Chapter 10
Noninvasive Mechanical Ventilation

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Noninvasive Ventilation (NIV) is defined as the application of assisted ventilatory support without the use of an invasive airway such as an endotracheal tube or a tracheostomy tube. Continuous airway pressure can be provided without the use of an artificial airway as well and while it does not provide active inspiratory support, it is still included in the discussion of NIV as a non-invasive modality. NIV can be applied via either positive or negative pressure. Positive pressure NIV (NIPPV) is provided by an interface that increases the proximal airway pressure whereas negative pressure NIV (NPV) is provided by creating a negative pressure around the chest wall. In both instances, the transrespiratory pressure, which is the pressure difference between the proximal airway pressure and the alveoli, is raised causing airflow into the lungs. Non-invasive ventilatory support has emerged as an important treatment modality for acute and chronic respiratory failure. Successful implementation of non-invasive adjuncts is related to appropriate patient selection,

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firm understanding of the limitations for each interface and device as well as the disease-specific pathology and pathophysiology. Primary benefit of these devices is the reduction in the rates of invasive ventilation and decreased hospital costs.

10.1 Non-Invasive Positive Pressure Ventilation (NIPPV)

NIPPV can be used in the acute (short-term) or sub-acute/chronic (long-term) care setting. Short-term NIPPV is initiated where positive pressure support is needed acutely in a hospital setting for conditions that are usually reversible within a few days (Table 10.1). Long-term NIPPV is indicated in conditions where respiratory failure is likely to be chronic or progressive.

10.1.1 Indications and Contraindications

A patient is considered a candidate for short-term NIPPV if the following criteria are met: (1) the cause of respiratory failure is reversible, (2) gas exchange cannot be maintained without positive pressure, (3) there is no immediate need for intubation and invasive mechanical ventilation, and (4) there are no contraindications to initiating NIPPV (Table 10.1). Short-term NIPPV may also be initiated to facilitate

Table 10.1 Indications and contraindications for short-term NIPPV

	Conditions
A. Indications	1. Potentially reversible condition a. Acute hypoxemic respiratory failure (e.g., ARDS) b. Acute cardiogenic pulmonary edema c. Acute lower airway disease (e.g., asthma, bronchiolitis) 2. Avoiding intubation a. Restrictive chest diseases b. Neuromuscular disorders c. Post-operative respiratory failure d. Post-extubation respiratory failure 3. Facilitate weaning and extubation
B. Contraindications	1. Need for immediate intubation and invasive mechanical ventilation 2. Hemodynamically unstable (hypotension, shock) 3. Poor airway protective reflexes (absent cough and gag) 4. Recent upper airway and esophageal surgery 5. Congenital facial malformation 6. Presence of facial pressure ulcers 7. Excessive secretions 8. Lack of cooperation/Agitation 9. Untreated pneumothorax 10. Inability for a good mask fit

extubation. In some patients, with certain terminal illnesses such as advanced cancer, NIPPV may be attempted to avoid intubation. If any of the above criteria are not met, the patient may not be a suitable candidate for short term NIV. The need for positive pressure and ventilatory assistance is evidenced by moderate to severe increase in work of breathing, retractions, paradoxical breathing, accessory muscle use, and abnormal gas exchange (ventilatory or oxygenation failure). If the patient requires only positive airway pressure to recruit the lung volume to improve oxygenation, then the patient can be placed on noninvasive continuous positive airway pressure (CPAP) through an appropriate interface. If the patient needs ventilatory assistance based on the clinical signs and symptoms or gas exchange derangements, then the patient is a candidate for NIPPV.

10.1.2 Clinical Application

Once the patient is considered to be a suitable candidate for NIPPV, it is important to choose the correct interface which is appropriately sized. The choice of the interface will depend on the level of support as well as the severity of the distress. If only CPAP is required, then a nasal or oronasal mask may suffice. If ventilatory assistance is required, an oro-nasal or a total face mask would be the most appropriate interface. It might take several attempts before a patient can tolerate the interface. Sometimes, it might be necessary to hold the mask gently in place with without securing it on the head. Once the patient is able to tolerate the interface and the respiratory support provided, it can be secured with the straps provided. Figure 10.1 shows the flowchart for initiation of NIPPV.

Once CPAP/NIPPV has been initiated, patient's response needs to be monitored. The level of CPAP/NIPPV is selected based on the clinical needs. Some patients improve rapidly with the initial settings and may not require further adjustments. If there is not an immediate improvement within 15 min of initiation, the ventilator settings may need to be adjusted further. The patient should be monitored for clinical improvement for the next 2–3 h. The decision-making once CPAP/NIPPV is initiated is described in the flowchart in Fig. 10.2.

Clinical improvement with NIPPV is indicated by: (1) decreased respiratory rate, (2) reduced work of breathing, (3) improvement of dyspnea, (4) an increase in pH, (5) better oxygenation, and (6) decreased arterial carbon dioxide ($PaCO_2$) levels. Additionally, there may be hemodynamic effects such as a reduction in heart rate, improved blood pressures and perfusion. Generally, short-term NIPPV is used continuously until the patient improves or fails.

