hypovolemic, this results in hypotension. Some patients, on the other hand, have augmented venous return to the thorax and an improvement in cardiac output.[1] If the patient has excessive secretions or a depressed (obtunded) epiglottic reflex response, airway management becomes a problem and requires an artificial airway.

Because older tank ventilators are controllers, they allow little, if any, adjustments if the patient makes spontaneous efforts. V_T is determined by the amount of negative pressure applied and the characteristics of the lung. Consequently, V_T must be measured during setup and throughout use of the tank ventilator. Newer models allow for patient-triggered ventilation.[61]

The Porta-lung (Philips Respironics) is a portable version of the iron lung that is smaller (2 m) and lighter weight (50 kg).[42] Current models allow for a ventilator rate (*f*) range of 12 to 24 breaths/min and a pressure range of −15 to −45 cm H_2O.

Starting NPV in the treatment of chronic respiratory failure is carried out in a manner similar to that with IPPV. For example, typically pressures of −12 to −25 cm H_2O are sufficient to generate an adequate V_T. Adjustments are based on the achieved V_T, blood gases, and pulse oximetry evaluation during use. It is important to understand that NPV may induce or exacerbate OSA.[67,68] If a patient has or develops OSA, the use of NPV, regardless of how it is applied, is contraindicated because it may aggravate the associated airway closure.[69]

The Chest Cuirass

The **chest cuirass**, or chest shell, partially compensates for some of the problems that occur with tank ventilators. The cuirass is a rigid shell that is placed over the patient's chest, touching the upper abdomen (Fig. 21.4). A space exists between the shell and chest wall. This design restricts most of the negative pressure to the thoracic area, thus relieving most of the abdominal area from exposure to negative pressure. Some models have a trigger device that detects changes in flow or pressure at the nostrils. When a patient's inspiratory effort is detected, an assist breath is delivered. These sensing devices are not as efficient as those used with positive pressure ventilators; therefore the patient's inspiratory work to achieve a ventilator response is greater.

The chest cuirass and body suit or body wrap (see later section on The Body Suit) are attached by hoses to an external pump that generates alternating negative pressure. The chest cuirass is the least efficient NPV device and may not be adequate for severely compromised patients. Pressures of −35 to −60 cm H_2O may be necessary to achieve sufficient V_T with the chest cuirass.[10] Sometimes sufficient negative pressure cannot be achieved. This may be attributable to leaks in the system, particularly with older sealing materials. Plastic wrapping that is placed around the shell and newer custom-made shells can help eliminate the leakage problem. Other problems with the cuirass include patient discomfort and skin abrasions at points of contact. In patients with severe chest wall deformities, a custom-made cuirass may be required. Despite some difficulties, the chest cuirass is still being successfully used in the treatment of patients.[70,71]

The Body Suit

A third type of NPV is the body suit, which is a rigid chest grid that, in some models, attaches to a flat back plate. The rigid portion is fitted with a "rain jacket" or poncho wrap with fittings at the neck, wrists, waist, and ankles, depending on the style (Fig. 21.5). Two of the currently available models are the Pulmo-Wrap (Lifecare International Inc., Lafayette, CO) and Poncho-Wrap (Emerson JH, Cambridge, MA).[61]

The body wrap is more portable than the tank ventilator. It also allows the patient to sleep in his or her own bed. However, it is less efficient and hard to completely seal. Negative pressure is applied to a smaller surface area than with the tank ventilator. Because it restricts movement and patient positioning, it can cause muscular and joint pain, particularly back pain.[61]

NPV is not used nearly as much as portable PPV for long-term ventilation. However, it still has an occasional place in patient support. For example, a patient may be able to be in a wheelchair during the day and use a portable volume ventilator with a mouthpiece as an interface.[71] At night, the patient could use NPV. Both techniques allow noninvasive ventilation and avoid the necessity of a tracheostomy.

Additional Noninvasive Devices

Two additional noninvasive techniques for assisting ventilation are the rocking bed and pneumobelt.[67,71-73] Both devices operate by the principle of moving the abdominal contents and diaphragm to aid in breathing. They both rely on the compliance of the abdomen and chest wall and are not appropriate for obese patients, those with severe chest wall deformities, or patients with intrinsic lung disease.[1]

The **rocking bed** (Fig. 21.6) is all but obsolete, but it has been used as an alternative form of noninvasive ventilatory support.[1,74]

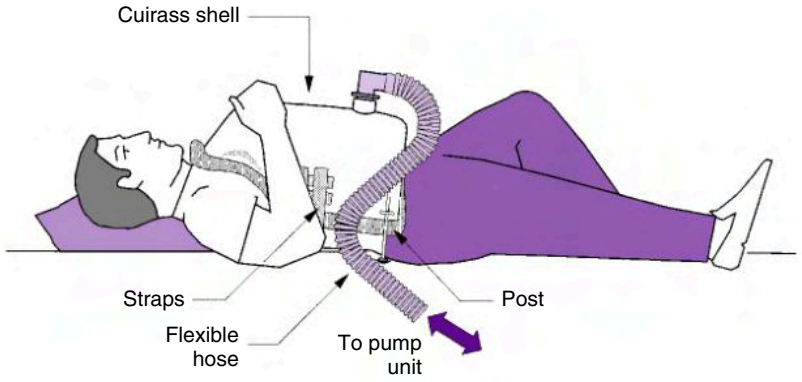

Fig. 21.4 Cuirass shell used for negative pressure ventilation. Patient is placed in supine position, and cuirass is stabilized with the use of straps and posts. (From Dupuis Y: *Ventilators: theory and clinical application,* ed 2, St. Louis, MO, 1992, Mosby.)

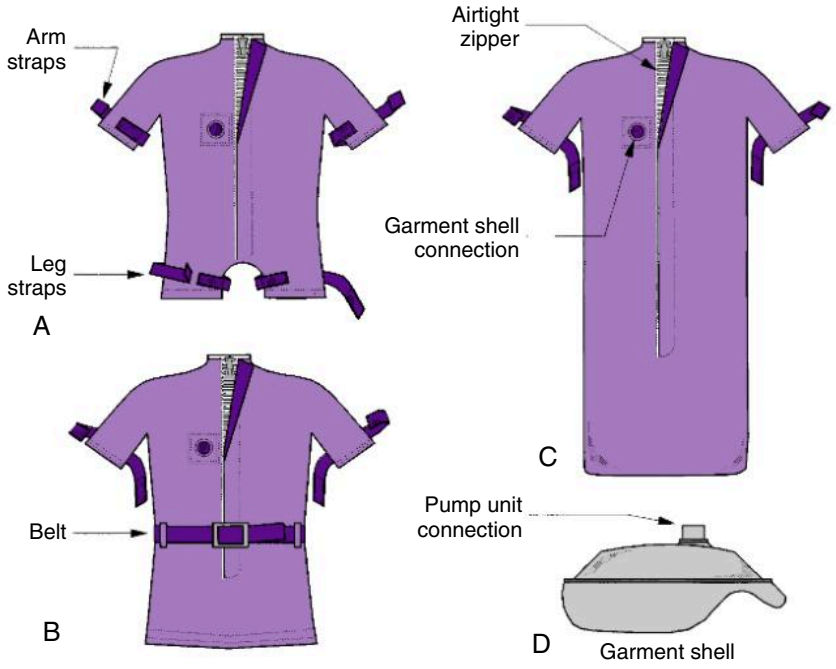

Fig. 21.5 Airtight garments used for negative pressure ventilation. (A) Garment is sealed at neck, arms, and legs. (B) Garment is sealed at neck, arms, and waist. (C) Patient is placed in bag sealed at neck and arms. (D) Shell fitted with pump connection extending through garment opening is used to keep garment off patient's chest and enhance ventilation. (From Dupuis Y: *Ventilators: theory and clinical application,* ed 2, St. Louis, MO, 1992, Mosby.)

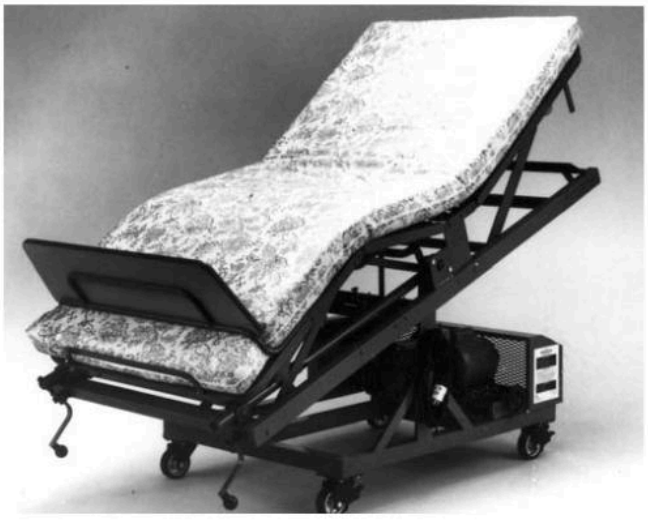

Fig. 21.6 The rocking bed. (Courtesy Emerson Company, Boston, Mass.)

For example, in one reported case, a 40-year-old woman with muscular dystrophy required nocturnal ventilatory support. Eventually, as her muscle weakness progressed, she had difficulty setting up her NIV circuit. The rocking bed turned out to be a successful alternative form of support.[75]

Another situation in which the rocking bed has been shown to be effective is in patients with bilateral diaphragmatic paralysis.[76] This condition can occur as a potential postoperative complication of cardiac surgery.

The rocking bed is a motorized bed that continuously moves in a longitudinal plane. The patient is placed in a supine position in the bed. As Fig. 21.6 shows, the patient's head and knees can be elevated, which may improve patient comfort and help prevent sliding. The bed supports ventilation by rhythmically moving through an arch of 40 to 60 degrees (Trendelenburg to the reverse Trendelenburg position). The rate of rocking is 12 to 22 times/min. The optimal range is approximately 12 to 16 times/min.[1] Expiration is assisted when the head is in the down position and the abdominal contents and diaphragm are moved by gravity toward the thorax (cephalad). When the feet are in the down position (reverse Trendelenburg position), the diaphragm and abdominal contents move toward the feet (caudad) and inspiration is assisted. The rocking bed generally does not cause motion sickness, probably because it rotates only in one plane.[1] Box 21.10 lists conditions in which the rocking bed should be avoided.

The **pneumobelt** (Fig. 21.7), also referred to as an *intermittent abdominal pressure ventilator*, contains an inflatable bladder that

BOX 21.10 Conditions in Which the Rocking Bed Is Not Effective or Should Be Used With Caution

- Obesity
- Excessively thin patients
- Severe chest wall abnormalities
- Infants
- Intrinsic lung disease

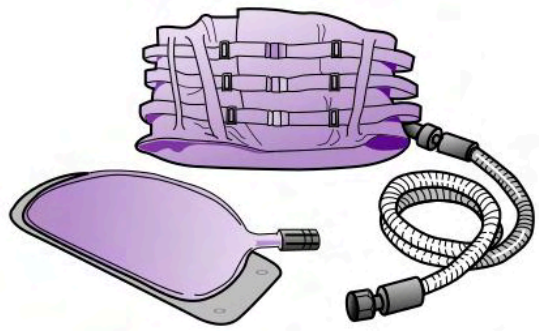

Fig. 21.7 The pneumobelt with positive pressure generator. (From Cairo JM, Pilbeam SP: *Mosby's respiratory care equipment*, ed 8, St. Louis, MO, 2010, Mosby.)

fits between the umbilicus (below the xiphoid process) and the pubic arch (over the abdomen) and is held in place by a nylon corset. Like the rocking bed, use of the pneumobelt is limited in clinical practice. The upper edge of the belt just overlaps the lower end of the rib cage. The patient must be in a seated position (45 degrees or more) to use this device. It is ineffective if the head is lower than 30 degrees from horizontal.[73] The pneumobelt should fit snugly in place but must not impede spontaneous ventilation. A motor inflates the bladder, which pushes the abdominal content up, moving the diaphragm upward (cephalad) to assist exhalation. Deflating the bladder allows the diaphragm to return to the resting position, allowing inhalation. The device is not very powerful. A positive pressure ventilator able to generate pressure of approximately 50 cm H_2O and an inspiration-expiration ratio of 1:2 can be used to power the device.[10] The inflation rate is set to approximate the patient's spontaneous rate (12—22 breaths/min). Pressure is increased from approximately 30 cm H_2O upward until a satisfactory V_T is achieved or until the patient reports discomfort.

The pneumobelt is best used for daytime and, like the rocking bed, may be effective for patients with bilateral diaphragmatic paralysis and patients with high spinal cord lesions. The pneumobelt can be used as an adjunct with other forms of assisting ventilation. Some patients can sleep in the upright position. In these cases, it also can be used during the night.

Diaphragm Pacing

Some patients with respiratory failure caused by high spinal cord lesions or central hypoventilation can benefit from diaphragmatic pacing. With this therapeutic intervention, the phrenic nerve is electrically stimulated through surgically implanted phrenic electrodes connected to an implanted receiver. The receiver obtains signal transmissions from an extracorporeal radiofrequency transmitter and antenna.

This technology has limited application. Not all patients will respond to this type of intervention because of inadequate phrenic nerve and diaphragm function. In addition, some patients experience obstructive apnea and a drop in S_pO_2 during sleep when using this technology. Diaphragmatic pacing systems do not have alarms, although failure can occur. This technology is also expensive, with initial costs in excess of $300,000.[10]

Although diaphragmatic pacing equipment is much smaller than a portable ventilator, it does not provide many additional advantages. Patients can learn to talk and eat with a TT in place by using a portable ventilator. The use of phrenic pacing is probably best reserved for children with high spinal cord injuries or central hypoventilation who cannot use other noninvasive methods to assist ventilation.[10]

Continuous Positive Airway Pressure for Obstructive Sleep Apnea

Clinicians should be aware of the fact that some patients who require some form of noninvasive support may have OSA and need additional assistance to treat this disorder. An accepted method of treating patients is the application of CPAP via a face mask or nasal mask.

The decision to use CPAP depends on the degree of upper airway obstruction that the patient demonstrates and his or her respiratory muscle strength. For those patients who have adequate respiratory muscle strength and do not require mechanical ventilation but become hypercapnic and hypoxemic during sleep, nasal CPAP may be all that is necessary to alleviate hypoxemia and alveolar collapse. This is especially true for patients with OSA. CPAP levels can be titrated to increase expired lung volumes during sleep and reduce inspiratory and expiratory resistance, resulting in improvement of P_aO_2, decreased respiratory rate, and prevention of air trapping. The diagnosis of OSA and the procedure for establishing the appropriate level of CPAP for the patient are typically performed in a sleep study laboratory.[41]

CPAP Systems

A nasal CPAP system for homecare consists of two main elements: an air blower unit and a nasal mask system.[75] The blower incorporates an electrically powered motor, fan assembly or turbine, and a mechanism for setting and controlling the pressure delivered to the circuit. Air from the blower is delivered to the nasal mask through a lightweight 21-mm-diameter corrugated plastic hose that is attached to a one-way valve or a whisper swivel valve. These specialized valves prevent expired gas from flowing into the inspiratory limb and typically include a fixed leak.

The nasal mask system usually includes a soft, translucent mask. The mask is available in a variety of sizes designed to custom fit faces (see Figs. 19.4 through 19.7).[77] Other alternatives to the nasal mask include the nasal pillow (Fig. 21.8; see also Fig. 19.8) and the oral mask. Nasal pillows are short silicone tubes that fit the patient's nares to eliminate excessive leaks. A small opening in the nasal interface allows for exhalation of gases. The oral mask is a soft silicone mouthpiece with an inner flap that fits inside the mouth and in front of the teeth. An outer silicone flap is positioned on the outside of the mouth, sealing the lips. Nasal masks, nasal pillows, and oral masks are secured to the face by lightweight, adjustable headgear.

Levels of CPAP ranging from 2.5 to 20 cm H_2O are available on most homecare units. Home CPAP units incorporate electronic pressure transducers that sense pressure changes in the circuit and regulate the amount of flow into the circuit. As the patient inhales and the circuit pressure decreases, the pressure transducers increase the blower speed, allowing more air to move into the circuit. As the patient begins to exhale and circuit pressure increases, the amount of air flowing into the circuit decreases. The increase and decrease of airflow in response to circuit pressure changes allow the patient to inhale and exhale against the same pressure.

Operation of these CPAP units by patients and their family simply involves turning the "on/off" switch to the "on" position. The level of prescribed CPAP is set by the respiratory therapist or medical supplier during installation of the unit in the home. Most

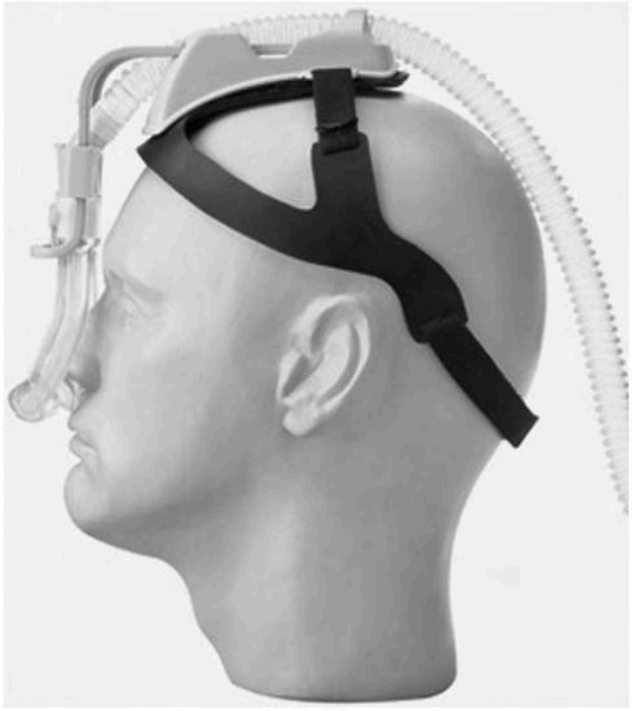

Fig. 21.8 The Aura nasal interface for the Aura CPAP system, fitted with specially designed nasal pillows. (Courtesy AEIOMed, Inc., Minneapolis, Minn.)

current devices have "hidden" menus and controls that prevent access by the user. Once the prescribed levels are set, a panel conceals the controls.

