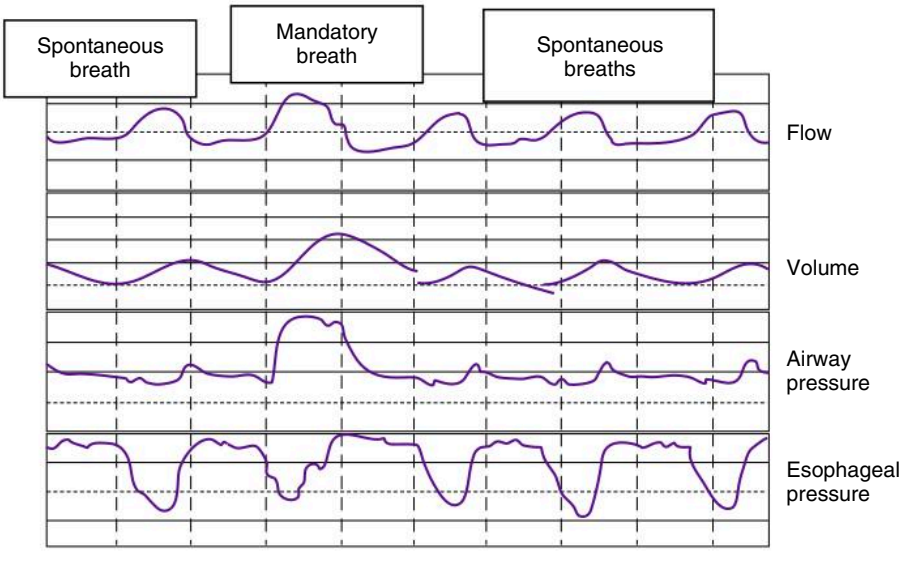

Fig. 20.3 Measurements of flow, volume, airway pressure, and esophageal pressure in a patient ventilated with synchronized intermittent mandatory ventilation. The esophageal pressure swings reflect the changes in pleural pressure and are the result of respiratory muscle contraction. These pressure swings are nearly as large during a mandatory breath as during spontaneous breaths. (From Hess DR: Mechanical ventilation strategies: what's new and what's worth keeping? *Respir Care* 47:1007–1017, 2002.)

by the ventilator system (i.e., the resistance of the ET, trigger sensitivity, demand-flow capabilities, and the type of humidifier used). (NOTE: Substantial air leaks [e.g., ventilator circuit leaks, around ET cuffs and chest tubes] can interfere with pressure-supported breath termination.)

T-Piece Weaning

T-piece weaning is the oldest of the available techniques. It originally involved removing the ventilator from the patient according to a predetermined schedule. The weaning process started when the patient was able to breathe spontaneously for brief periods without ventilatory support and the criteria for weaning had been met (these criteria are discussed later in the chapter). The original T-piece trial followed a schedule that progressively increased the length of time the patient was removed from ventilatory support. For example, the first period might have been 5 to 10 minutes, after which the patient was returned to the ventilator for the remainder of the hour. This process was repeated once an hour. The time off the ventilator was increased gradually until the patient was off the ventilator for 30 minutes and on for 30 minutes. The off time then was increased to 1 hour and so on.

The setup for a T-piece system includes a heated humidifier with a large reservoir. The humidifier is connected to a blended gas source (air/O_2) that provides a high flow of gas (at least 10 L/min) at the desired fractional inspired O_2 (F_IO_2). The humidified gas source is connected to a T-piece (Briggs adapter) with large-bore tubing, which is attached to the patient's ET. Another piece of large-bore tubing is attached to the exhalation side of the T-piece (volume of about 120 mL) to provide a reservoir or, as some clinicians refer to it, an afterburner (Fig. 20.4).[19] If the patient inhales and the gas flow through the tubing from the humidifier is inadequate, some of the patient's inhaled air can be derived from this reservoir and still contain gas at the desired F_IO_2. Patients are seated or semirecumbent for the procedure and should be continuously monitored by a clinician while disconnected from the ventilator. It is important to recognize that this method of weaning requires a high level of staff attention.