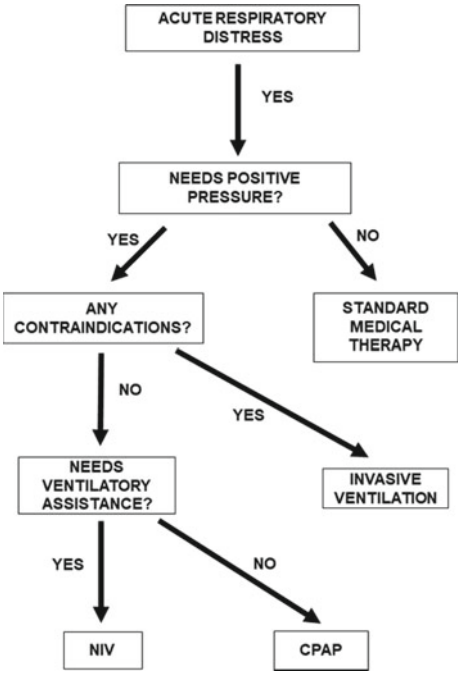

Fig. 10.1 Flowchart for initiation of CPAP/NIPPV. CPAP—Continuous positive airway pressure; NIPPV—Noninvasive positive pressure ventilation

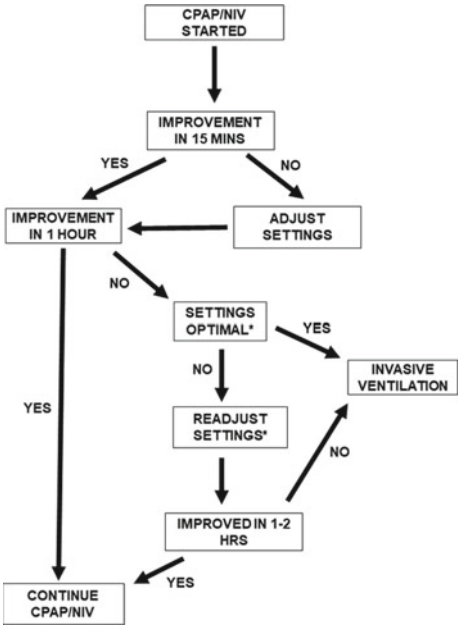

Fig. 10.2 Flowchart of decision making in the first 2 h after initiation of CPAP/NIPPV. CPAP—Continuous positive airway pressure; NIPPV—Noninvasive positive pressure ventilation; *If on CPAP, may need to escalate to NIPPV

10.1.3 Ventilator Settings

With short-term NIPPV, two strategies have been employed. A common approach is to place the patient on a spontaneous mode with assist which is called pressure support in ICU-specific ventilators and BiPAP or Bi-Level mode in ventilators dedicated for NIPPV. The inspiratory pressure is usually set 5–8 cm H_2O above the expiratory pressure. The inspiratory pressure limit with specific NIPPV ventilators is called *inspiratory positive airway pressure* (IPAP). The expiratory pressure is PEEP in ICU-specific ventilators and is called *expiratory positive airway pressure* (EPAP) in the NIPPV ventilators. Depending on the level of relief of symptoms, the inspiratory pressure limit can be gradually increased. When the inspiratory pressure required is > 20 cm H_2O without clinical improvement, then endotracheal intubation and invasive mechanical ventilation should be considered. This is called the *low–high approach*—start low and increase to a high level. The second approach is to start with a high inspiratory pressure (about 20 cm H_2O or higher). The goal of such an approach is for rapid clinical improvement. Once work of breathing is reduced and gas exchange has improved, the inspiratory pressure can be decreased to a lower level which still produces relief of symptoms. This approach is called the *high-low approach*—start high and decrease to a lower level. In general, the low–high approach is better tolerated by the patient, especially smaller children, since they can adapt to the increasing flow into the nose and face. The flow of gas associated with the high-low approach is not as well tolerated since the patient is often uncomfortable with the high flow of gas to the face. On the other hand, work of breathing may take much longer to be relieved with the low–high approach than the high-low approach. Within the first 1–2 h, subsequent adjustments may be necessary depending on the patient response. Expiratory pressure is used routinely during short-term NIPPV (either EPAP or PEEP). Maximal fraction of inspired oxygen (FiO_2) with bi-level ventilators is usually about 0.45–0.5. If a higher FiO_2 is required and endotracheal intubation is not indicated, an ICU-specific ventilator may be used, with a closed interface system. With this system there is an increased risk of aspiration.

Care should be taken to prevent excessive skin pressure from the interface with the use of adequate padding and monitoring how tight the interface is secured. In some patients, mild sedation may be considered to improve tolerance of the mask. Sedation of a patient already in respiratory distress needs to be monitored closely to prevent inadvertent hypoventilation and worsening respiratory failure. Humidification of the inspired gases is critical to prevent drying of the mucosa and to avoid patient discomfort.

10.1.4 Optimizing Patient-Ventilator Interaction

Optimal patient-ventilator interaction requires the ventilator to be able to detect the patient's inspiratory efforts as quickly as possible and terminate inspiration (cycling) as close to the beginning of the patient's exhalation as possible. Inspiratory trigger function differs significantly among the ventilators. Factors affecting the inspiratory trigger function include trigger response to the inspiratory flow, leak-induced auto-triggering, and pressure–time and flow-time waveform heterogeneity. Strategies to optimize cycling include setting a suitable threshold for the inspiratory time and adjusting the cycling flow-threshold. Patients with obstructive lung disease tend to do better with high inspiratory flow whereas patients with neuromuscular disease seem to do better with low inspiratory flows. An adjustable back-up rate is available in most modern ventilators used for NIPPV. It is particularly useful when sedation is used to improve patient compliance with NIPPV. Leaks around the interface reduce its effectiveness. Some amount of leak around the interface is expected with NIPPV. Complete elimination of air leak is not desirable as it comes at the expense of a very tight-fitting mask which may lead to patient discomfort and skin breakdown. Ventilators differ in their capacity to compensate for leaks. One of the drawbacks of a large air leak is auto-triggering. In the presence of large system leaks, the ventilator will increase flow provided to compensate for the loss in pressure. The increase in flow decreases the ventilator's ability to sense both the beginning and the termination of the inspiratory cycle. This results in asynchrony, increased work of breathing, and oxygen consumption. In the presence of a system leak, the patient must be assessed for the presence of asynchrony. Humidification is important to prevent mucosal drying. Humidification can be provided using a heated humidifier, heat and moisture exchange, or a pass-over humidifier.