Potential complications of CPAP. All forms of positive pressure ventilation have associated risks and complications. However, the risk for such problems is greatly reduced by using CPAP, compared with conventional mechanical ventilation. Complications associated with CPAP by nasal mask are reviewed in Chapter 19 and are summarized in Table 21.1.[56,77-80]

Glossopharyngeal Breathing

Glossopharyngeal breathing, or "frog" breathing, is a technique for assisting alveolar ventilation in patients with poor respiratory muscle strength. Patients who may benefit from learning this technique include those with spinal cord injury or *postpolio syndrome.* The technique requires good tongue strength, an intact gag reflex, absence of tracheostomy, and the ability to close the nasal passages and larynx and to swallow.[81]

Glossopharyngeal breathing is performed as follows. Approximately 50 to 100 mL of air is trapped in the oropharynx when the mouth and nasopharynx are closed. Then the jaw and larynx are raised while the continued forward motion of the tongue forces air from the larynx into the trachea. Then the glottis is closed and the technique is repeated. Approximately 10 to 15 rapid swallows are repeated in approximately 10 seconds, during which time the volume of air going into the lungs increases. The larynx is then opened and the patient exhales passively. A well-trained patient can perform 10 to 12 such breaths per minute, accomplishing adequate minute ventilation.[10]

The technique is difficult to learn, but once it is mastered, it can significantly increase inspiratory capacity and expiratory flow sufficient to generate effective coughs. It may also allow VAIs increased time off the ventilator and security in the event of ventilator failure during sleep.[81]

TABLE 21.1 Complications Associated With Mask CPAP or NIV Therapy

Problem	Possible Solution
Aerophagia—gastric distention	Lower peak inspiratory pressure (<20–25 cm H_2O) Use PSV Alter sleeping position Use abdominal strap
Hypoxemia/ desaturation	Correct mouth leaks Increase CPAP levels
Nasal dryness or congestion	Increase humidification Spray nasal passages with saline
Eye irritation	Correct mask leaks Use other interfaces
Patient discomfort from head straps	Alternate other interfaces
Nasal or dental pain, dental deformities	Alternate other interfaces

CPAP, Continuous positive airway pressure; PSV, pressure support ventilation.
Compiled from Bach JR, Saporito BA: Indications and criteria for decannulation and transition from invasive to noninvasive long-term ventilatory support, Respir Care 39:515–528.

EXPIRATORY MUSCLE AIDS AND SECRETION CLEARANCE

Patients with neuromuscular disorders, restrictive intrinsic lung disease, and COPD may use NIV techniques for as long as 24 hours a day, thus avoiding tracheostomy (see Chapter 19). However, one of the major difficulties with this type of support is the management of airway secretions, especially when respiratory infections are present. Adequate respiratory muscle function is critical for clearing airway secretions. Most VAIs do not have sufficient strength to produce an effective cough. That is, they cannot generate a vital capacity (VC) of more than 1.5 L or a peak cough expiratory flow (PCEF) of more than 3 L/s.[82] Some form of cough assistance is necessary if pulmonary complications are to be avoided. The following techniques have successfully improved lung volumes and reversed arterial desaturation from secretions and mucus plugging: assisted coughing, chest wall oscillation, and mechanical insufflation-exsufflation.

Assisted Coughing

Assisted coughing is a technique of applying abdominal thrusts or compression to a patient's anterior chest wall during the expiratory phase of breathing. The purpose is to increase expiratory gas flow. This maneuver requires a well-coordinated effort between the patient and caregiver. Before applying the thrusts, the patient is instructed to take a deep breath to maximum inspiratory capacity. If the patient's VC is less than 1.5 L, a positive pressure deep insufflation is administered before expiratory thrusts. A manual resuscitator can be used for this purpose. The expiratory thrusts

can increase the patient's expiratory flow to approximately 5 L/s provided that the patient is cooperative and the caregiver has adequate physical effort and coordination.[82] Manually assisted coughing is usually not effective for severe scoliosis or obesity and is contraindicated for patients with osteoporosis. It should not be performed on patients after they have consumed a meal.

Mechanical Oscillation

High-frequency mechanical oscillation is a technique in which rapid pressure pulses are applied to the chest wall or upper airway. The purpose is to assist in the mobilization of secretions. The Vest (Advanced Respiratory, Hill-Rom, Corp, St. Paul, MN) and the Hayek Oscillator (Breasy Medical Equipment Ltd, London, UK) are devices used to deliver high-frequency external chest wall oscillation.[41] With these devices, chest wall vibrations are delivered to a vest placed around the patient's thorax. Vibrations are produced through a series of air pressure pulses delivered to plastic bladders located on the inner walls of the vest. The air pressure pulses are produced by an air compressor connected to the vest by large-bore, corrugated tubing. For some VAIs, airway clearance with chest wall oscillation may be more effective than chest physical therapy or oscillating valve devices (e.g., Flutter device or Acapella). Additional studies are needed to support these findings.[83]

Mechanical Insufflation-Exsufflation

The theory of operation of mechanical insufflation-exsufflation (MI-E) involves inflating the patient's lungs via a mouthpiece, mask, or tracheostomy and then providing forced exsufflation as the positive pressure rapidly decreases to subatmospheric pressure. The insufflator-exsufflator (Courtesy Philips Respironics, Murrysville, PA) shown in Fig. 21.9 allows manual cycling between positive and negative pressure so that caregiver-patient coordination is optimized. Its use is typically reserved for patients in whom manually assisted coughing is inadequate.

Pressures can be adjusted from +65 to −65 cm H_2O, but pressures of ±30 to ±40 cm H_2O are the most commonly effective and best tolerated pressure ranges.[10,82] These ranges represent a 60 to 90 cm H_2O change in pressure over a 0.2-second period. One treatment consists of approximately five cycles of positive to negative pressure swings followed by short periods of normal breathing or positive pressure ventilation to allow the patient to rest. The cycles can be repeated every 10 to 15 minutes as needed.

The MI-E may be the most effective alternative for generating optimal PCEF and clearing airway secretions. PCEF has increased to as much as 6 to 10 L/s during therapy and can be increased more if a manual abdominal thrust can be synchronized with exsufflation.[82] MI-E does not cause the airway irritation and discomfort associated with tracheal suctioning and may actually decrease the production of airway secretions. Abnormal VC values, flows, and arterial O_2 saturation (S_aO_2) values can significantly improve with clearing of mucus plugs by MI-E.[82] No significant complications have been reported with the use of this device. However, it is contraindicated in patients with bullous emphysema or pulmonary disorders that predispose a patient to barotrauma.[1]

Fig. 21.9 CoughAssist mechanical insufflation-exsufflation device. (Courtesy Philips Respironics, Murrysville, PA.)

TRACHEOSTOMY TUBES, SPEAKING VALVES, AND TRACHEAL BUTTONS

As mentioned, the use of TTs is an important part of long-term ventilation. When a TT is used, methods for allowing the patient to talk should also be pursued if possible. When it is time for **decannulation** (removal of the TT), the option of using a tracheal button can be evaluated.

Tracheostomy Tube Selection and Benefits

As discussed in Chapter 20, placement of a TT is essential when long-term ventilation is required. Early placement of a TT in VAIs has several advantages (Box 21.11).[84,85] The type of TT used depends on the needs of patient. In patients at risk for aspiration and who are unable to speak, a cuffed tube is appropriate. For those who might aspirate but are able to speak, a specialized TT that allows for speech may be considered (see later discussion). Using a cuffless tube or deflating the cuff may promote speech for patients who have no trouble swallowing and have the ability to speak.[1,86] Cuffless tubes are also recommended for children younger than 8 years. Fenestrated TTs can be used for transitioning from a cuffed tube to decannulation. However, they are not recommended for long-term use because granulomatous tissue can grow into the fenestrations. When discontinuing a TT after long-term use, a general practice is to insert progressively smaller TTs. In this way,

BOX 21.11 Advantages of Early Tracheostomy Tube Placement in Ventilator-Dependent Patients

- Improved patient comfort
- Increased potential for speech
- Ability to eat by mouth
- More effective airway suctioning
- Decreased airway resistance
- Enhanced patient mobility
- A more secure airway
- Improved ventilator weaning times
- Reduced risk for ventilator-associated pneumonia
- Improved likelihood of transfer of ventilator-dependent patients from the intensive care unit

greater expiratory flow can be directed through the vocal cords, allowing for speech.[84,85]

Loss of Speech

The use of an artificial airway for patients requiring mechanical ventilation produces sudden loss of the spoken word, which makes communication difficult. The ability to speak has a profound effect on the quality of life for VAIs.

Patients in the ICU usually attempt to communicate by mouthing words, using gestures, and nodding the head,[87] but for VAIs, loss of speech can make emotional adjustments to a difficult life even more challenging, leading to anxiety, fear, and depression.[12] The ability to communicate through speech can dramatically improve a patient's outlook on life. Although the emotional aspect of providing speech to VAIs has not been extensively studied, those who work with VAIs notice a substantial change in patients' attitudes when they are able to talk.[88]

For an infant requiring a TT, its use may have to be extended into the period when the child learns the skill of speaking a language. For this reason, professional evaluation of the child's language and vocal skills is important.[89] Children are at risk for delays in communication skills development if therapeutic intervention does not occur.[89]

Various techniques and devices have been investigated that allow speech in patients with tracheostomies. This includes techniques of cuff deflation during ventilation with VC-CMV, bilevel positive pressure ventilation, and CPAP and the use of different devices that allow speech in patients who have normal-functioning oral and laryngeal structures. These devices include allowing for speech with a TT in place, electronically activated devices, self-activated pneumatic systems, speaking TTs, and one-way valves for speaking (e.g., Passy-Muir valve, Irvine, Calif.).

Speaking With Tracheostomy Tubes During Ventilation

In patients who can tolerate deflation of the TT cuff during ventilation or CPAP, speech can be accomplished. For speech to occur, tracheal pressures of approximately 2 cm H_2O are required to vibrate the vocal cords and produce a quality voice.[90] (Normal speaking pressure is 5–10 cm H_2O.)

With cuff deflation during positive pressure ventilation, air is allowed to flow around the cuff and through the vocal cords during the inspiratory cycle of the ventilator. During exhalation, with the cuff deflated, most of the exhaled air will exit the ventilator's expiratory valve and speech is interrupted.[91] If PEEP is applied, it impedes expiratory flow through the ventilator's expiratory valve so that air flows through the larynx. This occurs because most ventilators will increase flow during exhalation to maintain the set PEEP level when a leak (deflated cuff) is present. In this way, flow may pass through the larynx during exhalation as well. In addition, by using both a longer inspiratory time (T_I) and PEEP, an additive effect is produced that increases speaking time and speech quality.[91,92]

For patients receiving CPAP, the cuff can be deflated without substantial loss of pressure (median, 1 cm H_2O at CPAP of 7.5 or 10 cm H_2O). This allows patients to speak without clinically significant changes in heart rate, respiratory rate, or S_pO_2 levels.[86]

Cuff deflation of VAIs is not without potential problems. The size of the TT and its position in the airway may increase resistance of air movement and increase the patient's WOB. Additionally, if the upper airway becomes occluded, the result will be hyperinflation of the lungs, a drop in cardiac output, and possible barotrauma. During pressure support ventilation, in which the breath is flow cycled, the cycling of the ventilator may be affected by cuff deflation and the leak that results. The CareFusion LTV series ventilator has an option of time cycling a pressure support breath, which would assist with cycling in the presence of a leak. Cuff deflation for speech is not recommended with critical care ventilators because it can affect their function.

Patients who require the use of a TT for prolonged periods may have multiple defects in the swallowing mechanism. Before a cuff is deflated to allow speech, patients need to be evaluated for the ability to swallow, protect the airway, and avoid the risk for aspiration.[91,93]

Electrically Activated Speaking Devices

The handheld electronic larynx allows speech when the device is held against the outside of the neck and is frequently used by patients with laryngectomies to facilitate speech. The electronic larynx produces an unnatural vocal quality, which some patients find frustrating. It also requires hand coordination, which may be difficult for some physically impaired individuals.

Electronic resonators are also available. With these devices, a small tube is placed in the mouth, which activates a resonator as the patient attempts to speak. Notice that because the tube is inside the mouth, the patient may not be able to speak clearly.[94]

Speaking Tracheostomy Tubes

Three specialized TTs that allow for speech are the Portex Speaking TT (Smiths Medical, St. Paul, MN), the Pitt speaking TT (National Catheter Corp, division of Mallinckrodt, St. Louis, MO), and the voice tracheostomy tube (VTT). The Portex Speaking TT has an opening in the posterior portion above the cuff (Fig. 21.10). Through this opening an external flow of air is directed through

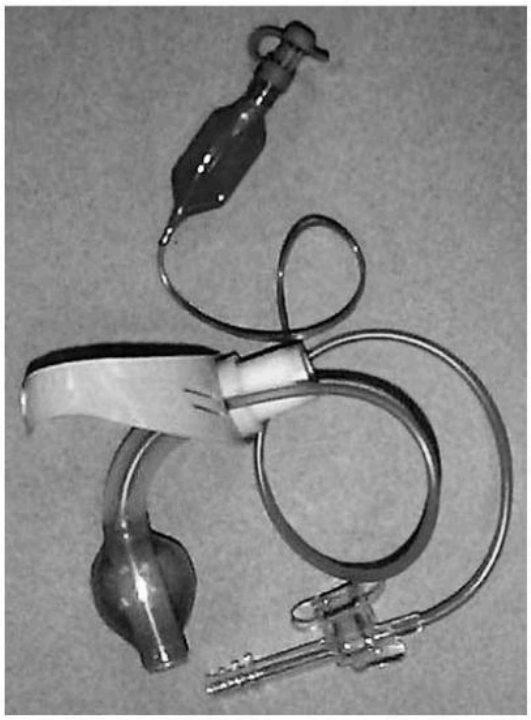

Fig. 21.10 The Portex speaking tracheostomy tube. (From Hess DR, MacIntyre NR, Mishoe SC, et al.: *Respiratory care principles and practice,* Philadelphia, PA, 2002, WB Saunders.)

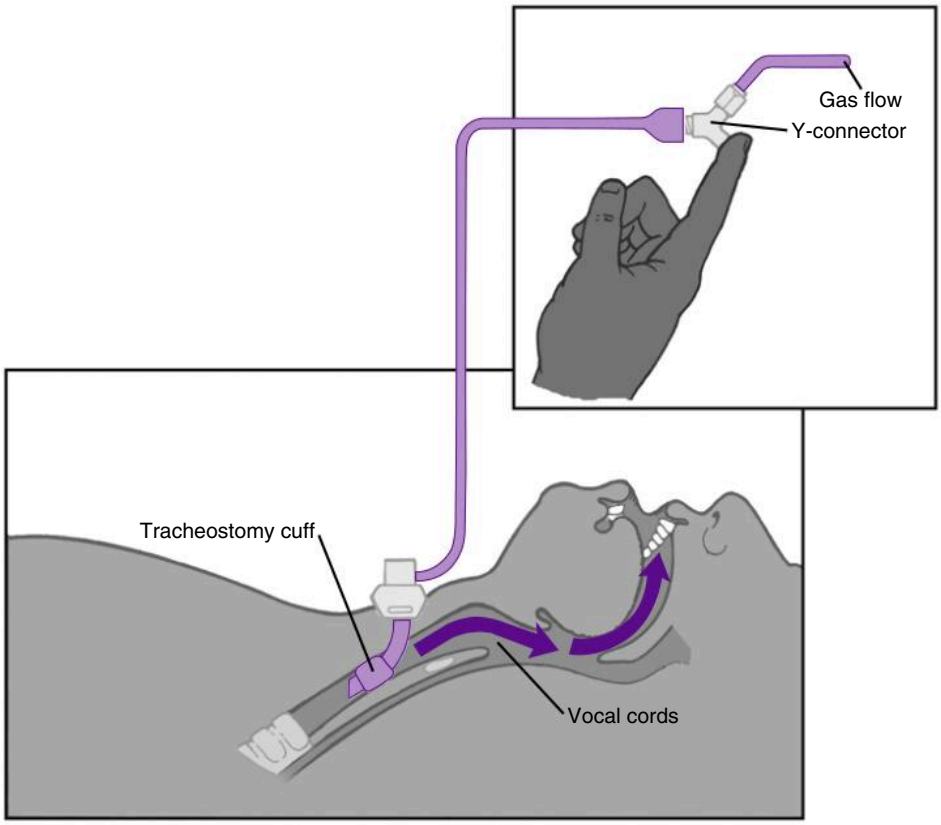

Fig. 21.11 A "talking" tracheostomy tube, in which gas flow to the airway is directed from an opening in the tracheostomy tube above the cuff and through the larynx when the patient obstructs the open port with the finger. (From Wilkins RL, Stoller JK, Scanlan CL: *Egan's fundamentals of respiratory care,* ed 9, St. Louis, MO, 2009, Mosby.)

the vocal cords and allows speech. The patient controls flow by covering the port on the air connection line (Fig. 21.11).[95,96]

The Pitt speaking TT (Fig. 21.12) uses an extra lumen through which gas can be directed either continuously or intermittently.[97] The gas flows upward through the larynx and allows speech.[98] These specialized tubes may require flows of 6 to 8 L/min to be effective and voice quality can still be poor. In addition, the port above the cuff can become occluded during use. The added flow for talking TTs may result in throat dryness.[89]

The VTT cuff inflates during the inspiratory phase of positive pressure and deflates during exhalation.[99] The VTT apparently allows patients to speak during ventilation while maintaining adequate alveolar ventilation, without aspiration and without damage to the tracheal mucosa. Additional studies may demonstrate the effectiveness of the VTT (Case Study 21.2).[88]

Tracheostomy Speaking Valves

Speaking valves are used to allow speech in patients with a TT in place. Examples of speaking tracheostomy valves include the Passy-Muir, Shiley (Mallinckrodt, Pleasanton, CA), Shikani (The Airway Company, Forrest Hill, MD), and Montgomery (Stuart K. Montgomery, Westborough, MA). Note that the Passy-Muir is currently the only valve that has approval from the U.S. Food and Drug Administration for use in line with a ventilator.