When T-piece weaning is accomplished through the ventilator, the ventilatory mode is set to spontaneous/continuous positive airway pressure (CPAP); that is, the mandatory rate is turned off. The advantage of using the ventilator is the availability of alarms; the disadvantage is that the patient's efforts to breathe through the ventilator system may result in an increased workload. However, current ICU ventilators typically provide a bias flow of gas through the system and flow triggering that supports any spontaneous breaths and reduces the patient's WOB. Basically, this is similar to a small amount of pressure support. Thus the T-piece trial using a ventilator provides a means of continuously monitoring the patient. This approach also provides backup apnea alarms or backup ventilator modes to support patients who become apneic.

Patients less likely to tolerate T-piece weaning include those who have severe underlying heart disease, have severe muscle weakness, or who are inclined to panic because of psychological problems or preexisting chronic lung conditions.

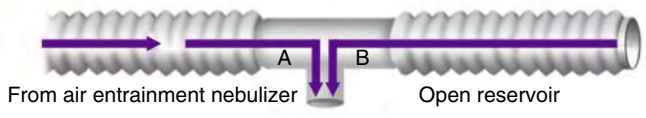

Fig. 20.4 Use of an open reservoir to enhance O_2 delivery with a T-piece. When the patient inhales, gas at the set fractional inspired O_2 (F_IO_2) is drawn first through the inspiratory side of the circuit from the gas source (A). If the patient's flow demand exceeds the output, gas is inhaled from the open reservoir (B). Only after the reservoir volume is fully emptied by the patient is room air entrained, compromising F_IO_2 delivery. (From Wilkins RL, Stoller JK, Scanlan CL, editors: *Egan's fundamentals of respiratory care,* ed 8, St. Louis, MO, 2003, Mosby.)

Comparison of Traditional Weaning Methods

Studies comparing the IMV, PSV, and T-piece weaning techniques have produced conflicting results.[10,12] Each mode offers particular benefits to certain patients. If one procedure does not work well for a patient, another might work. Ventilator discontinuation is best accomplished when expert, caring staff members work with willing, cooperative patients.

CLOSED-LOOP CONTROL MODES FOR VENTILATOR DISCONTINUATION

In a closed-loop control ventilatory mode, a set variable is compared with a measured control variable.[20] The ventilator uses a feedback signal to adjust the output of the system. Closed-loop modes of ventilation range from simple techniques, such as volume support, to more complex ones, such as **adaptive support ventilation**. Advanced closed-loop control techniques that have been used for weaning include automatic tube compensation (ATC), volume-targeted PSV (e.g., volume support), MMV, adaptive support ventilation (ASV), and an artificial intelligence system for weaning.

Automatic Tube Compensation

The WOB may increase when a spontaneously breathing patient breathes unaided through an ET.[20-22] The amount of the increase is directly related to the size of the artificial airway and the $\dot{V}_E$. Reducing the diameter or increasing the length of the tube increases the resistance to flow, as do kinks in the tube. These factors, coupled with high $\dot{V}_E$, increase the spontaneous WOB for the patient (see Chapter 17).

Clinicians often use low levels of pressure support (<10 cm H_2O) to compensate for the increased resistance and WOB associated with breathing through an ET.[21-23] However, the clinician must always keep in mind that a fixed pressure, as with PSV, cannot accurately compensate for the variable flow through the ET because inspiratory flow demand can vary.[24] Therefore a fixed level of pressure support can result in too little support when inspiratory flow is high or too much support when inspiratory flow is low.[25] In fact, PSV can result in excessive V_T and flow, which is uncomfortable for the patient.[26]

To overcome this problem, some ICU ventilators (e.g., Puritan Bennett 840/980 [Medtronics Minimally Invasive Technologies, Minneapolis, MN] and the Dräger Evita XL and V500 [Dräger Medical, Telford, PA]) are equipped with a feature called ATC. ATC was designed specifically to reduce the WOB associated with increased ET resistance.[15] Theoretically ATC delivers exactly the amount of pressure required to overcome the resistive load imposed by the ET for the flow measured at the time. In a sense, this is providing variable PSV with variable inspiratory flow compensation.[24] ATC targets pressure at the tracheal level, adjusting the delivered pressure to try to maintain tracheal pressure at a constant level (Fig. 20.5).[27,28] If the flow-resistive