10.1.5 Mechanisms of Improvement

In patients with parenchymal lung disease, the lung has a tendency to collapse due to the high critical closing pressure and closing capacity. Application of CPAP/NIPPV can increase the airway pressures above the critical closing pressure and recruit the lung. Recruitment of the lung increases lung volumes, improves compliance, and decreases venous admixture. CPAP/NIPPV can also decrease the work of breathing by unloading the inspiratory muscles facilitating the inspiratory flow. As an example, in an obstructive disease such as asthma exacerbation, the resistive work of breathing (WOB) is greatly increased (Fig. 10.3).

The equal pressure point (EPP), where airway pressure is equal to intrapleural pressure during expiration, is displaced distally (towards alveoli) with intrapulmonary airway obstruction (Chapter 1). Intrathoracic airway proximal to EPP is therefore subjected to increasing transmural pressure resulting in further narrowing

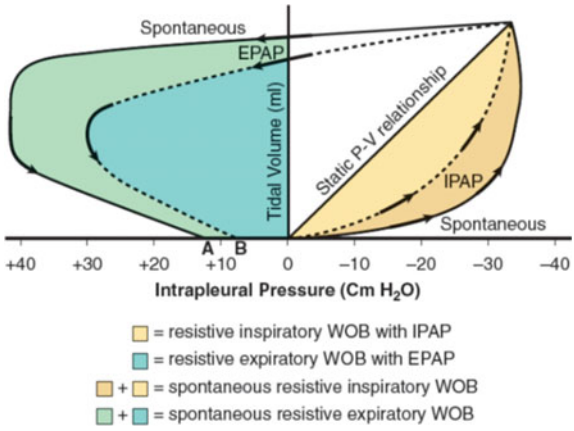

Fig. 10.3 Work of breathing (WOB) in status asthmaticus with and without NIPPV. In the expiratory limb of the respiratory cycle equal pressure point (EPP) is displaced distally causing airways to close at higher lung volume (increased closing capacity), dynamic hyperinflation, and auto-PEEP (Point A). Application of EPAP stents the airways, causes proximal displacement of the EPP, and decreases closing capacity, dynamic hyperinflation, auto-PEEP (Point B), and WOB. In the inspiratory limb, the patient needs to generate less negative pressure to initiate inspiration because of lower auto-PEEP. Inspiratory muscles are further unloaded by IPAP throughout inspiration for the given tidal volume. Both expiratory and inspiratory WOB is thus reduced by application of NPPV. *From Sarnaik AA, Sarnaik AP: Pediatr Crit Care Med 13:484–485, 2012*

and limitation of expiratory airflow. The resistive WOB (pressure x volume) is greatly increased especially during exhalation when airway narrowing is exacerbated. Closure of airways earlier in expiration also results in greater closing capacity, ventilation-perfusion (V/Q) mismatch, auto-PEEP and decreased cardiac output. The dynamic compliance (C_{dyn}) is greatly reduced compared to the static compliance (C_{stat}). The prolonged time constant, results in dynamic hyperinflation and increased end-expiratory-lung-volume (EELV) compared to the expected functional residual capacity based on static pressure volume relationship.

Application of NIPPV addresses many of these pathophysiologic derangements. IPAP is aimed at unloading the inspiratory muscles and therefore decreasing the inspiratory work of breathing. EPAP on the other hand, moves the EPP more proximally (towards the thoracic inlet), stent the airways, decrease transmural pressure and ameliorate airway collapse during exhalation. Delay in airway closure during exhalation will also result in decreased auto-PEEP, dynamic hyperinflation, improved C_{dyn}, and decreased closing capacity with improved V/Q match. Additional advantages of NIPPV in status asthmaticus are improved aerosol delivery to obstructed airways and better distribution of gases such as helium–oxygen mixture.

Clinical decision-making to continue CPAP/NIPPV depends on whether the respiratory failure is resolving, unimproved or worsened (Fig. 10.4). When respiratory failure is resolving, CPAP/NIPPV should be weaned. Depending on the

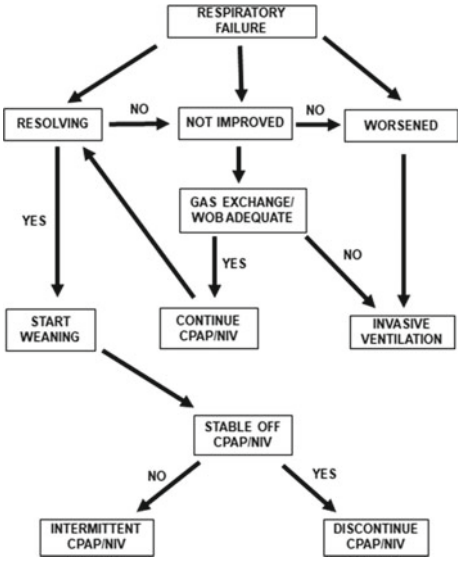

Fig. 10.4 Flowchart outlining the clinical decision-making depending on the trajectory of respiratory failure

degree of resolution, some patients may require positive pressure support intermittently for a while before they are able to discontinue it completely. When respiratory failure has not improved or worsened, then invasive ventilation needs to be considered to provide further respiratory support.

10.1.6 Equipment

Interfaces A properly fitting appliance is essential for the optimal application of NIPPV. There are currently several devices in use: (1) Adam's circuit and nasal pillows, (2) Nasal masks, (3) Oro-nasal masks, (4) Total face masks, (5) Helmet or Head Hood and (6) Mouthpieces. A correctly sized interface minimizes leaks, improves effectiveness of positive pressure support, and improves comfort. Current NIPPV delivery devices have the capacity to compensate for significant leaks. Some devices can compensate for leaks as high as 60 L/min.