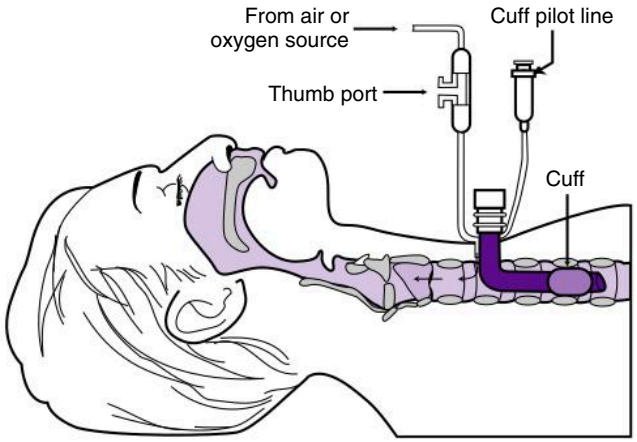

Fig. 21.12 A Pitt speaking tracheostomy tube. (From Cairo JM, Pilbeam SP: *Mosby's respiratory care equipment,* ed 8, St. Louis, MO, 2010, Mosby.)

Speaking valves do not require a separate air source; therefore the patient does not have to occlude a valve with the finger to speak. This could be an obvious advantage for some patients.[100] Speaking valves have a 15-mm inner diameter connector that fits over the proximal end of any standard TT. These valves are generally connected between the TT connector and the Y-connector.[100]

Case Study 21.2

Patient Case—Communication Difficulty

A 74-year-old male patient is being supported by IPPV through a tracheostomy tube. The patient has a history of progressive muscular dystrophy and chronic obstructive pulmonary disease. He is in a long-term ventilator care hospital. The patient is on IMV with a rate of 6 breaths/min, V_T of 750 mL, and PEEP of 5 cm H_2O. His F_IO_2 is 0.3. He is alert and cooperative. The patient expresses frustration with his inability to communicate with his wife. What might the respiratory therapist suggest to help reduce the patient's frustration and allow him to speak?

A piece of 22-mm-diameter flexible, corrugated tubing can be placed between the speaking valve (attached to the tracheostomy connector) and ventilator's Y-connector.[101] This may add a small amount of mechanical dead space to the circuit but can add flexibility to the circuit attachment (Fig. 21.13).

For the valve to work, the cuff of the TT must be deflated. With the Passy-Muir valve the one-way valve opens on inspiration, allowing gas to flow to the lungs. During exhalation the valve closes and air is directed to the larynx and upper airway (Key Point 21.4). The Passy-Muir valve has been shown to improve speech flow, reduce speech hesitancy, and increase speech time.[102] The Passy-Muir valve has been shown to reduce aspiration during swallowing.[103-106]

***Key Point* 21.4** A heat-moisture exchanger (HME) should not be used when a Passy-Muir valve or similar device is used. Expired gas must pass through the heat-moisture exchanger for it to function properly.

Speaking valves can be used on ventilator-dependent patients or spontaneously breathing patients with TTs. They can be used to help wean patients from TTs by allowing them to adjust to air moving through the upper airway again (Key Point 21.5). When using a speaking valve for the first time, the patient should be evaluated to ensure no untoward side effects occur. For example, if the space between the TT and tracheal wall does not allow adequate exhalation, or if the tracheostomy is in place because of tracheal stenosis, the patient may be unable to exhale effectively. This can lead to air trapping and hyperinflation of the lungs with the potential complications of pneumothorax and subcutaneous emphysema.[89] One method to test for air trapping is to remove the speaking valve and listen for a "puff" of air. The "puff" may occur as air that could not be exhaled through the mouth passes through the TT.[89] On the other hand, airway pressures may increase because of exhalation through the oropharynx, which causes a low level of PEEP. This may allow the readjustment of the set PEEP. If peak pressures rise above allowable limits, however, the valve needs to be immediately removed.[107] Initial evaluation of valve placement includes checking respiratory rate, heart rate, S_pO_2, changes in respiratory pattern or effort, increased coughing, increased peak pressures, and expressions of patient discomfort.

***Key Point* 21.5** A child with a TT in place should never be left unattended when a speaking valve is in place.[89]

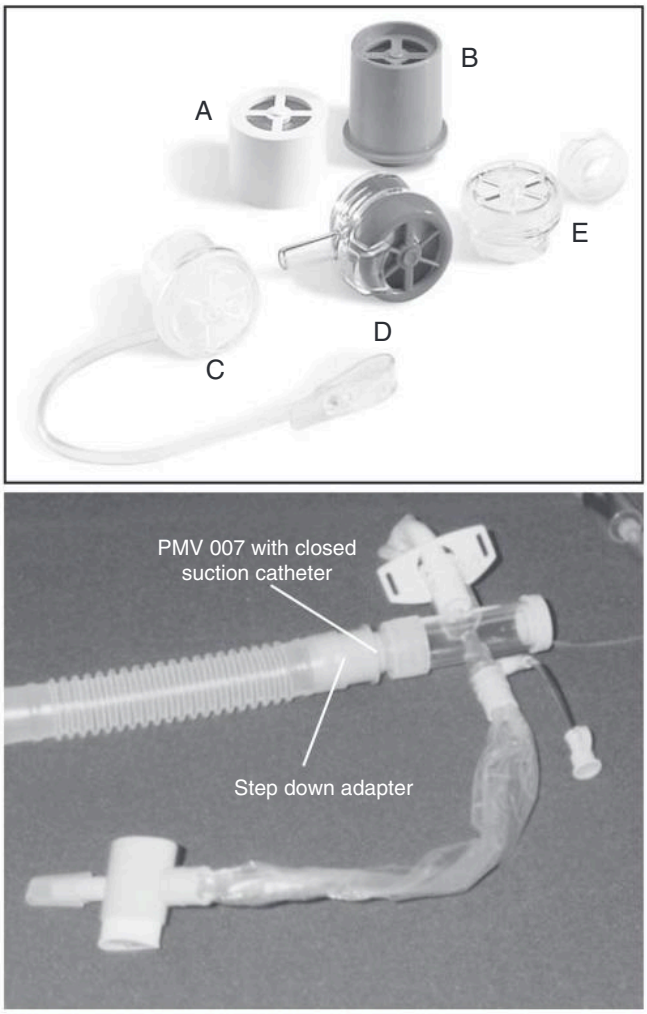

Fig. 21.13 *Top,* Examples of Passy-Muir speaking valves (PMV). (A) PMV005 (white); (B) PMV007 (aqua); (C) PMV2000 (clear) with the PMV Secure-It; D, PMV2001 (purple) with the PMV2000 oxygen adapter; (E) PMV2020 (clear) with the PMV2020-S adapter. *Bottom,* The valve in line during mechanical ventilation. (Courtesy Passy-Muir, Inc., Irvine, CA.)

Before a speaking valve is attached to a ventilated patient, the following steps are performed:

1. The upper airway and pharyngeal area above the cuff and trachea are suctioned.
2. Peak inspiratory pressure and V_T are checked.
3. The TT cuff is deflated.
4. The V_T setting may need to be increased to maintain adequate ventilation.
5. The peak pressure alarm and disconnect alarms are adjusted.
6. The patient's heart rate, respiratory rate, S_pO_2, effectiveness of cough, passage of air into the oral cavity, and subjective expression of comfort are monitored.[101]

If the cuff is deflated during mechanical ventilation, some air will leak. For patients who depend on a set volume delivery, the V_T setting can be increased. Activation of the peak pressure alarm may indicate poor exhalation (through the mouth) and buildup of pressure. Water condensate from the ventilator circuit can obstruct the valve. The volume must be readjusted and the cuff reinflated when a speaking valve is removed to avoid overinflation or hyperventilation. After use, ventilator parameters should be rechecked and the patient assessed. Currently the Puritan Bennett 760 ventilator has a speaking valve setup to accommodate the use of a speaking valve.[108]

Patients have reported feeling better and more motivated about their own care when a speaking valve is used. This is illustrated in the following Clinical Scenario.[100,109]

From Ellison B, Ellison J: *The Brooke Ellison story*, New York, 2001, Hyperion.

Clinical Scenario: A Patient's Experience With the Passy-Muir Valve

Brooke Ellison is a young woman who is quadriplegic and ventilator dependent. She presented an inspiring lecture during the American Association for Respiratory Care's 50th Anniversary International Congress in New Orleans, La. In part of her presentation she mentioned her first opportunity to speak, although she has a TT. This is an excerpt from the book *The Brooke Ellison Story* with her mother, Jean Ellison:

"When can we start weaning Brooke off the ventilator?" I asked the RT when he arrived to change Brooke's ventilator tubing.

"We'll be working on that," he said, but in a way that seemed to indicate that it was not on his list of priorities as it was on mine.

"What do you think about trying to speak, Brooke?" He asked, in a way that I couldn't tell whether he was just making conversation or whether he knew something that I didn't know.

"What?" Ed (Brooke's father) said, not really sure of what he had just heard.

"Would you like to speak, Brooke?" he asked again, pulling a small circular piece of blue plastic out of his pocket and holding it up for us all to see.

"What's that?" I asked.

"It's a Passy-Muir valve," he said.

"A what?" Ed asked again, not really understanding what he was saying.

"It's a Passy-Muir valve. We can put it in Brooke's ventilator tube to redirect her exhaled air over her vocal cords and, as a result, allow her to speak. Would you like to try it, Brooke?" he said.

Brooke, in excited disbelief, moved her lips and said, "Yes."

"How does it feel?" I said, after the RT fit it in her tube.

Brooke stared back and didn't say anything. She looked scared and confused as if she had forgotten how to speak.

"Brooke, Love, can you say something?" Ed said anxiously.

After a long pause, Brooke said: "This . . . feels . . . weird," in a raspy, breathy voice.

She wasn't used to how it worked, so each word she spoke came out slowly, separated by a breath or two from her ventilator. Ed and I looked at each other and started to cry.

"I . . . sound . . . that . . . bad?" she asked in the same raspy, staccato voice when she saw us crying.

"Oh, my God, no," I said. "It's the most beautiful sound I've ever heard."

Concerns With Speaking Tubes and Valves

Some precautions are needed with speaking valves. The cuff must be deflated when it is attached. Whenever a cuff is deflated, regardless of the reason, an increased risk for aspiration may exist. Increased resistance to breathing through the valve, the TT, or between the tube and the wall of the trachea may occur during spontaneous breathing and speech. If more than 10 cm H_2O of pressure is required for the patient to generate a breath through the tube, WOB may dramatically increase.

Supplemental O_2 may be required when using speaking tubes if a significant amount of room air is entrained and the S_pO_2 of the patient decreases. Speaking devices may be contraindicated in the following circumstances[89]:

- Comatose or unconscious patient
- Foam cuff in place or cuff that must remain inflated
- Increased or thick secretions
- Severe upper airway obstruction
- Increased airway resistance and increased compliance that may cause air trapping (e.g., COPD)
- Endotracheal tube in place (not TT)
- Reduced lung compliance
- Laryngeal and pharyngeal dysfunction

Tracheal Buttons and Decannulation

The need to constantly keep a TT in place may eventually end. When concerns exist about a patient's ability to tolerate decannulation, the procedure is best observed on an inpatient basis. This can be done in a nonacute care setting. However, a nurse, respiratory therapist, and physician should be immediately available during the procedure.[110] The airway is inspected to ensure the airway lumen is of an appropriate size and is not affected by scarring, narrowing, or obstruction. This can be accomplished with a flexible fiberoptic endoscope.

A protocol can be used that progressively downsizes the TT. The patient is observed during the size reduction process to be sure it is tolerated. Eventually the tube is capped. Once capping of the tube is well tolerated, the tube can be removed and the tracheotomy wound covered with an occlusive dressing. Most of the time the tracheotomy wound will heal without further intervention.

Occasionally a stoma must be maintained because the patient will require additional surgical procedures, such as head, neck, or maxillofacial surgery. The stoma can be kept patent by using a tracheal button. Tracheal buttons may be used to preserve the site for patients with OSA treated by tracheotomy.[78,110] The button consists of two pieces, a hollow inner cannula and an external cap (Fig. 21.14). The inner cannula fits between the outside of the patient's neck and inside of the trachea. To determine the appropriate depth before insertion, a toothpick-sized measuring device, which resembles a small golf club, is used to determine the depth of insertion of the cannula. The short L-shaped end is inserted in the stoma and hooked on the edge of the trachea. The clinician then places a gloved fingertip at the outside edge of the measuring device to mark the external point at the neck and then unhooks the distal end from the edge of the tracheal wall and removes the device. The distance from the fingertip to the end of the instrument is the cannula depth needed. To adjust cannula size, various rings can be added to the outer (proximal) part of the cannula. The cannula is then inserted. This is followed by placement of the cap. When the cap is inserted all the way, the flanges at the distal end of the cannula flare outward, locking the button in

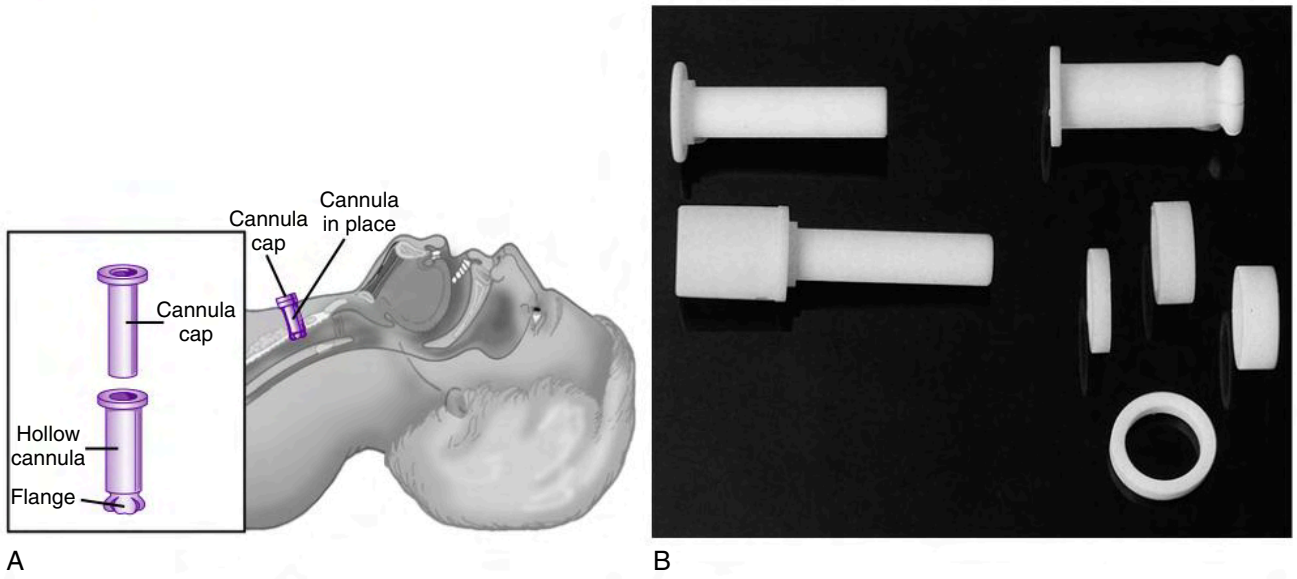

Fig. 21.14 The Olympic tracheostomy button showing various-sized rings for adjusting the depth of the button in the tracheal wall. (*A*, From Cairo JM: *Mosby's respiratory care equipment,* ed 9, St. Louis, MO, 2014, Mosby. *B*, From Kacmarek RM, Stoller JK, Heuer AJ: *Egan's fundamentals of respiratory care,* ed 10, St. Louis, MO, 2013, Mosby.)

place inside the trachea. It is recommended that the button be rotated approximately one-quarter turn daily to prevent tissue growth into the flange. A 15-mm adaptor is available to allow manual bag ventilation if needed.

Most patients will be anxious about removal of the TT. They are usually concerned about their ability to breathe, clear secretions, and protect their airway when the TT is no longer in place.[110] These concerns need to be addressed and the procedure performed in a safe and comfortable environment.

ANCILLARY EQUIPMENT AND EQUIPMENT CLEANING FOR HOME MECHANICAL VENTILATION

In addition to the mechanical ventilator, a patient ventilated at home requires various supplies for general daily care, including supplies for airway care, humidification, supplemental O_2, disposable circuits, and an emergency backup ventilator. The type and quantity of medical equipment necessary in the home depend on the patient's clinical status, age, and mode of mechanical ventilation. Patients receiving mechanical ventilation through noninvasive methods obviously require less equipment than patients with tracheostomies requiring continuous invasive mechanical ventilation. Box 21.7 lists the potential equipment and supplies that may be necessary for patients requiring continuous ventilatory support.