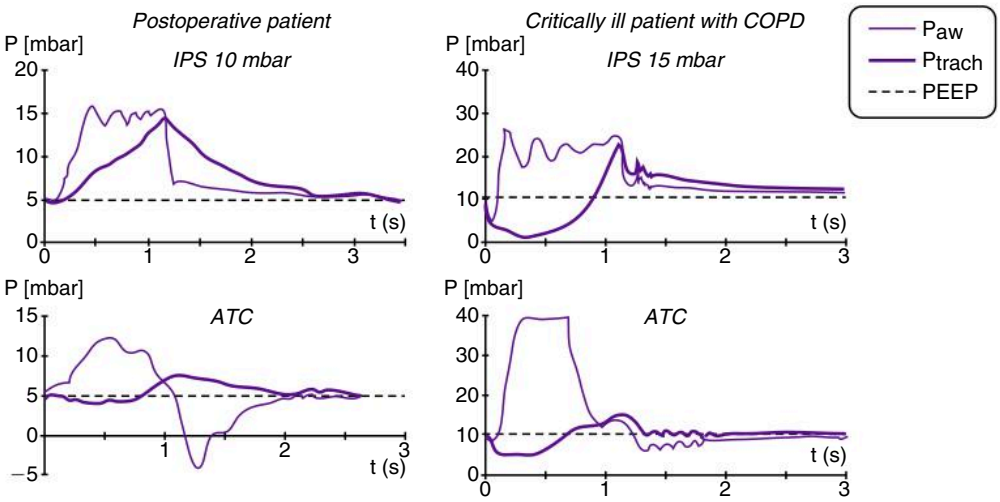

Fig. 20.5 Airway pressure (P_{aw}) and tracheal pressure (P_{trach}) curves using inspiratory pressure support *(upper graphs)* and automatic tube compensation (ATC) *(lower curves).* Curves on the left are from a patient who had open heart surgery. Curves on the right are from a critically ill patient with chronic obstructive pulmonary disease. *Bottom left,* Note that the ventilator lowers P_{aw} during expiration. Control of the expiratory valve keeps P_{trach} above or equal to the PEEP. *Bottom right,* Note that the patient with acute respiratory insufficiency using ATC generates an inspiratory flow greater than 2 L/s. This accounts for part of the difference between P_{trach} and PEEP. (From Fabry B, Haberthur C, Zappe D, et al.: Breathing pattern and additional work of breathing in spontaneously breathing patients with different ventilatory demands during inspiratory pressure support and automatic tube compensation, *Intensive Care Med* 23:545–552, 1997.)

properties of the artificial airway are known, tracheal pressure changes can be determined by measuring inspiratory and expiratory flows.[29]

ATC functions by using a closed-loop control of the ventilator based on calculated tracheal pressures.[27,30] The pressure delivered to the upper airway during ATC increases by an amount equal to the continuously calculated pressure drop across the ET during inspiration.[29] The pressure change required to maintain the flow for a known resistance can be estimated using the following equation:

$$\Delta P = R\dot{V}_E$$

where ΔP is the pressure change, R is resistance, and $\dot{V}_E$ is flow. The equation for calculating tracheal pressure is:

$$\text{Tracheal pressure} = \text{Proximal airway pressure} - (\text{Tubeco efficient} \times \text{Flow}^2)^{31}$$

In this equation, the tube coefficient relates to the size of the tube and its imposed resistance. (NOTE: ET resistance is a nonlinear function of flow, especially at higher flows.)[29,32]

To set ATC, the operator selects the ATC function on the ventilator and enters the type of tube (ET or tracheostomy) and the tube size. Some ventilators allow selection of both inspiratory and expiratory ATC.[31,33] Currently it is unclear whether expiratory ATC causes premature closure of unstable airways in patients with chronic obstructive pulmonary disease (COPD)[28] or whether it may, in fact, eliminate dynamic hyperinflation.[34] Further clinical studies are needed to evaluate this issue.

In relation to WOB, ATC may support spontaneous breathing without the overcompensation or undercompensation that occurs with PSV or CPAP.[28,31,35] In addition to the benefit of reduced WOB, patients seem to find ATC more comfortable than PSV.[26,36] (The respiratory discomfort in PSV seems to be related to lung overinflation.[26,27,36]) Box 20.2 lists the potential benefits of ATC.[34,37,38]

BOX 20.2 Potential Advantages of Automatic Tube Compensation

Automatic tube compensation may be useful for the following purposes:

- To support or overcome the work of breathing imposed by the artificial airway during spontaneous breathing by a ventilator-supported patient
- To improve patient–ventilator synchrony through variable compensation of inspiratory flow based on patient demand
- To reduce the risk for air trapping caused by expiratory resistance from the endotracheal tube
- To enhance patient comfort
- To preserve the natural, "noisy" breathing pattern
- To facilitate accurate prediction of readiness for extubation
- To unload the inspiratory muscles and increase alveolar ventilation without adverse cardiopulmonary side effects

Arguments Against the Use of Automatic Tube Compensation

Some clinicians question whether ATC is needed to support a spontaneously breathing, intubated patient. Until a patient's spontaneous $\dot{V}_E$ exceeds 10 L/min, the effect of the ET may not be significant (see Fig. 17.13).[15,20] A high V_E is seldom required for an intubated patient who is breathing spontaneously; otherwise, the patient would receive ventilatory support.

When an appropriate-size ET is used, the imposed WOB may not be any greater through the tube than it is through the upper airway once the patient has been extubated.[38] In several studies, ATC was found to be the equivalent of pressure support (5 cm H_2O) and CPAP (5 cm H_2O) in reducing WOB.[25,39] In some cases, ATC can give the false impression that the patient is ready to be extubated, when in fact the person is dependent on the support supplied by ATC even though it is minimal.[32] In addition, depending on the ventilator model, ATC may not provide sufficient compensation for WOB imposed by the ET.[32,33]

Summary of Automatic Tube Compensation

ATC may reduce resistive WOB and increase patient comfort, depending on the ventilator and the artificial airway used. Additional studies are required, however, to determine whether ATC provides all the benefits for which it was designed. Despite the concerns previously mentioned, ATC may represent another method that can be used successfully to extubate patients who are difficult to wean.[40,41]

Volume-Targeted Pressure Support Ventilation

Volume-targeted PSV was briefly described in Chapter 6. This mode, which is also called volume support (VS) ventilation on the Servo-i ventilator (Maquet Inc., Wayne, NJ), is basically PSV with a volume target. Volume-targeted PSV provides a set V_T while using PSV criteria (patient triggered, pressure targeted, flow cycled). Although volume-targeted PSV has the advantage of maintaining a target volume, its value in weaning patients from mechanical ventilatory support has not been established.[42] Furthermore, several drawbacks have been noted with using volume-targeted PSV (see Chapter 17 section on closed-loop ventilation asynchrony).

Automode and Variable Pressure Support/ Variable Pressure Control

Automode is available on the Servo-i ventilator. A similar mode, called variable pressure support/variable pressure control (VPS/VPC), is available on the Venturi ventilator (Cardiopulmonary Corp, Milford, CT).

When automode (or VPS/VPC) is activated, the ventilator can switch from a time-triggered mandatory breath to a patient-triggered support breath. For example, if a postoperative patient is still recovering from the effects of anesthesia and the ventilator operator has selected volume-controlled continuous mandatory ventilation with automode as the operating mode, all breaths are mandatory (time triggered, volume limited, and time cycled). If the patient begins to trigger breaths, the ventilator switches to VS (patient triggered, pressure limited, and flow cycled with a volume target) and remains in this mode as long as the patient is breathing spontaneously. If the patient becomes apneic again or if no patient effort is detected within a certain period, the ventilator switches back to the support mode (volume-controlled continuous mandatory ventilation). Automode can also be set to switch from pressure-controlled continuous mandatory ventilation to PSV and from pressure-regulated volume control to VS.

Automode has been shown to be an effective weaning technique that typically requires fewer ventilator manipulations than other techniques (e.g., IMV).[43,44] Additional clinical studies are needed to evaluate more completely the performance of automode as a weaning technique.[34]

Mandatory Minute Ventilation

MMV was first described in 1977 by Hewlett and colleagues.[45] MMV is available on the Dräger Evita XL ventilator. It is a closed-loop system in which the ventilator monitors set parameters and adjusts accordingly (i.e., the ventilator adjusts the pressure, frequency, or the V_T to maintain the desired $\dot{V}_E$).