Adam's Circuit or Nasal pillows

This device uses a "nasal pillow" which attaches to a manifold and Velcro strap system (headgear) that is placed over the top of the head. Some patients prefer this to the nasal mask. "Nasal pillows" are available in various sizes. One advantage with nasal pillows over the other interfaces is that patients can be fed if the work of breathing and respiratory rates are normal.

Nasal masks A nasal mask rests between the bridge of the nose and above the upper lip (Fig. 10.5). As a rule, the smaller the mask, the better the fit. In patients, who are unable to keep their mouth closed, chin straps may be used to close the

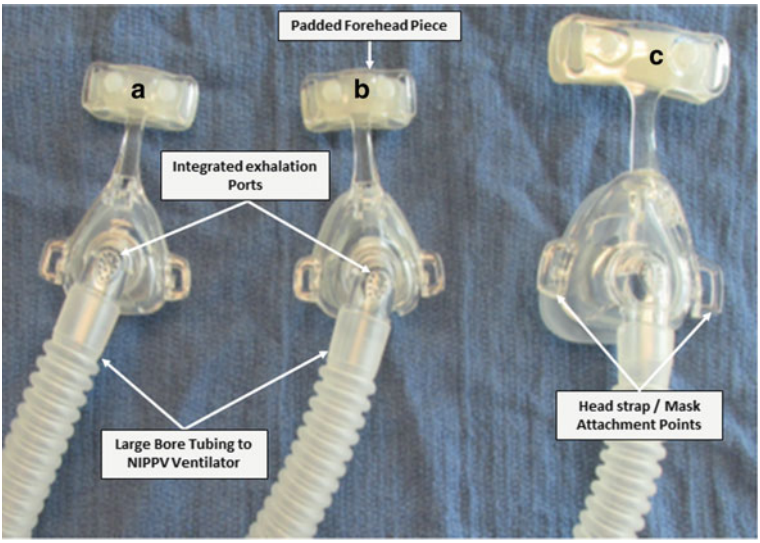

Fig. 10.5 Nasal masks. Three sizes of single-limb nasal masks **a** Newborn **b** Infant **c** Toddler. Integrated exhalation ports create a leak for CO_2 removal. Padded forehead piece maintains a comfortable fixation point on the patient's head, Head strap/mask attachment point holds the bottom portion of the mask to the face. Large bore tubing connects to the ventilator

mouth. Some nasal masks have integrated exhalation ports for exhaled gas to escape and prevent rebreathing of CO_2.

Oro-nasal Masks This is the most common interface used to provide NIPPV in children (Fig. 10.6). The ideal face-mask should be: (1) made of a clear material to allow visual inspection, (2) conforming to the contours of the patient's face, (3) easily moldable from its factory shape, (4) soft and does not apply excess pressure on the skin of the face, and (5) able to maintain its deformed shape (has "memory") when it is removed. The mask should extend from the bridge of the nose to just below the lower lip. The mask is secured using an anchoring system that goes around the head. Oro-nasal masks can be "vented" or "non-vented". Vented masks have integrated hole/holes for exhalation.

Total face mask This mask covers the whole face including the eyes (Fig. 10.7). The advantage of a total face mask is that it does not have to conform to the shape of the face and therefore does not have to be molded to fit every patient. The disadvantage is that it has an increased dead space and therefore, there may be difficulty in eliminating CO_2.

Head hood Also called a "helmet", it has been used successfully in a number of European ICUs. It appears best suited for application of CPAP. Dead space is a major concern and therefore, should be reserved for patients in the ICU.

Mouthpieces These are simple devices to be pursed between the lips for domiciliary mechanical ventilation (Table 10.2).

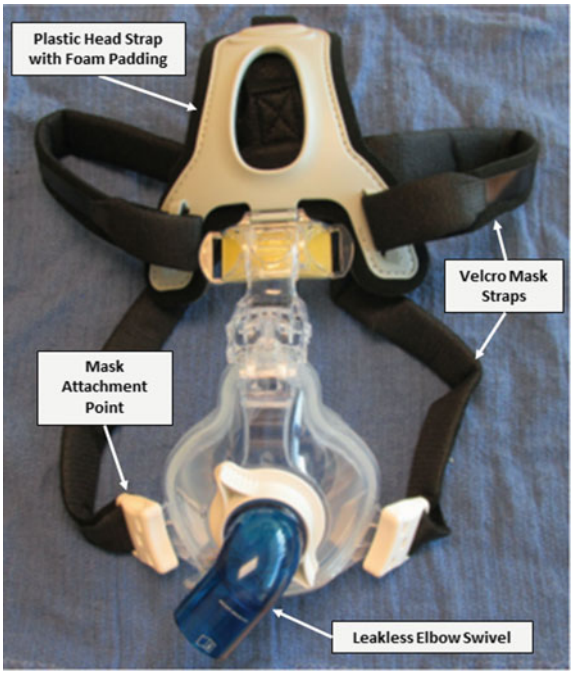

Fig. 10.6 Oro-nasal mask. Shown is a mask with a leakless elbow swivel used in dual limb ICU-specific ventilators. The type requires an active exhalation value for CO_2 removal. Padded plastic head piece maintains a comfortable fixation point on the patient's head. Velcro mask straps encircle the head and neck, and mask attachment point holds the bottom portion of the mask to the face. This model uses a plastic clasp for easy application and removal

Fig. 10.7 Total face mask. Total face mask with an integrated exhalation elbow swivel for use in single limb continuous flow ventilators allowing for CO_2 removal. The elbow swivel has a one-way valve that closes during inspiration and opens during exhalation. Velcro mask straps encircle the head and neck, and mask attachment point holds the mask to the face. This model uses a plastic clasp for easy application and removal