Disinfection Procedures

The presence of an artificial airway in a compromised ventilator-assisted patient makes the potential for infection from contaminated equipment a risk in the home setting, so infection control and decontamination procedures are taught to all persons involved in caring for the patient at home. Infection control measures emphasize avoiding person-to-person and object-to-person contamination. Family members and other caregivers are instructed to wash their hands thoroughly before and after touching the patient or equipment. The use of gloves (nonsterile) is encouraged when performing tasks such as suctioning or tracheostomy care.[111]

Ventilator Circuit Disinfection

As previously discussed, when circuits are changed less frequently, the risk for VAP decreases.[112-115] The National Center for Infectious Diseases suggests that circuits need not be changed unless they are nonfunctional or if they are visibly soiled with secretions or blood.[116] Changing the circuit less frequently is also less costly. The rates of VAP in long-term ventilated patients in long-term acute care hospitals and the home environment have been reported to be much lower compared with VAP rates in acute care facilities when national Centers for Disease Control and Prevention (CDC) guidelines are followed.[117-119]

When equipment is to be cleaned, it is first disassembled and rinsed with tap water. Then it is washed in a mixture of lukewarm water and mild detergent to remove all foreign matter. It is then rinsed thoroughly with tap water. The parts are soaked in an effective disinfectant solution for approximately 10 minutes.[1] Finally, it is rinsed thoroughly, air-dried, and placed in a plastic bag. Ideally a patient should have at least three circuits so that one can be in use while the other is being disinfected and the third drying.

Because Medicare does not reimburse for most disposable supplies or will reimburse for only a limited number of disposable supplies, many homecare patients are taught to clean and reuse supplies when possible. Suction catheters, for instance, are often cleaned and reused in the home. This is safe as long as the procedure for cleaning is followed carefully (Box 21.12). The American Association for Respiratory Care

BOX 21.12 Procedure for Reusing Suction Catheters

1. Wash two plastic containers in warm water and detergent solution. Rinse them under running water and soak in disinfectant solution for 10 minutes. Allow to air-dry. Store one container for later use and use the second container to store suction catheters between uses.
2. After a suction procedure is completed, tap water should be aspirated through the catheter to clear the inside. The outside of the catheter is wiped with a clean gauze or sponge.
3. The catheter is disconnected from the connecting tubing and placed inside the plastic container. The lid is then closed.
4. Catheters are removed from the container, to be reused as needed.
5. The catheter and plastic container are changed after 8 hours of use.
6. The dirty catheter is rinsed with cold tap water to remove all mucus.
7. The catheter is washed with a solution of warm water and detergent, rinsed under running water, and the excess water shaken off.
8. The catheter is then soaked in disinfectant solution for a minimum of 10 minutes.
9. Afterward, the catheter is removed, rinsed, and air-dried on a clean paper towel.
10. After drying the catheter completely, it is placed in a plastic bag and closed until ready for use.
11. The procedure in step 1 is followed to clean and disinfect the plastic container.

provides a clinical practice guideline for suctioning of the patient in the home.[111]

White vinegar mixed with distilled water (acetic acid content of 1.25%) is an adequate disinfectant solution but should be discarded after use and not reused.[120,121] Activated glutaraldehydes and quaternary ammonium compounds can also be used at home following manufacturer's recommendations.[111] Although these may be the disinfectant solutions of choice, their cost and availability are limiting factors. Whatever method is used, equipment must be processed in a clean, dry space separate from food preparation areas.

Water to be used as a diluent or in humidifiers needs to be boiled for 30 minutes and stored in a sterile container in a refrigerator. After 24 hours, the water should be discarded. Box 21.13 reviews a procedure for cleaning ventilator-related equipment in the home.[122,123]

Humidifiers

The CDC recommends the use of sterile water in the humidifier used for long-term ventilation. Because heated humidifiers are often used, condensate will normally build in the circuit. The condensate can pool in the dependent limbs of the circuit and make it difficult to both trigger the ventilator into inspiration and exhale. For this reason, the condensate should be removed from the circuit regularly. When handling the circuit, efforts must be made to avoid accidentally allowing circuit condensate to spill into the patient's airway.[11,116]

BOX 21.13 Guidelines for Disinfecting Home Ventilator Equipment

Preparation

1. Choose a clean, dry area.
2. Have all supplies ready for use.
3. Wash hands (gloves may be worn).

Procedure

1. Disassemble circuit completely. Wipe small tubes with clean, damp cloth.
2. Rinse large-bore tubing, connectors, humidifiers, and exhalation valve with cold tap water.
3. Soak equipment in warm, soapy water for several minutes.
4. Scrub equipment with a small brush to remove dirt and organic material.
5. Rinse thoroughly to remove any soap residue and drain off excess water.
6. Place equipment parts in disinfectant solution. Be sure that all parts are submerged.
7. After 15 minutes, rinse equipment thoroughly.
8. Drain off excess water, hang tubes to dry, and place small parts on a clean surface to dry.
9. When equipment parts are dry, reassemble circuit and store it in a clean plastic bag.

SUMMARY

- LTMV is required by two categories of patients: those recovering from an acute illness and those with chronic progressive disorders.
- The overall goal of LTMV at home or other alternative care sites is to improve the patient's quality of life.
- LTMV can be administered in acute care units, intermediate care facilities, and long-term care sites, including the home environment.
- Discharging VAIs to the home or an alternative care site is a complex process that involves careful patient selection, adequate financial resources, a knowledgeable and dedicated health care team, and a patient and family willing and able to take the responsibility for self-care management at home.
- The respiratory therapist assumes a large responsibility for selecting and placing primary and ancillary equipment, evaluating the home or alternative care site, coordinating in-hospital training of patients and caregivers, assisting in patient discharge and transfer, and following up with continuing care.
- Many types and models of ventilators are available for home use. Some of these are quite sophisticated, offering an array of modes, alarm systems, and other complex ventilatory characteristics.
- The most important factors in choosing a ventilator are its reliability, safety, versatility, whether its controls are easy to understand and manipulate, and whether it can be easy to cycle in the VC-CMV mode for patients with some spontaneous effort.
- The pulmonary, cardiovascular, and GI problems in VAIs are similar, in many respects, to those seen in critically ill patients on ventilation.

- In addition to the mechanical ventilator, a patient undergoing ventilation at home requires various supplies for general daily care, including supplies for airway care, humidification, supplemental O_2, disposable circuits, and an emergency backup ventilator.
- Perhaps one of the more important roles that the respiratory therapist must fill when caring for patients receiving LTMV is that of an educator. The ability to teach the patient and caregivers how to use the equipment properly and safely and alleviate the patient's fears and apprehension of ongoing care and emergency management is essential to the success of any home mechanical ventilation program.
- LTMV in the home environment is more likely to be successful when the patient and family are highly motivated, maintain hope, and communicate effectively.
- This increased awareness of the effectiveness of LTMV suggests that it is a desirable method of managing patients requiring long-term ventilatory support.[124]

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

1. All of the following are realistic goals of home mechanical ventilation except:
A. To extend life
B. To improve the physical, psychological, and social functions of the individual
C. To reverse the disease process
D. To reduce the amount of hospitalizations

2. According to the criteria for patient selection, which of the following conditions would be most suitable for successful homecare ventilation?
A. A patient with fibrotic lung disease on continuous ventilatory support with high F_IO_2 values and PEEP
B. A patient with progressive muscular dystrophy
C. A patient with severe COPD, cor pulmonale, and recurrent respiratory tract infections
D. A patient with terminal lung cancer who is postpneumonectomy

3. Which of the following factors must be considered when estimating a patient's cost of home mechanical ventilation?
1. Type of ventilator selected
2. Accessory medical supplies
3. Need for professional caregivers
4. Adequacy of third-party coverage
A. 1 and 2
B. 1 and 3
C. 2, 3, and 4
D. 1, 2, 3, and 4

4. In terms of cost and patient independence, the facility that is generally the least expensive and provides the most patient independence is:
A. A long-term acute care facility
B. An extended care facility
C. The patient's home
D. An in-hospital pulmonary step-down unit

5. Which of the following factors must be considered when selecting a ventilator for homecare ventilation?
1. Electrical adequacy of the patient's home
2. Ventilator versatility to accommodate the patient in all areas of the home
3. Sophisticated and elaborate alarm system
4. Ease of ventilator operation for caregivers
A. 1 and 2
B. 1, 2, and 3
C. 2, 3, and 4
D. 1, 2, and 4

6. Additional considerations for discharging a child to home mechanical ventilation include which of the following?
A. Reevaluation because of growth
B. Stamina for periods of play while ventilated
C. Well-educated family with good financial outlook
D. A large number of siblings to assist as caregivers

7. Which of the following NPVs is most efficient for providing ventilatory assistance but is cumbersome?
A. Pneumobelt (intermittent abdominal pressure ventilator)
B. Chest cuirass
C. Full-body chamber
D. Body suit (jacket ventilator)

8. Follow-up assessment of a home-ventilated patient on a regular service schedule generally includes which of the following?
1. Vital signs
2. ABG evaluation
3. S_pO_2
4. Portable chest radiograph
A. 1 only
B. 2 only
C. 1 and 3
D. 1, 2, 3, and 4

9. Which of the following are experienced by family members caring for VAIs in the home?
1. Loss of work time
2. Loss of privacy when outside caregivers are in the home 24 hours a day
3. Financial stress
4. Transmission of nosocomial infections from patient to family
A. 1 and 3
B. 2 and 4
C. 1, 2, and 3
D. 1, 2, 3, and 4

10. Which of the following pieces of equipment, besides the ventilator, is essential to accomplish IPPV in the home?
A. TT
B. Good-fitting nasal mask
C. Capnograph
D. Tracheal button

11. Which of the following should be available for patients who require continuous ventilatory support?
A. A 12-volt DC battery for backup power
B. A backup ventilator
C. A manual resuscitation bag
D. All of the above

12. Which of the following ventilator modes is not recommended for VAIs when using a first-generation portable/homecare ventilator?
A. VC-CMV
B. IMV (volume targeted)
C. Pressure support
D. Volume-targeted control (apneic patient)

13. A patient with stable COPD has been selected for homecare ventilation. His ABG values are stable while on a volume ventilator with VC-CMV with the following settings: VT of 500 mL, *f* of 10 breaths/min, and F_IO_2 of 0.3. What operational features need to be considered when selecting his home mechanical ventilator?
A. Optional modes of operation
B. Capabilities for the addition of O_2
C. Low and high minute ventilation alarm
D. High and low F_IO_2 alarm

14. A patient with high spinal cord injury has been selected for home mechanical ventilation. The patient has a tracheostomy and is on VC-CMV with room air. In addition to this patient's ventilator, what other equipment will be needed?
1. Backup ventilator
2. Tracheostomy care kits
3. Concentrator
4. Portable suction unit
5. Manual resuscitator
A. 1, 2, and 4
B. 1, 2, 3, and 5
C. 1, 2, 4, and 5
D. 1, 2, 3, 4, and 5

15. While preparing a patient for discharge home, the respiratory therapist should instruct the patient and family to do what?
A. Wash and dry the ventilator equipment as needed
B. Soak the equipment in warm soapy water, rinse, and towel dry twice daily
C. Soak the equipment in warm soapy water, scrub to remove organic material, rinse, and place in disinfectant solution and rinse again
D. Boil the equipment in water for 10 minutes and then allow it to air-dry before packaging

16. A patient with a progressive neuromuscular disorder has been selected for home mechanical ventilation. What should the health care team include in the discharge plan?
1. Instruct family and caregivers on aseptic suction procedures
2. Give detailed instructions on cardiopulmonary resuscitation
3. Provide a written protocol with directions for respiratory treatments and other aspects of care
4. Assess the caregivers as they demonstrate techniques they have learned
A. 1 only
B. 3 only
C. 2 and 4
D. 1, 2, 3, and 4

17. All of the following should be considered when preparing a patient for home mechanical ventilation except:
A. The family's critical care experience
B. The family's ability to operate the ventilator adequately
C. The availability of financial resources
D. The electrical safety and available space in the patient's home

18. A written report should be completed monthly during the follow-up and evaluation of patients on home mechanical ventilation. Which of the following conditions should this monthly report include?
1. ABG analysis
2. Patient and family apprehensions
3. Proper functioning of the equipment
4. Compliance with the therapeutic plan
A. 3 and 4
B. 1, 2, and 3
C. 1, 2, and 4
D. 1, 2, 3, and 4

19. Which of the following patients would benefit from CPAP by nasal mask or nasal pillows?
A. A patient with progressive neuromuscular disease requiring a chest cuirass at night only
B. A patient diagnosed with congestive heart failure who has good respiratory muscle strength
C. A patient with stable COPD requiring nocturnal ventilation
D. A patient with kyphoscoliosis who has episodes of hypercapnia and hypoxemia at night

20. A potential complication of providing NPV with a chest cuirass to a patient with COPD is
A. Increased cardiac output
B. OSA
C. Hyperventilation
D. Barotrauma from excessive pressures

21. Alternative methods of assisting ventilation noninvasively include which of the following?
1. NIV
2. Pneumobelt
3. Rocking bed
4. NPV
A. 1 and 4
B. 2 and 3
C. 2, 3, and 4
D. 1, 2, 3, and 4

22. A patient is receiving ventilatory support at night by NPV with a body suit. The suit is unable to achieve the normal target pressure of −30 cm H_2O. The most likely cause of the problem is:
A. The shell is not attached correctly to the back plate.
B. There is a leak in the system.
C. This device cannot achieve a pressure of −30 cm H_2O.
D. The patient is too small for the device.

23. A patient on nasal mask CPAP reports dried, irritated nasal passages. All of the following will be beneficial in remedying this problem except:
A. Readjusting the nasal mask for better fit
B. Periodically irrigating the nasal passages with normal saline
C. Using a chinstrap
D. Adding a humidifier to the circuit

24. The advantages of using MI-E in conjunction with PPV include
1. It generates optimal PCEF for clearing airway secretions.
2. It does not cause airway irritation or discomfort.
3. It may decrease the production of airway secretions.
4. It may improve VC and S_aO_2 associated with mucus plugging.
A. 1 and 2
B. 2, 3, and 4
C. 2 and 4
D. 1, 2, 3, and 4

25. Methods for improving secretion clearance, besides suctioning, might include:
    A. Assisted coughing
    B. Mechanical oscillation
    C. MI-E
    D. All of the above
26. List five factors that can contribute to psychological problems that can occur in VAIs.
27. Speaking can be accomplished in VAIs who are on non—critical care ventilators by deflating the cuff and making what ventilator adjustments?
28. The Portex and Pittsburg speaking tracheostomy tubes require the patient to perform what function?
29. What step is absolutely essential when using a speaking valve?
30. List six circumstances in which speaking devices may be contraindicated.

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CHAPTER 22

Neonatal and Pediatric Mechanical Ventilation

OUTLINE

KEY TERMS

- Bronchomalacia
- Bronchopulmonary dysplasia
- Choanal atresia
- Cleft palate
- Extracorporeal membrane oxygenation
- Meconium aspiration syndrome
- Neonate
- Patent ductus arteriosus
- Pediatric
- Prophylactic therapy
- Rescue therapy
- Tracheoesophageal fistula
- Tracheomalacia

LEARNING OBJECTIVES

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

1. Discuss the clinical manifestations of respiratory distress in neonatal and pediatric patients.
2. Identify differences in the level of support provided by different forms of noninvasive support.
3. Describe respiratory support device function and settings for different mechanical respiratory support strategies.
4. Identify the primary and secondary goals of ventilatory support of newborn and pediatric patients.
5. Explain some key areas of assessment that influence the decision on whether to initiate ventilatory support.
6. Recognize the indications, goals, limitations, and potentially harmful effects of continuous positive airway pressure (CPAP) in a clinical case.
7. Describe the basic design of nasal devices used to deliver CPAP to an infant.
8. From patient data, recognize the need for mechanical ventilatory support in newborn and pediatric patients.

9. Identify the essential features of a neonatal and pediatric mechanical ventilator.
10. Explain how the advanced features of a ventilator enhance its usefulness over a wide range of clinical settings.
11. Relate the major differences between older-generation neonatal ventilators and modern microprocessor-controlled mechanical ventilators.
12. Distinguish demand flow from continuous flow and discuss other modifications that have been made to the basic infant ventilator.
13. Select appropriate ventilator settings on the basis of the patient's weight, diagnosis, and clinical history; also discuss strategies and rationale for ventilator settings.
14. Discuss newborn and pediatric applications, technical aspects, patient management, and cautions for the following ventilatory modes: pressure-controlled ventilation, volume-controlled ventilation, dual-controlled ventilation, pressure support ventilation, airway pressure release ventilation, and neurally adjusted ventilatory assist.
15. Discuss the rationale and indications for high-frequency ventilation (HFV) in newborn and pediatric patients.
16. Compare the characteristics and basic delivery systems of the following HFV techniques: high-frequency positive pressure ventilation, high-frequency jet ventilation, high-frequency flow interruption, high-frequency percussive ventilation, and high-frequency oscillatory ventilation.
17. Explain the physiological and theoretic mechanisms of gas exchange that govern HFV and defend the mechanism thought to be most correct.
18. Explain how settings of a given high-frequency technique are initially adjusted, the effect of individual controls on gas exchange, and strategies of patient management.
19. Discuss the physiological benefits of inhaled nitric oxide therapy and suggest recommended treatment strategies.

RECOGNIZING THE NEED FOR MECHANICAL VENTILATORY SUPPORT

Mechanical ventilation of newborn and pediatric patients involves the use of devices that recruit and maintain lung volumes, improve gas exchange and lung mechanics, assist in overcoming the resistive properties of an artificial airway, and reduce the work of breathing (WOB). These devices may provide continuous positive airway pressure (CPAP), assist spontaneous ventilation (e.g., noninvasive positive pressure ventilation [NIV], bilevel positive airway pressure [BiPAP] units), or support part or all of the patient's ventilatory requirements (e.g., invasive mechanical ventilation).