With traditional weaning methods (e.g., IMV and PSV), a constant level of ventilation is not guaranteed. In contrast, MMV automatically increases the level of support if the patient's spontaneous ventilation decreases, thus maintaining a consistent minimum $\dot{V}_E$. Patients who regain the ability to breathe spontaneously can increase their own $\dot{V}_E$, and the machine automatically lowers support without the clinician having to change any specific ventilator settings. Some of the potential benefits of MMV are listed in Box 20.3.[45,46]

Although few clinical studies address the use of MMV as a weaning technique, several guidelines should be kept in mind. The target $\dot{V}_E$ is set slightly below the patient's total $\dot{V}_E$, which includes both mandatory and spontaneous breaths. If a patient is receiving CMV and is neither hypocapnic nor alkalotic, the $\dot{V}_E$ can be appropriately set at 80% of the patient's previous level. A lower $\dot{V}_E$ level (i.e., 75% or less) may be adequate if the patient is slightly alkalotic or hypocapnic. For patients on IMV, setting the $\dot{V}_E$ at 90% of the mandatory IMV value may be adequate.[45-47]

A potential problem with MMV is that a rapid, shallow respiratory pattern may provide the preset $\dot{V}_E$ but in this situation may result in an increase in dead space ventilation. This type of pattern can result from a decrease in compliance associated with pulmonary congestion, pulmonary edema, pleural effusion, fibrosis, atelectasis, and pneumonia. It can also be associated with abdominal distention or a decrease in ventilatory muscle strength. As a precaution, the high f and low V_T alarms must be set appropriately.

Other problems that can occur when using MMV include the development of auto-PEEP, delivery of very high V_T (inappropriately set upper pressure limit), increased dead space ventilation, and inappropriate settings resulting from clinician misunderstanding or misapplication of the mode. Clinicians must be aware of the potential consequences of changing dead space, carbon dioxide (CO_2) production, and patient WOB. The patient's breathing pattern and gas exchange can vary and therefore must be monitored regularly. Although MMV has been available for three decades, research data on the effectiveness of this mode are still lacking.

BOX 20.3 Potential Advantages of Mandatory Minute Ventilation

- Mandatory minute ventilation may offer greater control of a patient's P_aCO_2 than intermittent mandatory ventilation.
- Acute hypoventilation or apnea does not cause sudden hypercapnia.
- Acute hypoventilation is less likely after administration of sedatives, narcotics, or tranquilizers.
- MMV may provide a smooth transition from mechanical ventilatory support to spontaneous ventilation in patients recovering from a drug overdose or anesthesia.

Adaptive Support Ventilation

ASV is available on the Hamilton G5 ventilator (Hamilton Medical, Bonaduz, Switzerland). Both ASV and its predecessor, adaptive lung ventilation (ALV), were designed to make automatic adjustments from the time ventilation was initiated until ventilation could be discontinued. The technical aspects have been described elsewhere.[48,49] ASV is a patient-centered method of closed-loop mechanical ventilation that increases or decreases ventilatory support based on monitored patient parameters.

Basically, ASV provides pressure-limited breaths that target a volume and *f*. The *f* and V_T are selected by the ventilator's algorithm to provide the minimum WOB for the patient.[50] ASV monitors variables, such as pressure, flow, inspiratory and expiratory time, compliance, resistance, and time constants, to ensure delivery of an acceptable $\dot{V}_E$ based on practitioner settings. These settings include the patient's ideal body weight, the high-pressure limit, PEEP, F_IO_2, rise time, flow cycle, and percentage of predicted $\dot{V}_E$ desired. ASV is designed to minimize WOB and auto-PEEP. It is worth noticing that ASV has been shown to be an effective ventilator management strategy for a variety of patient situations, including during thoracic surgery.[51] It also has been studied as a strategy for ventilator discontinuation.[52-54] ASV appears to be as safe and effective as traditional methods of weaning, and it has been suggested that it may find increased use in the future.[34]

Artificial Intelligence Systems

This method of weaning patients from ventilatory support relies on artificial intelligence technology. Presently the only commercial system that is available for clinical use is the SmartCare/PS system, which is offered on the Dräger XL and Evita Infinity V500 ventilators. The SmartCare/PS system uses predetermined ranges for volume (V), *f*, and end-tidal CO_2 pressure ($P_{et}CO_2$) to adjust the inspiratory pressure automatically to maintain the patient in a respiratory "zone of comfort."[23,55] The patient's readiness for extubation is based on achieving the predefined lowest level of inspiratory pressure. Several factors can affect the lowest level of inspiratory pressure, including the type of artificial airway (i.e., ET vs. tracheostomy tube [TT]), the type of humidifier (i.e., heat-moisture exchange [HME] vs. heated humidifier), and the use of ATC.