Table 10.2 Advantages and disadvantages of commonly used interfaces

Interface	Feature	Advantages	Disadvantages
Nasal masks	Covers nose not mouth	Possibility of speaking and drinking Allows cough Reduced danger of vomiting Minimum risk of asphyxia	Air leaks if mouth is open Risk of pressure injury Needs patent nasal passages
Full face (or oronasal)	Covers nose and mouth	Few air leaks than nasal masks Cooperation is easier Can be adjusted for comfort	Difficult to fit at times Vomiting (needs NG drainage) Risk of aspiration Claustrophobia Risk of pressure injury Speaking and coughing difficult
Total face mask	Covers eyes, nose, and mouth	Minimum air leaks Little cooperation required Easy fitting and application Surprisingly, less claustrophobia	Vomiting (needs NG drainage) Claustrophobia Speaking difficult Risk of aspiration
Mouthpieces	Placed between lips and held in place	Can be applied as rotating strategy with other interfaces Usually used with sip-ventilation	Salivation Gastric distension Speaking difficulty Possible air leaks

Ventilator devices

The ventilators that are used for NIPPV can be classified into 3 categories: (1) ICU-specific ventilators with a double limb circuit without leak compensation, (2) devices with a single limb circuit with leak compensation, and (3) devices that combine the above 2 categories to include both leak compensation and having a double limb circuit. Category 1 devices can only be used in the hospital. Category 2 and 3 devices can be used both in the hospital and at home. The examples of these devices would be any of the ICU-specific ventilators that can provide pressure support with PEEP (Category 1), Respironics Bi-PAP (Category 2), and the Pulmonetics LTV ventilator (Category 3). The performances of these ventilators vary widely in delivered tidal volumes, air-leak compensation, response to simulated effort, inspiratory trigger, expiratory cycling, rebreathing, response to high ventilatory demands and patient-ventilator synchrony. Category 1 or ICU-specific ventilators operate with high-pressure gas sources with an oxygen blending system. Category 2 and 3 devices can operate without a high-pressure gas source. Bi-level ventilators do not have a blender and therefore, the delivered FiO_2 is unpredictable depending on the oxygen flow rate, ventilator settings, amount of leak, site of O_2 enrichment, and the type of exhalation port. Most common mode of NIPPV is

continuous spontaneous ventilation with assist such as bi-level pressure support (referred to as BiPAP) and pressure support ventilation with ICU-specific ventilators. While it is possible to provide volume-controlled or pressure-controlled mandatory breaths for NIPPV, these modes are not as common as the spontaneous modes with assist.

Circuits

Dual-limb and single-limb circuits are the two commonly used circuits with non-invasive ventilation. A dual-limb circuit is usually used with an ICU-specific ventilator to provide NIPPV (Fig. 10.8). The inspiratory limb is separated from the expiratory limb so that there is segregation of inspired and exhaled gases. In modern ventilators, the valves controlling the inspiratory and expiratory limbs are located within the ventilator. The expiratory valve closes during the inspiratory phase and the inspiratory valve closes during the expiratory phase. There is no rebreathing of exhaled CO_2 into the ventilator since the inspiratory valve is closed during exhalation.

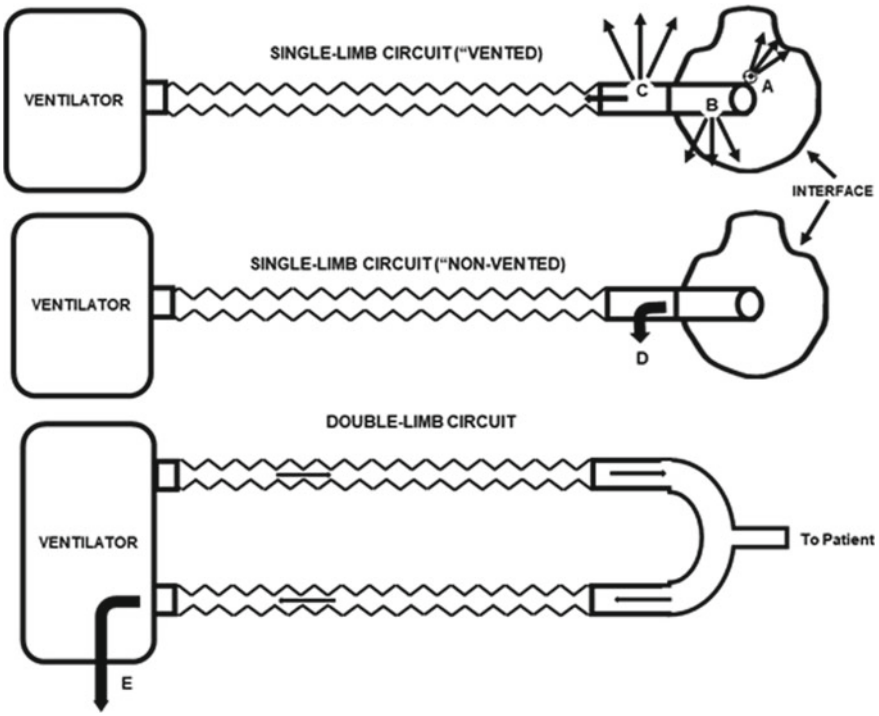

Fig. 10.8 Circuits for NIPPV. The circuit shown at the top is a Single-limb "vented" circuit. The "vent" can be in the interface (**A**), in the connector between the interface and the circuit (**B**), or in the circuit close to the connector (**C**). The circuit shown in the middle is a Single-limb "non-vented" circuit with an active exhalation post (**D**). The circuit shown at the bottom is a Dual-limb circuit where exhalation occurs through the expiratory port of the ventilator (E)

Single-limb circuits by definition have only a single hose exiting the ventilator (Fig. 10.8). Single limb circuits that are employed with bi-level ventilators can result in significant CO_2 rebreathing. Exhaled CO_2 needs to exit the circuit without significant rebreathing of CO_2 in the inspired gas. This can be accomplished by either passive or active exhalation mechanisms in the circuit. Exhaled gas can be vented through holes in the interface itself, or the connector between the circuit and the interface or in the circuit close to the patient as shown in Fig. 10.8. Passive exhalation occurs through these "vents" but a portion of the exhaled gas can enter the circuit resulting in some rebreathing of CO_2. With this system, there is a continuous flow through the entire breathing cycle inside the circuits. CO_2 removal (or rebreathing) is affected by EPAP, intentional and nonintentional leaks, and supplemental oxygen entrained in the mask.