Currently there are no well-defined, disease-specific criteria available to guide the decision on when to initiate or discontinue mechanical ventilatory support in newborns and pediatric patients in respiratory distress. In fact, many institutions with desirable outcomes prefer to implement ventilatory support before the onset of severe respiratory illness, making the process of initiating support even more complicated. The ongoing clinical management of patients requiring ventilatory support also remains an elusive practice that is based more on experience and clinician preference and less on experimental data obtained from large randomized controlled trials.

This chapter focuses on the best available clinical and experimental evidence for initiating and managing neonatal and pediatric respiratory support. For the purpose of this discussion, a **neonate** will be defined as any infant younger than 44 weeks of age, and **pediatric** will include any patient beyond the neonatal period and up to adolescence.

Clinicians caring for neonatal and pediatric patients must understand the causes and pathophysiology of the various diseases and conditions that affect the airways and lung parenchyma of these patients. They must also be knowledgeable about the theory of operation, limitations, and complications of the different ventilatory support devices used. In addition, clinicians must be able to interpret findings from the history and physical assessment, laboratory studies, radiographic findings, and physiological data derived from monitoring to evaluate the effectiveness of the ventilatory support provided. Keep in mind that although these data are a critical part of the decision-making process, other factors must be considered when initiating mechanical ventilation in these patients. In many cases, the approach to initiating ventilatory support may have to be individualized for neonates and pediatric patients, because anatomical structure, size, and disease severity can vary widely from one patient to the next.

Clinical Indications for Respiratory Failure

Respiratory failure is defined as the inability to establish or maintain adequate gas exchange. Respiratory failure can manifest at birth and persist throughout the neonatal period or after a catastrophic event. Many pediatric patients encounter respiratory failure as a chronic condition (e.g., bronchopulmonary dysplasia [BPD]). Although lung disease is the most common cause of respiratory failure, many extrinsic factors can predispose patients to this life-threatening event. For example, hemodynamic conditions associated with congenital cardiac anomalies can also contribute to respiratory failure. Neonatal and pediatric patients have smaller lungs, greater airway resistance (R_{aw}), lower lung compliance (CL), less surface area for gas exchange, and lower cardiovascular reserve than do adults, making them more vulnerable to rapid deterioration. In fact, respiratory failure is a major cause of cardiac arrest in neonatal and pediatric patients. As such, clinicians must act quickly to limit the potential adverse outcomes associated with respiratory failure by observing clinical signs and symptoms. These factors can guide timely intervention well before respiratory failure develops into full cardiopulmonary arrest.

Neonate

Neonates experiencing respiratory distress typically present with tachypnea, nasal flaring, and intercostal, substernal, and retrosternal retractions. The chest wall during infancy is composed primarily of cartilage, making the chest wall compliance much greater than that of the lungs. As the resistance and compliance worsen, neonates have to generate higher pleural pressures during inhalation, causing the "floppy" chest wall to collapse inward creating retractions. On exhalation, the neonatal chest wall lacks the necessary recoil to counteract the inward forces of the lungs, and thus the lungs are prone to premature collapse. Infants will attempt to maintain a back pressure in the lungs, to preserve the functional residual capacity (FRC), by narrowing the glottis and maintaining respiratory muscle activity (active exhalation). This can result in vocalization during exhalation, or "grunting," which is often mistaken for infants' crying. Grunting can usually be heard without auscultation and is a useful clinical sign of impending

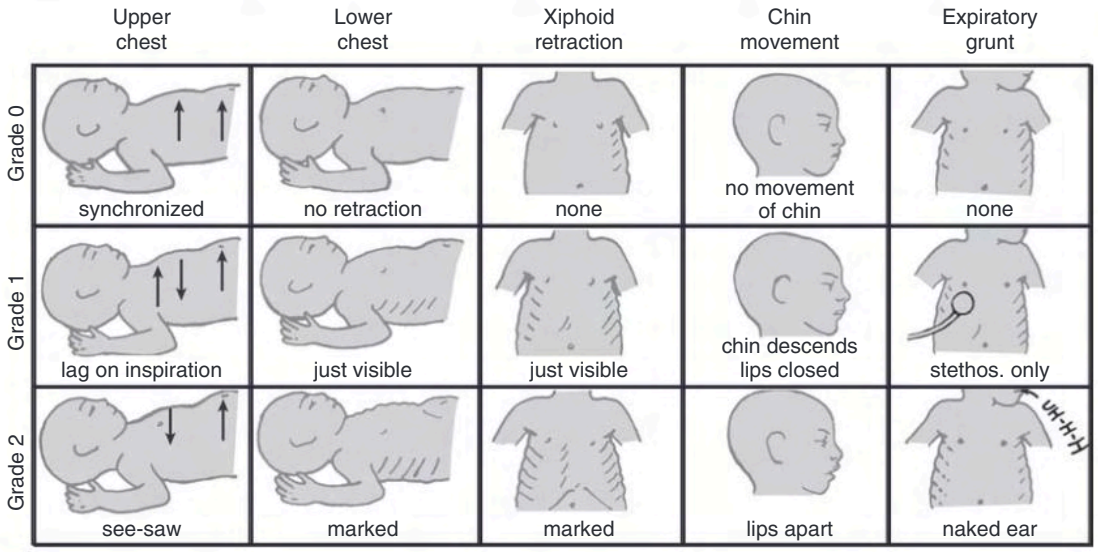

Fig. 22.1 The Silverman-Andersen score for assessing the magnitude of respiratory distress. (Modified from Silverman WA, Andersen DH: A controlled clinical trial of effects of water mist on obstructive respiratory signs, death rate and necropsy findings among premature infants. *Pediatrics* 17:1—10, 1956; Kacmarek RM, Stoller JK, Heuer AJ: *Egan's fundamentals of respiratory care,* 12th ed. St. Louis, MO, 2021, Elsevier.)

respiratory failure. The Silverman-Andersen respiratory scoring system is a useful clinical tool to assess the degree of respiratory distress in neonates (Fig. 22.1).

Although this tool has been available in the clinical setting for nearly three decades, it has recently been reintroduced in a number of institutions to better evaluate patient response to settings changes during CPAP and mechanical ventilation.[1]

Premature neonates can become apneic because of underdeveloped neural respiratory centers, poor gas exchange, and upper airway obstruction and may or may not respond to stimulation to reestablish spontaneous breathing. Infants who do not respond to gentle stimulation and caffeine therapy often require immediate respiratory assistance using a manual resuscitator, CPAP, NIV, and, when necessary, invasive mechanical ventilation.

Pediatric

Pediatric patients experiencing respiratory distress can present with some of the same clinical manifestations as neonates. However, larger pediatric patients have ossified or "stiffer" chest walls and can sustain longer periods of higher WOB than do neonates. Nonetheless, clinicians should be well versed in recognizing age-specific normal and abnormal respiratory and hemodynamic parameters before implementing mechanical respiratory support.

Determining Effective Oxygenation and Ventilation

Arterial blood gas (ABG) analysis is considered the gold standard for determining oxygenation, ventilation, and acid-base balance in neonates and pediatric patients with respiratory failure. It is important to recognize that frequent ABGs can deplete the circulating blood volume of small patients. Noninvasive techniques (i.e., pulse oximetry [S_pO_2], end tidal carbon dioxide [$etCO_2$], and transcutaneous carbon dioxide [$tcCO_2$] measurements) are alternative methods for trending gas exchange in most patients. Interpretation of ABG or noninvasive gas exchange values must also be coupled with data obtained from physical assessment and other clinical and laboratory data. For example, observing the color of the skin and mucous membranes can be used to assess tissue oxygenation; oxygen (O_2) delivery and tissue perfusion can be evaluated clinically by noting capillary refill. Indeed, close attention to vital signs and physical assessment findings can help prevent deterioration of ABG/acid-base status.

Patients with certain congenital heart defects often require a high pulmonary vascular resistance to prevent excessive pulmonary blood flow and maintain adequate systemic circulation and cardiac output; thus abnormal values are acceptable in this patient population before surgical correction. In addition, allowing CO_2 levels to rise and pH levels to fall to abnormal levels has become a common standard for lung protection during mechanical ventilation. If necessary, an individualized or standardized approach for managing gas exchange during ventilatory support should be identified early in management.

Chest radiographic evaluation is another important tool that can add to the overall clinical assessment of patients with respiratory failure or those receiving respiratory support. Because lung volumes are difficult to measure in neonatal and pediatric patients, chest radiographs can provide valuable insight into the approximate level of lung expansion in patients susceptible to developing atelectasis or hyperinflation. Many clinicians use the chest radiograph to guide the setting of ventilator parameters. It is important to realize the limitations of chest radiographs and understand that frequent radiography may expose patients to unnecessary high levels of radiation. The following sections provide more in-depth information about clinical and laboratory indications for mechanical ventilatory support.

GOALS OF NEWBORN AND PEDIATRIC VENTILATORY SUPPORT

The goals of mechanical ventilatory support in newborn and pediatric patients are as follows:

- To provide adequate ventilation and oxygenation
- To achieve adequate lung volume
- To improve lung compliance
- To reduce WOB
- To limit lung injury

One may argue that avoiding mechanical ventilatory support altogether or minimizing the duration of support should be the first goal, because even short-term ventilation can result in ventilator-induced lung injury (VILI).

Maintenance of an appropriate FRC ensures optimum lung mechanics, which leads to improved gas exchange, reduced WOB, and reduced VILI. To move gas into and out of the lungs, a patient with respiratory distress must generate relatively high intrathoracic pressures to balance the resistive and elastic components that resist lung inflation. Positive pressure ventilation can significantly reduce this burden and improve recovery in patients with lung disease. In fact, some patients receive chronic mechanical ventilatory support as a means of reducing caloric utilization by the respiratory muscles. These patients are often able to breathe spontaneously, but at a significant caloric cost that could prevent patients from growing normally. Mechanical ventilatory support can help promote normal function and development of the respiratory system, especially in neonatal patients with lung disease.

NONINVASIVE RESPIRATORY SUPPORT

Continuous positive airway pressure (CPAP) is used in spontaneously breathing patients and may be applied *with* or *without* an artificial airway. CPAP provides a *continuous distending pressure* to the lungs, which increases FRC and thus helps improve C_L. Often R_{aw} is also reduced, and the patient's WOB dramatically decreases with the use of CPAP.[2] CPAP is most commonly applied noninvasively to the nasal airway opening using nasal prongs or mask and has become more widely used over the past decade in the neonatal population as a strategy to avoid intubation and invasive mechanical ventilation and minimize VILI. In this discussion, the term *CPAP* refers to *nasal CPAP* (N-CPAP) in neonates. CPAP is often recommended for patients who have adequate alveolar ventilation and yet are hypoxemic despite receiving a fractional inspired oxygen (F_IO_2) >0.5. CPAP may be used to prevent atelectasis and reduce WOB in patients who have been weaned and extubated from the ventilator.

Noninvasive Nasal Continuous Positive Airway Pressure in Neonates

Indications and Contraindications

When introduced in 1971, CPAP was considered the "missing link" because it could provide O_2 therapy and minimize the need for invasive mechanical ventilation in the neonate.[3] Used appropriately, CPAP is a less invasive and less aggressive form of therapy than other forms of ventilatory support. Newborns with retained lung fluid, atelectasis, insufficient surfactant production, or respiratory distress syndrome (RDS) are good candidates for CPAP. Such patients include very-low-birth-weight (VLBW) and premature infants.[4] CPAP can be used successfully in infants with respiratory distress arising from other causes, including transient tachypnea of the newborn, **meconium aspiration syndrome**, primary pulmonary hypertension, pulmonary hemorrhage, and paralysis of a hemidiaphragm. CPAP is also used after surgical repair of diaphragmatic hernias, congenital cardiac anomalies, congenital pneumonias, respiratory syncytial virus (RSV), bronchiolitis, apnea of prematurity, and congenital and acquired airway lesions.[5]

Box 22.1 lists the indications for CPAP in neonates originally established by the American Association for Respiratory Care (AARC).[6]

Compared with standard O_2 therapy, CPAP reduces grunting and tachypnea, increases FRC and arterial O_2 partial pressure (P_aO_2), decreases intrapulmonary shunting, improves C_L, aids in the stabilization of the floppy infant chest wall, improves distribution of ventilation, and reduces inspiratory WOB.[5] CPAP is believed to reduce the severity and duration of central and obstructive apneas by mechanically splinting the upper and lower airways, promoting better alveolar recruitment, oxygenation, and stimulation of the infant to breathe.[7]

BOX 22.1 Indications for Continuous Positive Airway Pressure (CPAP) in Newborns Via Nasal Prongs, Nasopharyngeal Tube, or Nasal Mask

Abnormalities on Physical Examination

- Increased work of breathing (WOB), as indicated by a 30% to 40% increase above the normal respiratory rate *(f)*
- Substernal and suprasternal retractions
- Grunting and nasal flaring
- Pale or cyanotic skin color
- Agitation
- Inadequate arterial blood gas (ABG) values:
  - Inability to maintain a partial pressure of arterial O_2 (P_aO_2) above 50 mm Hg with a fraction of inspired O_2 (F_IO_2) of 0.6, provided minute ventilation $\dot{V}_E$ is adequate, as indicated by a partial pressure of arterial carbon dioxide (P_aCO_2) of 50 mm Hg and a pH of 7.25 or higher
- Poorly expanded and/or infiltrated lung fields on a chest radiograph
- Presence of a condition thought to be responsive to CPAP and associated with one or more of these:
  - Respiratory distress syndrome (RDS)
  - Pulmonary edema
  - Atelectasis
- Apnea of prematurity
- Recent extubation
- Tracheal malacia or other abnormality of the lower airways
- Transient tachypnea of the newborn
- Very-low-birth-weight infants at risk for the development of RDS as an early intervention along with surfactant administration
- Administration of controlled concentrations of nitric oxide in spontaneously breathing infants

Modified from American Association for Respiratory Care: AARC Clinical Practice Guidelines: application of continuous positive airway pressure to neonates via nasal prongs or nasopharyngeal tube or nasal mask, *Respir Care* 49:1100–1108, 2004.

Although there is no consensus on how best to manage neonates on CPAP, two general approaches are currently being used to minimize the use of invasive mechanical ventilation and better protect the fragile neonatal respiratory system from VILI. Early CPAP involves implementing therapy in the delivery room or neonatal intensive care unit (NICU) only after the infant is stabilized and effectively breathing on his or her own. This is performed prophylactically even if the neonate is not exhibiting respiratory distress or apnea. The goal is to recruit air spaces and maintain lung volumes early to promote gas exchange and reduce the likelihood that respiratory failure and apnea will occur. This approach is beneficial for premature infants who lack lung surfactant and are at risk for developing atelectasis. Breathing at low lung volumes can result in unnecessary lung injury (atelectotrauma), which can hinder surfactant production. Many premature neonates can be managed successfully using CPAP without ever requiring NIV or endotracheal intubation and mechanical ventilation. If a premature patient does develop respiratory failure, he or she is either supported with NIV or intubated, given lung surfactant, and then promptly weaned from the ventilator and extubated. This approach is a drastic departure from earlier approaches that were used over the past 30 years, in which neonates would be intubated and placed on a ventilator for weeks or even months until they were a certain size or weight. Centers that implement early CPAP report a low incidence of infants developing chronic lung disease or BPD because the lungs are not being subjected to the relatively large inflation volumes and pressures generated with mechanical ventilation.[8,9] This early CPAP approach in premature infants has been shown to result in less need for intubation and fewer days of mechanical ventilation, and infants were more likely to be alive and free from the need for mechanical ventilation after a week than were neonates intubated for surfactant and supported with invasive mechanical ventilation for at least 24 hours.[10]

Another clinical approach in preterm infants implements elective intubation, prophylactic surfactant administration, short-term lung-protective ventilation, and rapid extubation to CPAP within hours of birth. (NOTE: This approach is also known as *InSURE* [*I*ntubate, *SUR*factant, *E*xtubation] and is implemented shortly after birth.[11]) The *InSURE* approach ensures that all premature infants will receive at least one dose of surfactant, but it does not eliminate the potential that even short-term ventilation can result in some degree of VILI. The *InSURE* approach has been associated with lower incidences of mechanical ventilation duration, air-leak syndromes, and BPD than an approach that administers surfactant and embraces prolonged mechanical ventilation support.[12]

The major question that remains is whether these two disparate approaches affect long-term survival and the development of chronic complications (e.g., BPD). Another important outcome related to these different approaches is the incidence of CPAP failure and subsequent ventilation requirements among neonates. Approximately 25% to 40% of infants with birth weights between 1000 and 1500 g may fail early CPAP and require intubation and mechanical ventilation, whereas 25% to 38% of infants with similar birth weights may fail CPAP using the *InSURE* approach.[5] Some institutions use a combination of these approaches in which smaller premature neonates (younger than 28 weeks' gestational age), with lower surfactant production in the lungs, will be supported initially using *InSURE* and larger neonates are supported using the early CPAP strategy. Both of these strategies strive to minimize invasive mechanical ventilation and have redefined the approach to supporting premature infants at risk for developing respiratory failure. Minimally invasive ventilation strategies, such as CPAP, have likely been a major reason why premature neonates are able to survive at a lower gestational age and with fewer complications than ever before. Given the recent findings showing lower rates of chronic lung disease/death compared with prophylactic or early surfactant, the American Academy of Pediatrics now recommends using N-CPAP immediately after birth, with selective surfactant as needed.[13] Additionally, they conclude there is no evidence for increased adverse outcomes and that, in fact, early N-CPAP may lead to a reduction in the duration of mechanical ventilation and use of postnatal steroids.[13]

Any neonate who has recently been extubated from mechanical ventilation is at risk for developing hypoxemia, respiratory acidosis, and apnea. Extubation to CPAP, regardless of whether surfactant was administered, has been associated with a reduction in the incidence of respiratory failure and the need for additional ventilatory support in neonates.[14]

Infants with certain congenital heart diseases reportedly benefit from CPAP. Cardiac anomalies that increase pulmonary blood flow can reduce C_L and FRC, thus increasing WOB and worsening hypoxia. The most common defects associated with increased pulmonary blood flow are ventricular septal defects, atrial septal defects, atrioventricular (AV) canal, and **patent ductus arteriosus**. Positive intrathoracic pressure produced by a CPAP system can mechanically reduce pulmonary blood flow while restoring FRC.[15,16]

Use of CPAP is not appropriate and is potentially dangerous in infants who show signs of nasal obstruction or severe upper airway malformation, such as **choanal atresia**, **cleft palate**, or **tracheoesophageal fistula**.[15] CPAP has been used in patients with bronchiolitis, but its use in these patients has been controversial and may be contraindicated in some cases.[6,17,18] More recent evidence suggests, however, that CPAP can result in favorable outcomes in infants affected with bronchiolitis by reducing CO_2 levels and eliminating the need for mechanical ventilation.[19]

Patients who have severe cardiovascular instability, severe ventilatory impairment (pH <7.25, P_aCO_2 >60), refractory hypoxemia (P_aO_2 below 50 Torr on >0.6 F_IO_2), or frequent apnea that does not respond to stimulation or intravenous caffeine therapy or patients who are receiving high levels of sedation may require intubation and mechanical ventilation rather than CPAP.[15] CPAP or any form of noninvasive positive pressure to the airway should not be used in infants with untreated congenital diaphragmatic hernia; these infants should be intubated to prevent gastric insufflations and distention and further compromise of the heart and lungs.[17] Some surgeons discourage the use of CPAP in infants after any surgical procedure involving the gastrointestinal (GI) tract.