Once the lowest level of inspiratory pressure is achieved, a period of observation is initiated during which the patient's V_T, *f*, and $P_{et}CO_2$ are monitored. If the patient successfully passes this modified spontaneous breathing trial (SBT), the system automatically displays a message suggesting that the clinician should consider separating the patient from the ventilator.[23] It has been suggested that this approach to weaning may be a viable alternative because it reduces the duration of mechanical ventilation and ICU stays.[56,57] Additional clinical trials will be required to better define the use of these systems.

EVIDENCE-BASED WEANING

The challenge of successfully liberating a patient from a ventilator has been the subject of considerable debate. Solid evidence on identifying a patient's readiness to wean and ways to accomplish this task remain points of intense discussion among clinicians. In 1999, the federal Agency for Healthcare Policy and Research asked the McMaster University Outcomes Research Unit to do a comprehensive review of the literature on ventilator withdrawal issues to establish the evidence on which ventilator weaning is based.[58] Using the results of the literature review, a task force of the American College of Chest Physicians (ACCP), the Society for Critical Care Medicine (SCCM), and the American Association for Respiratory Care (AARC) created evidence-based guidelines for ventilator weaning for patients requiring more than 24 hours of ventilation.[59] These guidelines (Box 20.4) form the basis for the material presented in the remainder of this chapter.[1,59] Additional information is provided from a recent clinical practice guideline produced by a collaborative effort between the American Thoracic Society (ATS) and the ACCP.60 The ATS/ACCP clinical practice guidelines outline additional evidence-based recommendations to optimize liberation from mechanical ventilation in critically ill patients.

EVALUATION OF CLINICAL CRITERIA FOR WEANING

The following three key points have evolved as criteria for weaning:

1. The problem that caused the patient to require ventilation must have been resolved.
2. Certain measurable criteria should be assessed to help establish a patient's readiness for discontinuation of ventilation.
3. An SBT should be performed to firmly establish readiness for weaning.

Recommendation 1: Pathology of Ventilator Dependence

Although it is often overlooked, the primary pathological event that led to initiation of ventilatory support must be corrected. The clinician must determine whether this disease process or condition has improved or been reversed. If not, weaning attempts are unlikely to be successful.[59]

The ACCP/SCCM/AARC task force's first recommendation is that a search for all the causes that may be contributing to ventilator dependence should be undertaken for patients who require mechanical ventilation for longer than 24 hours. This recommendation is especially important for patients for whom attempts to be weaned from the ventilator have failed. Reversing all possible ventilator and nonventilator issues is a key part of the ventilator discontinuation process. Box 20.5 provides a summary of factors that must be evaluated to determine a patient's readiness for ventilator disconnection.[6,60,61] Even if the disease process or condition that led to mechanical ventilation has improved or has been reversed, other factors must be considered such as the patient's overall medical condition, a physical assessment of cardiopulmonary reserve and WOB, and the patient's psychological readiness (see Box 20.4).

Box 20.6 lists the clinical factors used to help evaluate a patient's overall condition. Any measured parameter that is out of the normal range may interfere with the patient's ability to breathe spontaneously without ventilatory support. However, occasionally one or more of these criteria may be slightly abnormal and the patient will still be able to support ventilation successfully. This type of situation presents the greatest challenge to clinicians trying to predict whether a patient is ready to be weaned.

BOX 20.4 Selected Recommendations From the American College of Chest Physicians (ACCP)/American Association for Respiratory Care (AARC)/Society of Critical Care Medicine (SCCM) Evidence-Based Weaning Guidelines Task Force

Recommendation 1: Pathology of Ventilator Dependence

All factors that may be contributing to ventilator dependence should be identified for patients requiring mechanical ventilation for longer than 24 hours. This is particularly true if attempts to withdraw the mechanical ventilator have failed. Reversing all possible ventilatory and nonventilatory issues is an important part of the ventilator discontinuation process.