The second mechanism by which exhaled gas can exit the circuit without significant rebreathing is to have an active exhalation port which prevents the exhaled gas from the entering the circuit. This can be accomplished by having an exhalation valve similar to a PEEP valve or a valve with a pressure line that is controlled by the ventilator (Fig. 10.9). Rebreathing of CO_2 is lowest when the exhalation port is closest to the patient.

Important points to consider when selecting interfaces and circuits.

When using an ICU-specific ventilator, a non-vented interface is the interface of choice and a vented interface should be avoided since these ventilators do not have adequate leak compensation. When using a single-limb circuit, if there the interface is vented, then the circuit should not have any other ports for exhalation. If the interface is non-vented, then it is important to use a single-limb circuit with a passive or active exhalation port.

10.1.7 Complications and Concerns During Short-Term NIPPV

Aerophagia and gastric distension can occur with NIPPV. Higher the pressures used, the greater the risk of gastric distension. Regurgitation of gastric contents and aspiration into the lungs are major concerns with the use of an oro-nasal, total face masks and a helmet. Close monitoring is needed to prevent aspiration. A nasogastric tube to keep the stomach decompressed is necessary in these acutely ill patients. Pressure sores related to the masks are other major concerns. It should be possible to pass one or two fingers between the headgear and the face. Care should be taken to avoid fitting the interface too tightly. A spacer with a soft padding can reduce the incidence of pressure sores on the face.

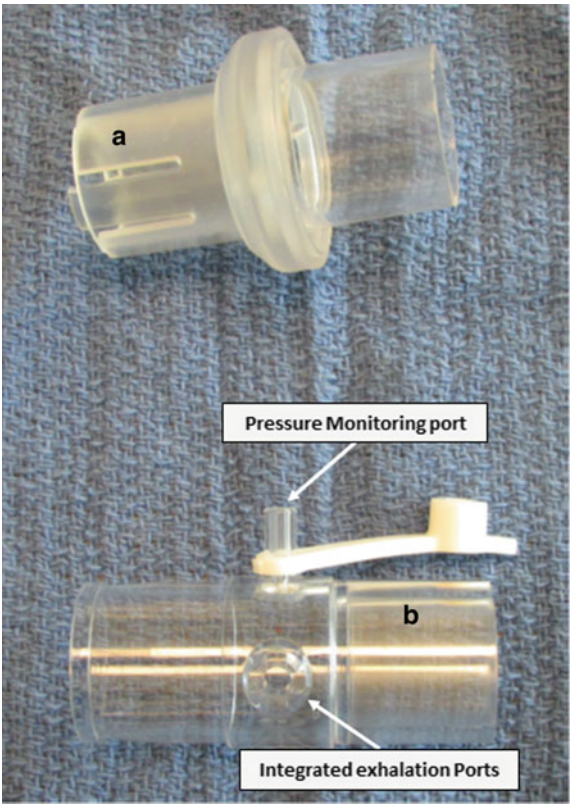

Fig. 10.9 Integrated exhalation valves. Two commercially available integrated exhalation values (e.g., Whisper-valves) **a** Non-disposable—exhalation ring for expired gas evacuation. **b** Disposable—has a pressure monitoring port and an integrated port for exhalation. Both exhalation valves create a leak for CO_2 removal. The rate of escape via the exhalation ports must be greater than the patient's exhaled gas flow

10.2 Negative-Pressure Ventilation

Negative-pressure ventilation (NPV), defined as noninvasive mechanical ventilation where sub-atmospheric pressure is applied to the external chest wall through either a tank/chamber device or chest "shells" causing inspiratory flow into the lungs at timed intervals. The negative pressure applied to the chest wall decreases the pleural and alveolar pressures resulting in chest expansion due to the pressure gradient created between the mouth and the alveoli. This mode of breath delivery provides a more physiologically supported breath by pulling atmospheric gas into the ventilator units, similar to the gas flow created by the diaphragm during inspiration. Usually, exhalation is passive due to the elastic recoil of the lung and

chest wall. Some devices are capable of applying positive pressure to the thorax during the expiratory phase to facilitate exhalation in clinically indicated situations.

NPV was first applied via the iron lung to support respiratory failure secondary to the poliovirus epidemic. Popularity of the iron lung waned as a result of its large size, personnel required to support patients, and the detrimental effect on the cardiovascular system. Invasive positive-pressure ventilation alleviated these issues and quickly became the standard of care. Newer NPV devices have addressed the size and venous return issues by developing plastic cuirasses, which create a seal around the thorax—allowing access to the patient, increased patient portability, and providing increase range of motion without loss of ventilation.

10.2.1 Indications

Acute Respiratory Failure: Negative pressure ventilation is used in the pediatric population for treatment of acute respiratory failure such as in bronchiolitis, status asthmaticus, pneumonia, post-cardiothoracic surgery, and extubation support (Table 10.3). The most commonly used mode is CNEP. Evidence regarding the use of NPV in the pediatric population is mostly low-level—consisting of case-reports and single-center retrospective cohort studies. Given the lack of well-designed, controlled trials regarding this indication, use of NPV should be considered secondary or as an adjunct to other support strategies. The risks and benefits should be considered as they relate to other therapeutic options. Upper airway obstruction is a common reason for NPV failure due to upper airway collapse from negative extra-thoracic pressure. The patient should be monitored for paradoxical breathing pattern as this is the hallmark for upper airway collapse in children.