Most commonly, CPAP is applied via nasal prongs; however, some clinicians prefer to use CPAP in intubated neonates while weaning from mechanical ventilation to observe whether the infant is experiencing apnea. Prolonged support using this approach should be discouraged whenever possible because it has been associated with an increased need for reintubation after the breathing tube has been removed.[14]

Application of N-CPAP

Because newborns are obligate nose breathers, N-CPAP can be applied in several ways. Previously, a short endotracheal tube (ET) was placed into one of the nares and taped to the face to provide nasopharyngeal (NP) tube CPAP. A snug-fitting set of short binasal prongs is the most commonly used interface. Neonatal

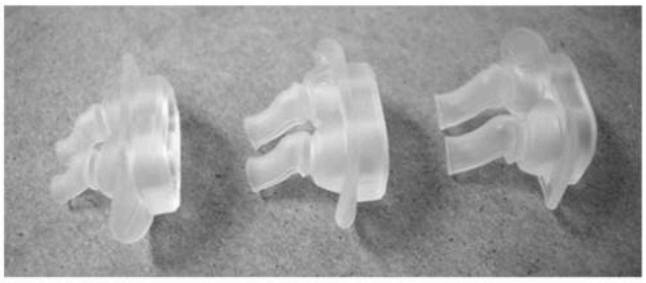

Fig. 22.2 Infant prongs for continuous positive airway pressure (CPAP) (see text for additional information).

nasal masks are gaining popularity among some clinicians. It is common practice to alternate between these two nasal airway interfaces. Both devices are effective, but the distending pressure they provide can be lost when the infant cries or breathes through the mouth. Binasal prongs and masks may be more beneficial than an NP tube because they are less invasive and provide the least amount of resistance to gas flow and hence lower imposed (or resistive) WOB and facilitate mobilization and oral feeding.[16,20] In addition, short binasal prongs were found to be more effective than using a single NP tube in reducing the rate of reintubation in premature neonates supported with CPAP.[21]

Nasal prongs and masks must be fitted correctly so that they do not leak or cause trauma to the patient. Nasal prongs and masks are usually made of a latex-free material, such as silicone. Molded into a manifold or attached to one, the prongs are placed just inside the infant's nares (Fig. 22.2). Prongs are available in a variety of sizes. The fit of the prongs is critical; they must fit snugly into the nares but must not be so tight as to cause skin blanching. If a nasal mask is used instead of prongs, it, too, must be carefully selected for proper size and fit. Masks can cause pressure injury to the skin if improperly fitted, and they may not seal if they are too large or small.

The entire CPAP apparatus is stabilized on the patient's head with headgear or a fixation system consisting of a bonnet, cap, or straps (Fig. 22.3). Many commercial system configurations are available. The correct size of straps and head coverings must be carefully chosen and adjusted so that no part of the infant's head is subjected to squeezing or occlusive pressure points.

Recent advances in noninvasive nasal interface technology have ushered in a hybrid-type interface that resembles a high-flow nasal cannula and does not require a bonnet fixation device. The Neotech Ram Cannula (Neotech Products, Valencia, Calif.) has wider tubing than a standard high-flow cannula that allows for flow and pressure delivery with noninvasive support. Although this device is approved for O_2 administration, many clinicians are using it with great success for CPAP and NIV.[22-24] Other investigators have shown that even small leaks with the RAM cannula result in large reductions in pressure.[25] However, effective pressures can usually be maintained with small leaks, despite the added tubing length and resistance.[26,27] This device has gained widespread acceptance to provide N-CPAP and nasal intermittent mandatory ventilation (N-IMV) because it is relatively easy to maintain and requires fixation similar to that of a nasal cannula.[27]

After the CPAP delivery device has been attached to the CPAP manifold, the CPAP level and F_IO_2 are set. The CPAP system is assessed frequently to ensure effective delivery. The patient's nose is checked regularly for signs of pressure necrosis, and the prongs must be checked routinely for patency.

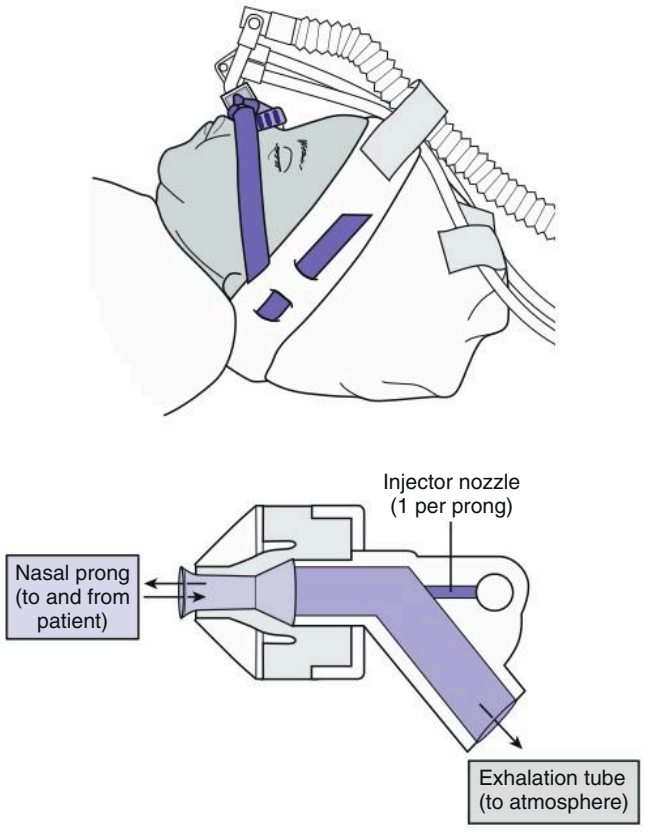

Figure 22.3 (A) Infant Flow and nasal prongs and bonnet fixation (B) Infant Flow Pressure Generator used with Infant Flow nasal CPAP and SiPAP unit (Becton, Dickinson and Company). (From Diblasi RM: Nasal continuous positive airway pressure [CPAP] for the respiratory care of the newborn infant, *Respir Care* 2009;54(9):1209-1235.)

***Key Point* 22.1** The success by which continuous positive airway pressure (CPAP) is applied to neonates is probably based more on the clinicians' abilities to understand the system and identify pathophysiological changes in response to settings changes than is the type of CPAP device or nasal interface being used.

The CPAP system functions primarily to regulate gas flow during inhalation and exhalation and to maintain a consistent pressure at the nasal airway opening. The CPAP system consists of the following five essential components:

1. A heated/humidified blended gas source
2. A nasal interface
3. A patient circuit
4. The pressure regulation mechanism
5. A means for monitoring and limiting the airway pressures[5]

Numerous studies have compared differences in gas exchange, WOB, and requirement for (re)intubation with the available CPAP devices; however, it is important to note that no single device has been shown to be superior to another when major outcomes (i.e., mortality and morbidity) in neonates are considered (Key Point 22.1).[5]

Over the past three decades, the most common CPAP system that has been applied noninvasively has been accomplished using a

mechanical ventilator. Ventilator CPAP also has been referred to as *conventional CPAP* in the clinical setting. Ventilator CPAP is convenient because it traditionally has been used after extubation from mechanical ventilation and does not rely on having to use a separate device to apply therapy. Many ventilator manufacturers have designed specific noninvasive CPAP modes into the ventilator platform exclusively for neonates. The clinician can set the CPAP level, and the exhalation valve regulates the pressures accordingly. Another advantage of these modes is that the ventilator may be able to deliver noninvasive "backup breaths" based on a preset apnea interval when the neonate has stopped breathing. One potential limitation of ventilator CPAP is that the demand flow system may not respond to changes in patient respiratory efforts because pressure is being measured at the ventilator and not at the patient's airway. In addition, new evidence suggests that the expiratory resistance of newer neonatal ventilator's exhalation valves may impose additional resistance and hence increase the WOB during spontaneous breathing.[28]

Freestanding CPAP devices that use fluidic gas principles have been widely used to provide CPAP to infants. The CareFusion Infant Flow SiPAP System (Becton, Dickinson and Company, Franklin Lakes, N.J.) (see Fig. 22.3A and B and Fig. 22.4) has a fully integrated flow controller, a delivery circuit, different-sized nasal prongs and masks that attach to a gas delivery manifold, and a bonnet with Velcro straps to secure the nasal interfaces. The manifold incorporates a fluidic flip-flop valve mechanism at the infant's nasal airway opening to regulate flow, match the infant's inspiratory demand, and provide a consistent pressure level (see Fig. 22.3B). The controller provides gas flow with an adjustable F_IO_2 and monitors CPAP pressure. Turbulence caused by continuous flow is minimized with this system to make exhalation easier and reduce WOB. The manufacturers have attempted to provide better-fitting, easier-to-secure nasal prongs to make CPAP more effective and patient care easier. These devices are particularly effective at reducing WOB in VLBW infants so that CPAP is better tolerated, which helps avert the need for intubation and positive pressure ventilation.[29]

Fig. 22.4 Infant flow "sigh" positive airway system (SiPAP) System. (© 2021 Vyaire Medical, Inc.; Used with permission.)

Bubble CPAP (B-CPAP) is a technique for delivering CPAP via a simple freestanding system and water column (Fig. 22.5). It has been used with homemade systems for more than 30 years and is again gaining favor over other CPAP techniques. In the United States, commercially available B-CPAP devices are now available (e.g., Fisher and Paykel Healthcare Bubble CPAP System, Auckland, NZ). B-CPAP systems consist of a blended and humidified gas source, patient circuits, nasal interfaces (prongs or masks), pressure manometer, and an underwater seal or water column. The blended gas flow is adjusted between 5 and 8 L/min, and the CPAP level is regulated by varying the depth of the distal expiratory circuit below the water surface (i.e., 5 cm = 5 cm H_2O CPAP). The CPAP delivery to the patient could increase when using higher flows[30,31] and may exceed the CPAP setting based on the submersion depth of the distal expiratory tubing. Thus clinicians should use the lowest flow possible to maintain constant bubbling throughout the respiratory cycle. An additional safeguard involves measuring the pressure at the nasal airway interface using a pressure manometer and limiting excessive pressures with a safety pop-off valve during B-CPAP.

Tiny vibrations or oscillations in the airway pressure created by gas bubbling through the water column may enhance gas exchange and lung recruitment. Anecdotal reports made by clinicians have observed the chest walls of premature neonates supported by B-CPAP oscillating at frequencies similar to those provided by high-frequency ventilation (HFV). However, these ventilation effects have never been quantified in neonates using leaky nasal prongs.[32]

Initial pressures for CPAP are commonly set at about 4 to 6 cm H_2O.[33] The CPAP level requirements are likely to fluctuate throughout treatment, and the optimal level results in adequate lung inflation without overdistending the lung parenchyma.[5] If little clinical improvement is seen, the level is gradually increased to 8–10 cm H_2O in increments of 1 to 2 cm H_2O.[11] The response is considered adequate when the required F_IO_2 is 0.5 or less and the P_aO_2 is at least 50 mm Hg.[34] Adequate oxygenation is usually accompanied by reduced WOB, as manifested by a 30% reduction in the respiratory rate and a decrease in retractions, grunting, and nasal flaring. In some cases, the chest radiograph indicates improvement by showing better aeration and increased lung volumes (Key Point 22.2).[35] Continuous noninvasive monitoring of transcutaneous CO_2, pulse oximetry, and Silverman-Andersen respiratory scores can provide reliable trending of physiological response in patients when adjustments are made to the CPAP level. A chin strap is useful for reducing oral leakage of gas and maintaining CPAP in the lungs. Also, an oral gastric tube is useful to eliminate gas from accumulating in the stomach, which can increase distress during CPAP.

Key Point 22.2 Regardless of the type of nasal prongs or nasopharyngeal tube used for continuous positive airway pressure, the clinician must always verify the patency of the device and strive to reduce injury by frequently assessing the proper fit.

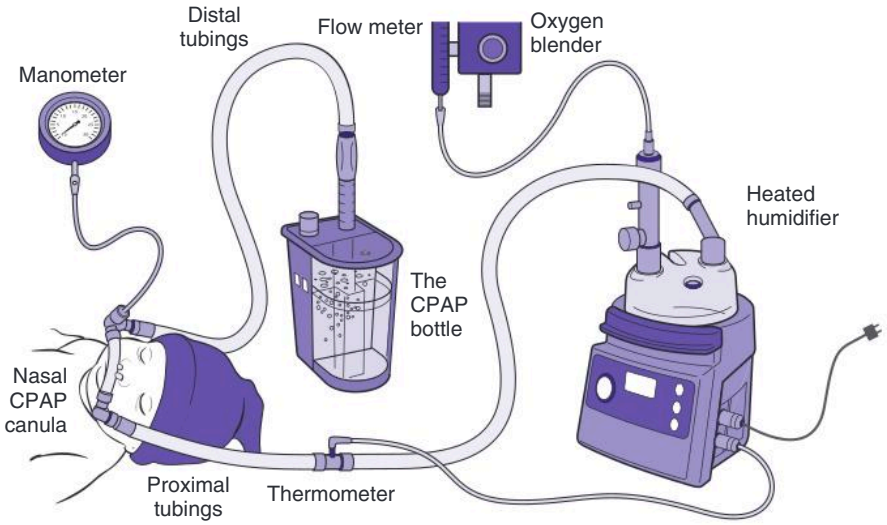

Fig. 22.5 Diagram of the bubble continuous positive airway pressure (CPAP) delivery system. (Redrawn from Aly H, Milner JD, Patel K, El-Mohandes AA: Does the experience with the use of nasal continuous positive airway pressure improve over time in extremely low birth weight infants? *Pediatrics* 2004;114:697–702.)

Complications of CPAP

CPAP can cause pulmonary overdistention and can lead to ventilation/perfusion ($\dot{V}/\dot{Q}$) mismatching, decreased pulmonary blood flow, increased pulmonary vascular resistance, and decreased cardiac output.[36] Marked overdistention can increase WOB and cause CO_2 retention.[37] Air-leak syndromes have also been reported.[38] The clinician must be aware that the CPAP system can cause abdominal distention and gastric insufflation, which can lead to aspiration if not detected and corrected early.[39] Perforations of the GI tract, although rare, are possible.[16] Excessive pressure from the application devices can injure the nose and nasal mucosa, and inadequate humidification can contribute to injury.

Noninvasive Positive Pressure Ventilation in Neonates

As noted in the previous discussion, a large percentage of neonates supported by CPAP still develop severe respiratory failure requiring endotracheal intubation and mechanical ventilation. Recent evidence suggests that invasive mechanical ventilation contributes to the development of BPD and other complications in neonates.[40] It is unclear whether this is related exclusively to the VILI or high oxygen levels or whether the presence of the ET in the airway is also a contributing factor. The neonate can experience endotracheal intubation as a traumatic and painful procedure, especially if proper sedation levels are not achieved. Intubation is accompanied by significant hemodynamic instabilities, airway injury, colonization of the trachea, reduced ciliary movement, secretions, high resistance to airflow, and increased WOB.[41]

Also known as "CPAP with a rate," NIV is an established form of noninvasive ventilatory support in adults and pediatric patients. It is accomplished by using superimposed synchronized or nonsynchronized positive pressure inflations with CPAP. NIV has become a standardized intermediary approach between CPAP and invasive mechanical ventilation to reexpand atelectatic areas, improve gas exchange, reduce respiratory distress, prevent apnea, and potentially avoid the need for invasive mechanical ventilation. NIV is commonly used as an initial form of respiratory support in neonates after extubation from invasive mechanical ventilation.[42] Like CPAP, NIV assists spontaneous breathing patients only, and thus neonates with persistent apnea cannot be supported by this method of mechanical ventilator support. Furthermore, not all neonates can be supported by NIV alone and intubation is indicated for severe ventilatory impairment (pH <7.25, P_aCO_2 >60), refractory hypoxemia (P_aO_2 <50 Torr on >0.6 F_IO_2), and frequent apnea that does not respond to stimulation or intravenous caffeine therapy.[43] The same complications that arise during CPAP and mechanical ventilation can also occur with NIV.