Recommendation 2: Assessment of Readiness Using Evaluation Criteria

A formal patient assessment should be performed to determine whether the criteria have been met for discontinuation of ventilation. The following criteria are recommended:

1. Evidence of some reversal of the underlying cause of respiratory failure.
2. Adequate oxygenation: arterial partial pressure of O_2 (P_aO_2) $\geq$60 mm Hg with fractional inspired O_2 (F_IO_2) $\leq$0.4; ratio of arterial partial pressure of O_2 to fractional inspired O_2 (P_aO_2/F_IO_2) $\geq$150 to 200 mm Hg; required PEEP $\leq$5 to 8 cm H_2O; F_IO_2 $\leq$0.4 to 0.5; and hydrogen ion concentration (pH) $\geq$7.25.
3. Hemodynamic stability; that is, no clinically important hypotension and no requirement for vasopressors or a requirement only for low-dose vasopressor therapy (e.g., dopamine or dobutamine $<$5 mcg/kg/min).
4. Patient capable of initiating an inspiratory effort.

The decision to use these four criteria must be adapted for each patient. Some patients may not satisfy all the criteria (e.g., patients with chronic hypoxemia below the thresholds cited) but may be ready for attempts at discontinuation of mechanical ventilation.

Recommendation 3: Assessment During Spontaneous Breathing

Formal discontinuation assessments should be done during spontaneous breathing rather than while the patient receives substantial ventilatory support. An initial brief period of spontaneous breathing can be used to assess the patient's ability to perform a formal spontaneous breathing trial (SBT). The criteria used to assess a patient's tolerance of an SBT are (1) respiratory pattern, (2) adequacy of gas exchange, (3) hemodynamic stability, and (3) subjective comfort. Patients who tolerate an SBT of 30 to 120 minutes should promptly be considered for ventilator discontinuation.

Recommendation 4: Removal of the Artificial Airway

For patients whose support from the ventilator has been successfully discontinued, the decision regarding removal of the artificial airway should be based on assessment of airway patency and the patient's ability to protect the airway.

Recommendation 5: SBT Failure

If SBT fails, the causes of the failure and the reasons the patient continues to require ventilatory support should be determined and corrected. Once the reversible causes of failure have been corrected, and if the patient still meets the criteria described in Recommendation 2, an SBT should be performed every 24 hours.

Recommendation 6: Maintaining Ventilation With SBT Failure

Patients receiving mechanical ventilation for respiratory failure who fail an SBT should receive a stable, nonfatiguing, comfortable form of ventilatory support.

Recommendation 7: Anesthesia and Sedation Strategies and Protocols

Anesthesia and sedation strategies and ventilator management should be directed toward early extubation for patients who have had surgery.

Recommendation 8: Weaning Protocols

Protocols for ventilation discontinuation that are designed for clinicians other than physicians should be developed and implemented by intensive care units (ICUs). These protocols should aim to optimize sedation.

Recommendation 9: Role of Tracheostomy in Weaning

When it becomes apparent that a patient will require prolonged ventilator assistance, tracheotomy should be considered. Tracheotomy should be performed after an initial period of stabilization on the ventilator and when the patient appears likely to benefit from the procedure.

Recommendation 10: Long-Term Care Facilities for Patients Requiring Prolonged Ventilation

Unless evidence of irreversible disease is present (e.g., high spinal cord injury, advanced amyotrophic lateral sclerosis), a patient who requires prolonged ventilatory support should not be considered permanently ventilator dependent until 3 months of weaning attempts have failed.

Recommendation 11: Clinician Familiarity With Long-Term Care Facilities

Critical care practitioners need to be familiar with facilities in their communities or units in their hospital that specialize in managing patients who require prolonged mechanical ventilation. Clinicians need to stay current with peer-reviewed data from long-term ventilation care units.

Patients who fail discontinuation attempts in the ICU should be transferred to long-term ventilation care facilities when they are medically stable. These long-term care facilities should have demonstrated competence, safety, and success in accomplishing ventilator discontinuation. These facilities are characterized by less staffing and less costly monitoring equipment; therefore they generate less cost per patient than do ICUs.

Recommendation 12: Weaning in Long-Term Ventilation Units

Weaning of a patient who requires prolonged ventilation should be slow paced and include gradual lengthening of SBTs.

Modified from ACCP/AARC/SCCM Task Force, MacIntyre NR: Evidence-based guidelines for weaning and discontinuing mechanical ventilatory support: a collective task force facilitated by the American College of Chest Physicians, the American Association for Respiratory Care, and the American College of Critical Care Medicine, *Chest* 120(suppl 6):375S-395S, 2001; also in *Respir Care* 47:29–30, 2002; and MacIntyre N: Evidence-based ventilatory weaning and discontinuation, *Respir Care* 49:830–836, 2004.