Neuromuscular Disorders: The available evidence suggests NPV provided by a chamber device (i.e. iron lung) can be effective in supporting acute respiratory failure in patient with neuromuscular disease (Table 10.3). However, size, cost and availability of chamber devices create significant barriers regarding its mainstream use within the acute care setting. Currently, only the Porta-lung® chamber is FDA approved in the United States. The device is compatible with older negative-pressure driving systems, such as the Respironics NEV-100 or Emerson 33-CR devices, as well as at the Negavent DA-3 Plus Pegaso V. More commonly

Table 10.3 Indications for NPV

Acute Respiratory Failure
Post-cardiac surgery
Chronic respiratory insufficiency
Neuromuscular disease
Mask intolerance
Facial deformity
Increased pulmonary secretions
Facial pressure ulcers

used devices are those using a chest cuirass interface that increases access to the patient while adding patient comfort and mobility. These systems allow for addition of adjunctive therapy such as pulmonary hygiene or supplemental oxygen.

Other indications Noninvasive positive pressure ventilation is not effective with the following factors: (1) mask intolerance in infants and younger children, (2) sizing constraints, (3) congenital facial malformation, and (4) the presence of facial pressure ulcers (Table 10.3). Use of NPV may be a viable alternative to provide mechanical ventilation without an artificial airway. Chest cuirass interfaces alleviates the potential for mask intolerance by providing respiratory support without covering the face with a tight-fitting interface. Inability to properly fit a total face or oro-nasal mask in patients with congenital facial deformity results in a failure to deliver consistent pressures and volumes. Improper fit also increases the risk of pressure ulcer across bony prominences. Use of NPV may deliver better respiratory support while decreasing the need for escalation of care.

10.2.2 Contraindications and Side-Effects

Although NPV is indicated in both acute and critical care environments, several important contraindications must be considered when initiating NPV for non-invasive support (Table 10.4).

Children with documented central and/or sleep apnea syndromes should not be considered for NPV support. Absence of a central respiratory drive may result in clinically significant respiratory insufficiency leading to hemodynamic compromise. Negative pressure ventilation also increases the severity of upper airway collapse in obstructive sleep apnea—from negative intrathoracic pressure created by the device. Patients with tracheostomy are potentially less affected by the increase in thoracic negative press as the source of upper airway obstruction is bypassed by the artificial airway. Unconscious or patients with altered mental status are

Table 10.4 Contraindications and side-effects of NPV

Contraindications	Sleep-Apnea Syndrome Severe obesity Severe kyphoscoliosis Claustrophobia Rib fractures Recent abdominal surgery No protective airway reflex Extra-thoracic airway obstruction
Side-effects	Extra-thoracic airway collapse Back pain or discomfort Fatigue or depression Esophagitis Rib fracture Poor tolerance

contraindications, as often there is a loss of protective airway reflexes increasing the risk of aspiration. Some have suggested the use of an oral airway to support patients with upper airway obstruction caused by soft tissue and posterior displacement of the tongue. Use of an oral airway should only be used as a temporary adjunct until a more definitive airway can be placed. An oral airway should not be used continuously with NPV.

Additional contraindications include the morphology of the chest wall and abdomen. Severe obesity and kyphoscoliosis create an inability for the chest cuirass to fit snuggly are around the chest and abdomen, resulting in situations where neither negative nor positive pressure is achieved inside the cuirass rendering the therapy ineffective. Rib fractures and recent abdominal surgeries are also contraindications as the interface device will create discomfort and potentially result in complications. In these situations, non-invasive positive ventilation may be preferred to increase patient comfort and therapeutic effect.

10.2.3 Equipment for NPV

Design of negative pressure ventilators The basic design of all negative pressure ventilators include a negative pressure generator (pump), large-bore tubing, a pressure monitoring/trigger line (either a nasal cannula or a direct pressure line to the chamber), and a chamber in which sub-atmospheric pressure is created. The chamber may cover the entire body except for the head and neck (tank respirator, isolette, or a body suit) or only the chest and the upper abdomen (cuirass). The tank respirator has both the chamber and the pump in one unit. In all other cases, the two units are separate. The cuirass can be prefabricated or custom-designed to fit the contours of the chest. Custom-designed cuirasses are especially useful in patients with skeletal or spinal deformities. All body suits fit over a hard shell similar to the cuirass placed over the chest and the upper abdomen. Most negative pressure pumps in use today are pressure-cycled which means that when the target inspiratory pressure is reached, inspiration is terminated, and exhalation is started.

Tank/Whole Body Ventilator Modern tank ventilators are either made of aluminum or plastic and have separate rotary pumps. There is a mattress inside the chamber on which the patient's body rests. The head and neck rest on a pad or pillow outside the chamber. Some models have windows and portholes to allow access and to observe the patient as well. One of the advantages of the tank respirator is that they do not need to be designed to fit each patient. It requires only one effective seal at the level of the neck. The disadvantage is that it is difficult to access the patient. Aspiration of material from the pharynx into the trachea and bronchi may occur, especially with swallowing dysfunction.

Inspiration is time-triggered and the pump generates a negative pressure in the chamber. The tidal volume is directly proportional to the peak negative pressure within the chamber and inversely proportional to the patient's respiratory system dynamic compliance. When the negative pressure reaches a peak threshold value,

inspiration is terminated and expiratory phase is initiated. The breaths delivered by the tank respirator are all mandatory breaths and pressure-cycled. Ventilator rate and the I:E ratio are selected by adjusting the appropriate controls. Tank ventilators do not allow synchronization of the mandatory breaths to the patient's efforts. This ventilator does not provide any assist to spontaneous breathing like pressure support since all the breaths are mandatory. Supplemental oxygen can be administered through standard oxygen delivery devices such as nasal cannula or a face-mask.