Most commonly, NIV is applied using short binasal prongs or a nasal mask and a fixation technique similar to that of CPAP. As improvements in nasal airway interfaces and ventilator devices have evolved, clinicians have begun implementing different forms of NIV in neonates with little experimental evidence to support their use. The following section discusses the most common methods and approaches for applying NIV in neonates.

Nasal Intermittent Mandatory Ventilation in Neonates

Nasal synchronized and intermittent mandatory ventilation, or *nasal IMV* (IMV or N-IMV), is the most commonly used form of NIV in neonates, and pressure control is the most common mode for providing NIV in neonates. Like nasal CPAP, it requires placement of an NP tube or snugly fitting nasal prongs or mask. In addition to the CPAP effect of the ventilator, the patient's spontaneous breaths are assisted by patient-triggered or machine-triggered, time-cycled, positive pressure inflations using a ventilator. Although ventilators equipped with proximal flow sensors have been used for patient-triggered N-IMV, appropriate triggering is difficult to obtain because of the large leaks that can occur between the patient airway and nasal interface.

Traditionally, the most commonly used device for patient-triggered N-IMV in neonates has been the Stars Synch abdominal capsule used with the Infrasonics Infant Star ventilator (Infrasonics Mallinckrodt, St. Louis, Mo.). The Infant Star ventilator is no longer being supported by the manufacturer; thus machine-triggered,

N-IMV breath types are being used with apparent success. In two recent publications there were no clinically relevant differences in WOB and gas exchange or rate of patent ductus arteriosus, intraventricular hemorrhage, periventricular leukomalacia, retinopathy of prematurity, necrotizing enterocolitis, or death/BPD in neonates, comparing patient-triggered with machine-triggered breath types during N-IMV.[44-46] A more recent study comparing N-CPAP with non–N-IMV shows N-IMV as a feasible mode of extubation in preterm infants with significant beneficial effects of reduced duration of NIV support, supplementary O_2, and decreased rates of chronic lung disease.

Advances in ventilator technology have recently introduced neonatal-specific N-IMV modes that are capable of synchronizing neonatal breathing efforts with positive pressure inflations without having to use a flow sensor.[47] A novel form of patient-triggered N-IMV called noninvasive neurally adjusted ventilatory assist (NAVA) is currently being used clinically. NAVA controls the ventilator by using the electrical activity of the diaphragm (EAdi). The EAdi signal is obtained by nine miniaturized electrodes embedded on a conventional nasogastric/orogastric tube. When properly positioned in the lower esophagus, the EAdi signal represents the spontaneous central respiratory drive. This signal is used to trigger the breath on and off, as well as help guide the inspiratory pressure level based on the EAdi and NAVA setting. Although this exciting new NIV option may result in improved synchrony, patient comfort, and gas exchange, there needs to be more research to determine whether noninvasive NAVA could affect outcomes differently compared with N-IMV in infants.[48]

Suggested initial N-IMV settings in neonates are inspiratory pressure of 16 to 20 cm H_2O, positive end-expiratory pressure (PEEP) of 4 to 6 cm H_2O, inspiratory time (T_I) of 0.35 to 0.45 seconds, rate 40 to 60 breaths/min, and F_IO_2 adjusted to keep saturations 90% to 96%.[43,48] Subsequent adjustments in peak inspiratory pressure (PIP) are made to improve chest rise, and ventilator rate is adjusted to maintain CO_2 levels. Pressure support ventilation is typically not provided to assist spontaneous breaths because of large airway leaks and ineffective triggering.

Compared with standard CPAP approaches, N-IMV has been shown to improve chest wall stabilization and synchrony, reduce WOB and apnea, and promote better gas exchange. These physiological differences are likely related to the use of higher mean airway pressures and the ability to provide active stimulation and sighs to recruit airspaces and prevent apneic episodes during N-IMV.[49] On the basis of findings from several clinical trials, premature neonates supported with patient-triggered N-IMV had fewer requirements for endotracheal intubation and less BPD than those supported by CPAP.[50] However, this form of support still remains controversial.[51] In a study comparing N-CPAP to N-IMV in extremely low-birth-weight (LBW) infants, the rate of survival to 36 weeks of age without BPD did not differ between the two forms of noninvasive support.[52] In addition, there have been no reported risks for GI insufflation or perforation related to the use of N-IMV in neonates. It has been suggested that the reduction in BPD from previous trials may be related to the absence of an ET and the natural pressure release created at the neonate's mouth and nasal airway, which may limit excessive pressure transmission to the distal airways during N-IMV.

Nasal "Sigh" Positive Airway Pressure in Neonates

Nasal "sigh" positive airway pressure (S) (nasal SiPAP) (see Fig. 22.4) is a form of N-IPPV used to assist spontaneously breathing infants in the NICU. Nasal SiPAP is different from other forms of NIV because it allows the neonate to breathe continuously at CPAP and during a sustained sigh breath to recruit lung units at two different lung volumes. Simply put, the neonate is able to breathe at high and low CPAP settings. The sum of alveolar ventilation depends on both the neonate's spontaneous minute ventilation and the minute ventilation created by nasal SiPAP when transitioning between the two preset CPAP levels. The higher CPAP level is generally set at 2 to 4 cm H_2O higher than the baseline CPAP pressure (4–6 cm H_2O), the breath hold at the higher CPAP level is set at 0.5 to 1 second, and the respiratory rate controls the frequency of the machine-triggered sigh breaths. The same nasal prongs, masks, and fluid-flip mechanism as the infant flow N-CPAP is used during SiPAP. Several small preliminary clinical studies in neonates after extubation have demonstrated that SiPAP provides better gas exchange and results in less need for invasive mechanical ventilatory support than conventional CPAP without causing additional lung injury.[53,54] Compared with similar mean airway pressures such as nasal N-CPAP, SiPAP does not improve CO_2 removal or oxygenation. Thus it may be important to set the mean airway pressure higher than CPAP when using this form of support, especially if a patient is failing conventional CPAP.[55]

Noninvasive Nasal High-Frequency Ventilation in Neonates

Nasal high-frequency ventilation (N-HFV) has been used more commonly as a form of NIV in clinical practice over the past decade. Unlike N-IMV and nasal SiPAP, N-HFV uses smaller pressures and higher frequencies and may be more lung protective than other NIV devices that apply higher pressure to the lungs. The most common ventilator that has been used to apply N-HFV is the Infrasonics Infant Star ventilator. The N-HFV is applied using either an NP tube or binasal prongs with fixation. N-HFV is unfortunately such a new form of NIV that there are few published papers to suggest a strategy for long-term management of neonatal patients. Initial mean airway pressure is usually set to equal the previous level of CPAP, its frequency is set at 10 Hz, and amplitude is adjusted to obtain visible chest wall vibration and increased every 30 minutes by 4 to 6 units, if necessary, to maintain clinically appropriate chest wall vibration or blood gases.[56] Research has demonstrated a significant reduction in P_aCO_2 in neonates transitioned from CPAP to short-term nasal HFV.[57,58] A similar study did not show differences in P_aCO_2.[56] There is also potential that nasal HFV could provide better CO_2 elimination than N-IMV.[59] Another short-term study showed that nasal HFV promotes better alveolar growth and development in preterm lungs than invasive mechanical ventilation.[60] This research has stimulated considerable interest in using nasal HFV as an initial form of ventilatory support for neonates failing CPAP and after extubation from mechanical ventilation. Although the widespread use of nasal HFV is not common, recent research has demonstrated that nasal HFV reduces the need for intubation and duration of mechanical ventilation than CPAP or NIMV in neonates with respiratory distress.[61]

Continuous Positive Airway Pressure and Bilevel Positive Airway Pressure in Pediatric Patients

Although CPAP is used less often for pediatric patients than adults, it is useful in children to restore FRC and reduce WOB

with acute hypoxemia, neuromuscular disorders, and conditions that cause abdominal distention. It is also used to relieve the airway obstruction associated with obstructive sleep apnea (OSA) or airway lesions such as laryngotracheal malacia. The use of CPAP for many of these purposes follows the guidelines established for adults (see Chapters 13 and 19).

Some clinicians recommend the use of ventilator CPAP trials to help evaluate an intubated patient's readiness for extubation after a weaning period during mechanical ventilation. The intent of the CPAP trial is to evaluate spontaneous breathing. However, WOB can increase markedly when CPAP is provided through a small ET. When spontaneous breathing evaluations are performed, enough pressure support to overcome ET resistance should be provided, or ET resistance compensation, a feature found on some ventilators, should be used. This approach is explored in more detail in the chapter on weaning and discontinuation of mechanical ventilation (Chapter 20).

In addition, CPAP may be provided effectively through a tracheostomy tube (TT). Patients who fatigue easily because of neuromuscular weakness or who are susceptible to lung collapse seem to tolerate CPAP by TT, especially if continuous or nearly continuous support is needed.

In nonintubated patients, nasal prongs, a nasal mask, or a full-face mask can be used in children through the toddler years. Nasal prongs that are designed for neonates are unable to be used in larger infants and toddlers. Furthermore, these patients may not be able to trigger the demand flow systems effectively in these devices. These factors pose a unique challenge for clinicians and manufacturers considering CPAP in this patient population. Children who are 3 years old or older, who require CPAP, are generally encouraged to use a nasal mask. Some of these patients are better managed with a full-face mask, especially if they require CPAP only intermittently. Pediatric patients with airway obstructions often benefit from CPAP. Certain obstructions, such as **tracheomalacia** or **bronchomalacia**, can make weaning from ventilation and extubation difficult. A decision may be made early in a patient's course to perform a tracheotomy and to apply CPAP on a 24-hour basis. Other patients with less severe obstructions may have difficulty breathing only when they are sleeping. These patients can avoid a tracheotomy and continue to rely on CPAP provided by nasal prongs. Many patients with obstructive lesions require surgery, and CPAP is often necessary until correction is complete.

Some patients have mechanical obstruction of the upper airway caused by soft tissue or excessive loss of muscle tone during sleep (i.e., OSA). OSA involves obstruction by either the tongue or soft palate. Often, CPAP can stent open these obstructions and dilate the oropharynx during sleep and reduce apnea.

The BiPAP system (Philips Respironics, Eindhoven, The Netherlands) delivers CPAP by nasal or full-face mask to children and adolescents. This device is useful for patients with higher inspiratory flow rates and can overcome leaks at the mask by increasing flow. It can also monitor the tidal volume (V_T) and minute ventilation, and it provides high and low alarms and high F_IO_2 levels.

CPAP systems are available for home use in patients who require chronic support. These units are recommended for nasal CPAP using nasal prongs or a mask in older children and adults. BiPAP units (e.g., Philips Trilogy) can also be set to deliver CPAP. These units are recommended for adults and children older than 1 year who require little or no supplemental O_2. Like home CPAP systems, these units are intended to be used with nasal prongs (pillows) or masks held in place by adjustable headgear. The BiPAP unit can be easily switched from CPAP to BiPAP without modifications for patients who need additional support (Case Studies 22.1 and 22.2).

The use of BiPAP systems and NIV, using critical care ventilators, has gained considerable popularity in pediatric intensive care unit settings as an alternative to invasive mechanical ventilation to support spontaneously breathing patients with acute respiratory failure and acute exacerbations of chronic lung disease. It is also being used to support patients after extubation who are difficult to wean from the ventilator or are thought to have difficulties after extubation. Patients with acute exacerbation of asthma, acute respiratory distress syndrome (ARDS), cystic fibrosis, neuromuscular disorders, and respiratory infections (e.g., pneumonia) have been supported successfully using this approach.

Both BiPAP and NIV have been shown to improve gas exchange and reduce the need for invasive ventilation by 40% in pediatric patients with acute respiratory failure.[62] Inspiratory positive airway pressure (IPAP) settings are initially set low and increased slowly to provide time for the patient to become comfortable and allow the clinician to assess accurately the

Case Study 22.1

Assessment and Treatment of a Newborn

About 30 minutes ago, a 3.5-kg male infant was born prematurely. The footling breech presentation was delivered at term by cesarean section after 24 hours of labor. He is currently in the neonatal intensive care unit receiving blow-by O_2. His respiratory rate ranges from about 67 to 83 breaths/min, he has a Silverman-Andersen score of 7, and his fingers and toes have a blue tinge. Periodically, he shows mild retractions. What steps would you take in the respiratory care of this infant?

Case Study 22.2

Adjustments to Home Therapy

A 2-year-old girl with spinal muscular atrophy (SMA) is on BiPAP at home. She has a gastrostomy tube, and her parents are the primary caregivers. She is taken to the emergency department for moderate respiratory distress. Breath sounds reveal coarse crackles throughout both lung fields. The S_pO_2 is 87% to 91% on room air; the respiratory rate is in the low 50s (breaths/min) and shallow, and the heart rate is 130 beats/min. The patient is afebrile.

The parents state that the patient was not tolerating the BiPAP because of a weak, persistent cough. They say she occasionally coughs up small amounts of thick white secretions. The father says that every time he applied the BiPAP mask, she began to cough and fight the BiPAP machine.

The respiratory therapist (RT) is asked to evaluate the patient and make recommendations. How should the RT proceed?

reduction in WOB. The PEEP or expiratory positive airway pressure (EPAP) settings are usually set between 4 and 10 cm H_2O. The maximum inspiratory pressure or IPAP level depends on patient size and lung pathology. Older pediatric patients may tolerate inspiratory pressure as high as 20 cm H_2O, but in all cases a nasogastric or orogastric tube should be placed and small amounts of sedation should be considered to improve comfort. Gastric insufflation has been observed in pediatric patients (older than 1 year) using inspiratory pressure >15 cm H_2O with a full-face mask.[63] However, larger patients may tolerate higher inspiratory pressure, but the patient should have a gastric tube and be monitored frequently for abdominal distention. In patients who do not tolerate this strategy or continue to develop severe respiratory failure and poor gas exchange, invasive mechanical ventilation is indicated.

CONVENTIONAL MECHANICAL VENTILATION

Conventional mechanical ventilation or *invasive* mechanical ventilation involves the use of positive pressure inflations in intubated patients who are breathing spontaneously or who are heavily sedated or paralyzed. Many of the techniques for managing neonatal and pediatric patients during conventional mechanical ventilation have been based on adult strategies. Neonatal and pediatric patients present with a multitude of respiratory diseases that warrant fundamentally different ventilator approaches. There have been no large randomized clinical trials in this patient population to suggest that a particular ventilator mode or ventilator brand is preferable over another in managing different lung diseases. However, there is overwhelming agreement among clinicians that the management of such patients should be to avoid invasive ventilation whenever possible to minimize VILI. This section discusses the techniques most widely practiced in neonatal and pediatric ventilator management. Clinicians working with children should always keep guidelines in mind, but they also should be able to "think outside the box" when faced with the unique challenges these patients sometimes present.

Indications for Ventilatory Support of Neonates

New advances in noninvasive ventilatory support have resulted in less frequent use of invasive ventilation; however, mechanical ventilation is a lifesaving intervention that remains an essential tool for managing neonates with respiratory failure. Infant mortality caused by RDS in the United States decreased from ≈268 in 100,000 live births in 1971 to 98 in 100,000 live births in 1985 and 17 in 100,000 live births in 2007.[64,65] The decrease in mortality from 1971 to 1985 was in large part a result of the development and widespread availability of mechanical ventilators designed to work well in neonates. Approximately 2% of neonates born in the United States require mechanical ventilatory support at or shortly after birth.[66,67] About 75% of these patients are either VLBW neonates (i.e., weighing <1500 g) or LBW neonates (weighing 1500–2500 g).[66] As a result, ventilator care of the newborn is often an integral part of the broader management of premature infants.

Most newborns who require full ventilatory support are placed on infant ventilators or infant-through-adult ventilators specifically designed to respond to even the smallest patients. The indications for mechanical ventilation of neonates are listed in Box 22.2.[68]

BOX 22.2 Clinical Indications for Invasive Mechanical Ventilation in Neonates[53]

The presence of one or more of the following conditions constitutes an indication for mechanical ventilation:

- Respiratory failure despite the use of continuous positive airway pressure (CPAP), noninvasive positive pressure ventilation (NPPV), and supplemental O_2 (i.e., fractional inspired O_2 [F_IO_2] of 0.6 or higher)
- Respiratory acidosis with a pH <7.25
- Partial pressure of arterial O_2 (P_aO_2) <50 mm Hg
- Abnormalities on physical examination:
  - Increased work of breathing, demonstrated by grunting, nasal flaring, tachypnea, and sternal and intercostal retractions
  - Pale or cyanotic skin and agitation
- Neurological alterations that compromise the central drive to breathe
  - Apnea of prematurity
  - Intracranial hemorrhage
  - Congenital neuromuscular disorders
- Impaired respiratory function that compromises the functional residual capacity as a result of decreased lung compliance and/or increased R_{aw}, including but not limited to:
  - Respiratory distress syndrome
  - Meconium aspiration syndrome
  - Congenital pneumonia
  - Bronchopulmonary dysplasia
  - Bronchiolitis
  - Congenital diaphragmatic hernia
  - Sepsis
- Impaired cardiovascular function
  - Persistent pulmonary hypertension of the newborn
  - Postresuscitation state
  - Congenital heart disease
  - Shock
- Postoperative state characterized by impaired ventilatory function

Infants with low Apgar scores who do not respond to initial resuscitation efforts may require early intubation and ventilatory support. Intubation and mechanical ventilatory support are usually necessary when an infant has been diagnosed with congenital anomalies that are likely to interfere with normal ventilatory function (e.g., diaphragmatic hernia, cardiac structural defects). The decision to provide mechanical ventilation for infants who do not have any of the previously described conditions is more subjective. The degree of respiratory distress is a valuable indicator even when ABG values are within acceptable ranges. Intercostal and substernal retractions, grunting, and nasal flaring are classic warning signs of impending ventilatory failure. Increasing supplemental O_2 requirements may be a sign that gas exchange is worsening. These indicators, along with the patient and maternal histories, are often more persuasive for initiation of ventilatory support than laboratory data. Infants who are intubated for reasons other than respiratory failure are often sedated and mechanically ventilated for at least a short period. In many such cases, airway protection is the only indication for intubation. In other situations, sedation is required to alleviate discomfort during certain procedures. When ETs are placed, the WOB from R_{aw} can increase

markedly. Even when these patients have sufficient drive to breathe spontaneously, minimum positive pressure or pressure support can help overcome ET resistance and help prevent lung collapse.