BOX 20.5 Evaluation of Systems to Determine Etiology of Respiratory Failure

Neurological Factors
- The brainstem (controller) should be structurally sound (e.g., absence of a history of cerebrovascular accident [CVA, also known as *stroke*] or central apnea).
- No electrolyte disturbances should be present, and no sedatives or narcotics should be required that might affect the function of the brain.
- Peripheral nerve failure may be present as a result of structural or metabolic problems or drug use.
- Obstructive sleep apnea may be present and is often overlooked.

Respiratory Factors
- Weakness of respiratory muscles (e.g., atrophy from lack of use or injury from overuse).
- Presence of neuropathy and myopathy (neuromuscular blocking agents, aminoglycosides, and corticosteroids can contribute to neuropathy and myopathy).
- Excessive loads may be placed on the ventilatory muscles, possibly as a result of hyperinflation, compliance and resistance changes, and high minute ventilation demands (>10 L/min).
- Increased work of breathing (WOB) increases O_2 consumption and CO_2 production. Failure of withdrawal attempts may be related to capacity/load imbalance. These patients tend to have rapid, shallow breathing patterns.
- Wasted ventilation (increased dead space volume [V_D] and arterial partial pressure of carbon dioxide [P_aCO_2]) may be present.
- Impaired gas exchange (e.g., ventilation/perfusion imbalances and shunt) may be a factor.

Metabolic Factors and Ventilatory Muscle Function
- Hypoxic ventilator response and hypercapnic ventilatory response deteriorate under conditions of inadequate nutrition (i.e., semistarvation).
- Overfeeding (i.e., increased carbohydrate load) may lead to increased CO_2 production.
- Electrolyte imbalances, especially phosphate and magnesium deficiencies, are associated with muscle weakness.
- Severe hypothyroidism and myxedema directly impair diaphragmatic function; adequate O_2 delivery is also essential to this process.

Cardiovascular Factors
Patients with susceptible reserves may develop ischemia or heart failure when ventilator support is reduced. Possible causes include the following:
- Increased metabolic demand with increased WOB as the patient transitions from mechanical ventilation to spontaneous breathing
- Increased venous return with spontaneous ventilation (negative intrathoracic pressure)
- Increased left ventricular afterload imposed by negative pleural pressure swings

Psychological Factors
- Fear of loss of life support
- Stress
- Poor ambulation
- Loss of sleep

From Cook DJ, Meade MO, Perry AG: Trials of miscellaneous interventions to wean from mechanical ventilation, *Chest* 120(suppl 6):438S–444S, 2001.

BOX 20.6 Clinical Factors That Aid Evaluation of a Patient's Overall Condition

- Acid-base balance
- Anemia or abnormal hemoglobin
- Body temperature
- Cardiac arrhythmias
- Caloric depletion (malnutrition or protein loss)
- Electrolytes
- Exercise tolerance (e.g., up in a chair)
- Fluid balance
- Hemodynamic stability (blood pressure, cardiac output, presence of shock)
- Hyperglycemia or hypoglycemia
- Infection
- Pain (can be minimized without oversedation)
- Psychological condition
- Renal function
- Sleep deprivation (an important and often overlooked problem)
- State of consciousness

Weaning Criteria

When a patient's medical condition is stable and the patient is breathing spontaneously, alert, and cooperative, clinicians typically evaluate certain ventilatory mechanics and gas exchange values to help assess readiness for ventilator discontinuation (see Box 20.4).[2,59,62,63] These values are often called weaning criteria. About 75% of patients who meet certain weaning criteria tolerate an initial SBT in establishing readiness for ventilator discontinuation.[64] It should be mentioned that even among patients who never satisfy weaning criteria, about 30% eventually can be weaned from the ventilator.[65]

Considerable interest has focused on the establishment of specific, measurable criteria for predicting the success of attempts to wean patients from mechanical ventilation. Table 20.1 lists a number of physiological parameters that can be used for weaning and extubation in adults.[2,59,62,63] However, no single measure has yet been established that is uniformly successful in predicting patient ability to be weaned and to have uncomplicated extubation. An ideal weaning index would involve several parameters and might include the requirements listed in Box 20.7.[66]

It is interesting to note that 462 potential weaning predictors have been identified.[11,58,63] Of those identified, relatively few predictors