Indications for Ventilatory Support of Pediatric Patients

In contrast to premature infants, term infants and older pediatric patients have a wider variety of conditions requiring mechanical ventilatory support. One of every six term infants and children who are admitted to an intensive care unit (ICU) requires some form of mechanical ventilation. Airway obstruction is a common cause of intubation and ventilation. A study by the Pediatric Lung Injury and Sepsis Network found that 13.5% of children requiring mechanical ventilation for longer than 24 hours were intubated as a result of airway obstruction.[69] The most frequently diagnosed cause of respiratory failure in children younger than 1 year old was bronchiolitis; pneumonia was most often the cause for children older than 1 year.[69,70]

Recognizing the need for ventilatory support in older pediatric patients typically involves much of the same criteria used to assess adult patients. Unlike adult patients, children have a limited capacity for compensation of acute illness and are more likely to develop respiratory distress with apnea and hypoxemia early. In pediatric patients, ventilation that is insufficient to provide adequate gas exchange is determined primarily by ABG results and additional clinical assessments. Box 22.3 provides a list of indications for mechanical ventilation in pediatric patients.[71]

BOX 22.3 Indications for Use of Mechanical Ventilation in Pediatric Patients

Respiratory Failure
- Partial pressure of arterial carbon dioxide (P_aCO_2) over 50 to 60 mm Hg
- Partial pressure of arterial oxygen (P_aO_2) under 70 mm Hg

Neuromuscular or Hypotonic Disorder
- Muscular dystrophies
- Spinal muscular atrophy
- Guillain-Barré syndrome
- Myasthenia gravis

Intrinsic Pulmonary Disease
- Viral/bacterial pneumonia
- Aspiration pneumonia
- Asthma

Increased Intracranial Pressure
- Direct trauma
- Diabetic ketoacidosis

Near-Drowning

Infection

Neurological Disorders
- Seizure disorders

Postoperative Management
- Surgical procedures involving the head, neck, chest, or abdomen

The Pediatric Ventilator

Ventilators designed for infants and small children have been available since the late 1960s. Even with the availability of neonatal care units, many clinicians used adult models for neonates and small pediatric patients through the 1970s and early 1980s. They were more familiar with adult units and often found it difficult to justify financially the purchase of a ventilator that could be used only for a limited number of patients. Most current-generation, microprocessor-controlled ventilator platforms can provide seamless ventilation for any size of patient, from premature newborns to adults. A single ventilator for all patient sizes and age ranges may provide several advantages related to institutional cost, training, and patient safety. Commercially available neonatal and pediatric ventilators should incorporate the essential features described in Box 22.4.

Current-generation ventilators also provide several choices of modes, including volume-controlled continuous mandatory ventilation (VC-CMV), pressure-controlled continuous mandatory ventilation (PC-CMV), volume-controlled intermittent mandatory ventilation (VC-IMV), pressure-controlled intermittent mandatory ventilation (PC-IMV), CPAP, and pressure support ventilation (PSV). In the past decade, other forms of volume-targeted or hybrid modes of ventilation, known as dual-controlled CMV (DC-CMV), dual-controlled IMV (DC-IMV), and dual-controlled PSV (DC-PSV), have been used successfully.

For nearly 30 years, infants were ventilated with infant-specific, time-cycled, pressure-limited, intermittent mandatory ventilation (TCPL/IMV) breaths. Unlike current microprocessor-controlled ventilators, these TCPL/IMV ventilators used a preset continuous flow of an O_2—air mixture. The patient could breathe from the flow during spontaneous breaths but was unable to trigger mandatory breaths from the ventilator (Fig. 22.6A). In this design, a machine-triggered positive pressure breath resulted when the

BOX 22.4 Essential Features for Commercially Available Neonatal/Pediatric Ventilators[46]

- Pressure-controlled ventilation (PCV), volume-controlled ventilation (VCV), pressure support ventilation (PSV), and dual-controlled ventilation (DCV) modes
- Continuous mandatory ventilation (CMV), intermittent mandatory ventilation (IMV), and continuous spontaneous ventilation (CSV)
- Flow or pressure triggering
- Visible and audible alarms for high and low pressures and volumes
- High-pressure release to ambient capability
- Visible and audible alarms for low and high O_2 concentrations
- Visible and audible alarms for loss of power and gas source
- Servo-regulated humidifier with low-compressible-volume water chamber and continuous-feed water supply system
- Low-compliance ventilator circuit and/or capability for ventilator to measure and subtract compressible volume from delivered and monitored volume displays
- Proximal flow sensor (essential for neonatal patients) or compliance factor (sufficient for larger patients)
- Mechanism to drain water condensate from circuit or heated inspiratory/expiratory circuit limbs

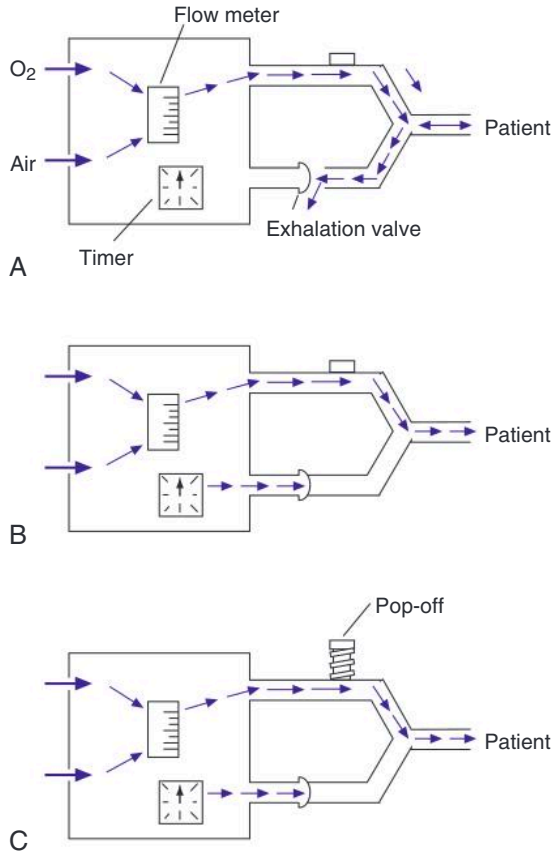

Fig. 22.6 Schematic for a continuous flow neonatal ventilator circuit. (A) Spontaneous phase. (B) Inspiratory phase. (C) Pressure-limiting phase. (From Koff PA, Gitzman D, Neu J, editors: *Neonatal and pediatric respiratory care,* ed 2, St. Louis, MO, 1993, Mosby.)

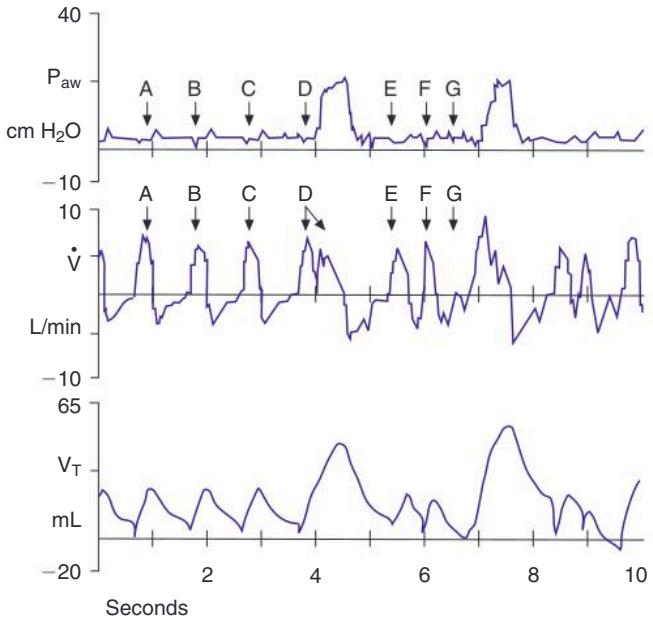

Fig. 22.7 Time-triggered, pressure-limited, time-cycled ventilation (TPTV) with inadequate patient triggering of mechanical breaths (see text for explanation). (From Wilson BG, Cheifetz IM, Meliones JN: *Optimizing mechanical ventilation in infants and children,* Palm Springs, CA, 1995, Bird Products.)

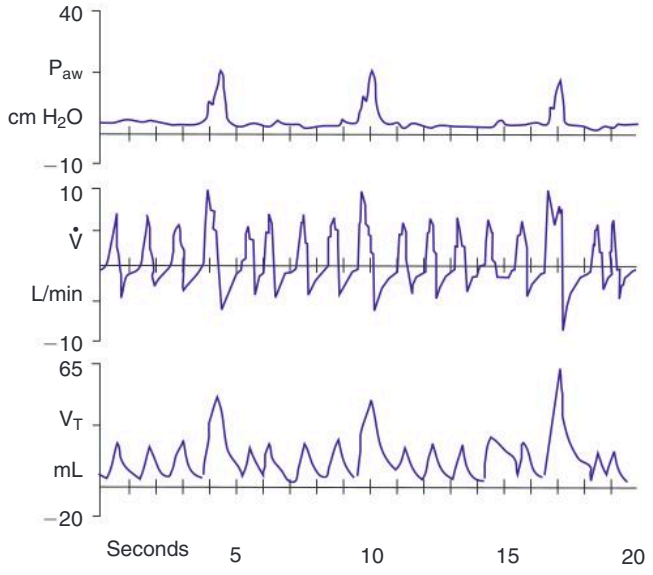

Fig. 22.8 Same patient as in Fig. 22.6; flow triggering has improved patient-ventilator synchrony. (From Wilson BG, Cheifetz IM, Meliones JN: *Optimizing mechanical ventilation in infants and children,* Palm Springs, CA, 1995, Bird Products.)

machine's exhalation valve closed, permitting the gas mixture to flow to the patient (see Fig. 22.6B). When a preset inspiratory pressure was reached, the pressure was maintained until the ventilator time cycled into expiration (Fig. 22.6C). When the exhalation valve opened, the expiratory phase began. As long as the exhalation valve remained open, a constant flow of the gas mixture passed by the patient's airway and was available for spontaneous breathing.[71] The ventilator's inability to permit patient triggering of mandatory breaths during spontaneous respiratory efforts led to asynchrony in spontaneously breathing patients. Nonetheless, the operation of previous TCPL/IMV ventilators still serves as a simple conceptual model for explaining the fundamental operation of neonatal mechanical ventilators and the major advances in pediatric mechanical ventilation.

Neonates who exhibit asynchrony during TCPL/IMV are at an increased risk for developing intraventricular hemorrhage and possibly pneumothorax. Heavy sedation and paralytic drugs (e.g., pancuronium) may reduce these risks, but these drugs also pose potential complications that may prolong ventilator support.[72] In Fig. 22.7, initial patient efforts (breaths *A, B,* and *C*) appear to be synchronous; however, when a mandatory breath (breath *D*) is delivered on top of a spontaneous breath, the ensuing spontaneous breaths (breaths *E, F,* and *G*) are asynchronous. A mandatory breath delivered in the middle of a spontaneous breath can result in breath stacking. When flow triggering is used, mandatory breaths can be delivered between spontaneous breaths, resulting in better patient-machine synchrony with a reduction in WOB and caloric and sedation requirements (Fig. 22.8).[73] Although some current pediatric ventilators still allow the option to use a preset continuous flow during PC-CMV and VC-CMV, machine-triggered TCPL/IMV has been replaced with patient-triggered PC-IMV.

Major improvements in ventilator technology now provide the ability for even the smallest patients to be able to control sophisticated demand flow systems to improve triggering and synchrony with mandatory ventilator breaths. Patients can trigger breaths based on a pressure or flow change that is sensed by the ventilator. Flow sensing is more sensitive and allows better synchronization than pressure triggering in neonates.[74,75] In addition, patient triggering may reduce the need for heavy sedation and paralytics during mechanical ventilation. Compared with earlier forms of nontriggered ventilation, patient-triggered ventilation is associated with a shorter duration of ventilation.[72]

Because all ventilators now provide patient-triggered ventilation, the term *PC-IMV* has replaced the previously used TCPL/IMV constant-flow mode. As such, synchronized intermittent mandatory ventilation (SIMV) and assist/controlled (A/C) have been replaced with IMV and CMV, respectively.[76] In addition, mandatory breaths denote fully supported ventilator breaths (i.e., PC-CMV, VC-CMV) and can be initiated by the patient or ventilator and terminated based on time, whereas spontaneous breaths are always initiated and terminated by the spontaneously breathing patient (i.e., CPAP, PSV). During CMV, every breath from the ventilator is mandatory, or fully supported, whereas during IMV the patient can breathe using both mandatory and spontaneous breath types. Each manufacturer may use completely different names to differentiate modes and breath types, and as a result, there is great confusion among clinicians, educators, researchers, and manufacturers about mode classification. Efforts are being made to standardize ventilator mode classification on the basis of the approach used in this discussion.[76]

Another important advancement in the design of neonatal and pediatric ventilators has been the development of sensors that allow clinicians to obtain more accurate measurements of airflow and V_T in very small patients. These advances in mechanical ventilator technology have greatly enhanced the ability of clinicians to assess dynamic compliance, static compliance, R_{aw}, and ventilator waveform graphics. The availability of bedside lung mechanics measurements and ventilator graphics can eliminate much conjecture when managing a patient on a mechanical ventilator. V_T and airway graphics are usually obtained by using proximal airway sensors that measure airflow at the connection of the ventilator's circuit and the patient's artificial airway. It has been shown that ventilators that do not measure V_T with a sensor at the proximal airway produce measurements that are not sufficiently accurate to use for managing the ventilator in neonates.[77] Thus the most effective neonatal-capable ventilators are those that have proximal airway flow sensors for accurate determination of V_T, lung mechanics, and ventilator graphics. The use of a proximal flow sensor also allows more precise flow triggering and graphics monitoring than those provided at the ventilator valve. It is important to mention that a major limitation of proximal flow sensors is that condensation and secretions can form on the flow-sensing elements. Clinicians must remain wary of this limitation and replace or clean flow sensors when changes in the ventilator graphics are observed.

Additional features or enhancements can make ventilators more useful in a wide range of clinical situations (Box 22.5). Many ventilators have advanced features that allow clinicians to modify the gas flow within the breath to fine-tune or improve patient-ventilator synchrony and gas delivery. The slope, or *rise-time,* setting is an advanced feature that can be used during pressure control, dual-control, and pressure support ventilation to adjust the aggressiveness of initial gas delivery at the start of the breath. A fast rise time and rapid pressurization may reduce asynchrony in patients with high flow requirements, and a slow rise provides slower and hence more laminar gas delivery during inhalation (Fig. 22.9).

BOX 22.5 Desirable Features for Commercially Available Neonatal/Pediatric Infant Ventilators

Some features and enhancements can make ventilators more useful in a wide range of clinical situations. Such features include the following:

- Digital display of inspiratory/expiratory tidal volume (V_T) and minute ventilation ($\dot{V}_E$) with high- and low-volume alarms
- Digital display of endotracheal tube and system leak
- Digital display of lung mechanics measurements (compliance and resistance)
- Waveform display, with user selection of time/parameter scales
- Advanced breath features for pressure-controlled ventilation and pressure support ventilation features, including intrabreath pressurization rate (slope or rise time adjustment) patient flow triggering and patient termination of inspiratory phase (flow cycle); selection of termination flows and times
- Volume-cycled intermittent mandatory ventilation (IMV) with endotracheal tube leak compensation for positive end-expiratory pressure (PEEP) and V_T
- Helium-oxygen delivery with accurate volume/waveform monitoring
- Integrated end-tidal carbon dioxide monitoring
- Cessation of gas flow when ventilator is disconnected from the patient
- Integrated noninvasive continuous positive airway pressure (CPAP), pressure support ventilation (PSV), bilevel positive airway pressure (BiPAP), IMV, and continuous mandatory ventilation (CMV) with backup ventilation (when necessary)
- Air pressure release ventilation (APRV)

Flow cycling is another feature that allows patients to terminate the breath based on flow rather than on time. Flow cycling is described in greater detail later in this chapter. Sophisticated leak-compensation algorithms are available for invasive and noninvasive ventilation. When this option is activated, loss of end-expiratory pressure caused by an ET leak triggers the addition of flow to the ventilator circuit to maintain constant PEEP. Some ventilators have also incorporated leak compensation during inhalation to provide stable volume delivery in the presence of large ET leaks. The potential advantages of this feature are discussed in a later section.

As respiratory monitoring has grown more comprehensive and sophisticated, sensing adapters at the proximal airway have become necessary. With some ventilator models, monitoring of end-tidal CO_2 ($EtCO_2$) and flow-volume loops require two airway sensors. These sensors add extra weight to the ET, which can lead to excessive tube movement and possibly accidental extubation. These devices can also add dead space to the system, resulting in excessive accumulation of CO_2 at the airway and consequent