Isolette Ventilator Isolette-type respirator is a negative-pressure ventilator, used in neonates and small infants, consisting of two Plexiglas chambers, one for the body and one for the head. The two chambers are connected by an opening equipped with a neck sleeve. The infant's body is placed on a mattress in the body chamber with the neck placed in the opening between the two chambers. The head is positioned on a head rest. When the neck sleeve is gently closed around the neck to obtain a relatively tight seal with all the openings in both chambers being closed, negative pressure ventilation can be instituted. The depth of ventilation and therefore, the tidal volume, is controlled by the peak inspiratory negative pressure. Ventilator rate and the I:E ratio are selected by adjusting the appropriate controls. Humidified oxygen can be delivered either by nasal cannula or directly into the head chamber. The infant's body temperature can be maintained using servo-control regulation available as part of the isolette. In some ventilators, the mandatory breaths can be synchronized.

Cuirass ventilators Most cuirasses are made of clear plastic with a durable foam seal around the outer edges. The foam creates a seal ensuring that the pressure generated is maintained throughout the respiratory cycle. Located at the top of the cuirass is a large bore opening for the pressure hose to connect. The pressure tubing is large bore so as to accommodate the gas flow that is needed during both inspiration and exhalation. In theory, a cuirass that covers only the chest should be easier to use than a tank ventilator. A properly fit cuirass should cover the chest with an airtight seal and allow the anterior abdominal wall to freely expand during inspiration. In some patients, standard sizes may fit poorly and fail to provide an airtight seal around the chest or allow free movement of the abdomen requiring a cuirass to be custom fit. Development of pressure sores at the points of contact between the cuirass and the patient is a disadvantage that needs to be monitored. Similar to the tank ventilator, the tidal volume achieved with a cuirass is proportional to the peak negative pressure within it.

Jacket ventilation The first effective jacket ventilator was the Tunnicliffe jacket, developed in the 1950s. The design consists of an airtight synthetic garment with an inner framework made of metal or plastic. Most of the models cover the chest and abdomen up to the level just below the hips. Though several sizes are available, they are still too large for the infants and children. They are also not quite effective in patients with skeletal abnormalities. A pump intermittently evacuates the air within the jacket similar to that used in a cuirass ventilator. The developed tidal volumes are usually smaller than that of a tank respirator. The most commonly used are the Tunnicliffe jacket, the Lifecare PulmoWrap, and the Lifecare Numo Garment.

10.2.4 Available Controls

Inspiratory pressure—Inspiratory pressure is the negative extra thoracic pressure applied to the chest wall that generates inspiratory flow into the lungs. Increasing the negative pressure increases the tidal volume which can be measured with a mouth-piece attached to a spirometer. Decreasing the level of negative pressure decreases the level of support, placing more work of breathing on the patient.

Expiratory pressure—Expiratory pressure is the pressure applied to the thorax during exhalation. When it is set to zero cm H_2O, exhalation will be passive due to the elastic recoil of the lung and chest wall. When it is set to be greater than zero cm H_2O, the positive pressure assists the exhalation of the lungs.

Respiratory frequency—These are mandatory breaths that can be set in control, assist control, and assist with plateau modes. Initial rate is usually set at least 2 breaths/min above the patient's current spontaneous respiratory rate. Some devices have synchronization modes, allowing for improved patient tolerance as the device adjusts the rate and shape of breath in response to the patient's pattern and effort.

I/E ratio—While setting the I:E ratios, it is important to pay attention to the actual inspiratory and expiratory times for each breath. Based on the respiratory system time-constants, I:E ratios can be adjusted for optimal lung inflation as well as exhalation.

Plateau pressure—Used in spontaneous mode, the plateau pressure can be used to extend the inspiratory time and maintain the set inspiratory pressure for the additional time. A time is set usually between 1.0 and 2.0 s. The pause allows for longer duration of distending pressure thus increasing mean airway pressure.

Trigger—In most devices, the trigger to initiate a breath is time or pressure. In some devices, just as with synchronized mandatory ventilation (SIMV), a patient effort can trigger the mandatory breath. The trigger to activate such synchronized breaths is pressure which may be sensed in the chest cuirass or a nasal cannula.

10.2.5 Available Modes

There are 2 types of NPV support, which are pressure-controlled ventilation and continuous negative extrathoracic pressure (CNEP). All ventilatory modes in NPV are pressure-controlled—the peak inspiratory pressure is limited or controlled with the tidal volume varying depending on the mechanical properties of the respiratory system. The following summary of the modes available in these ventilators will be described according to Chatburn's classification system with the corresponding proprietary names provided by the manufacturer.

1. Unsynchronized mandatory ventilation—All devices are capable of this mode of ventilation where all the breaths are machine-triggered and machine-cycled using time as the variable for triggering and cycling. The ventilator delivers a set rate with predetermined inspiratory and expiratory pressures and a fixed I:E

ratio. The total number of breaths delivered in this mode of ventilation is the set rate. Patient's spontaneous efforts do not have any impact on the total number of breaths provided by the ventilator and are not used to trigger any of the breaths. This is referred to as the *Control mode* by the Hayek ventilator and as *Timed mode* by the Pegaso V ventilator. The inspiratory pressure limit is set to provide the desired chest expansion. The expiratory pressure can be set to be a negative pressure, ambient pressure (zero) or a positive pressure. When the expiratory pressure is negative, it functions similar to PEEP in maintaining a certain lung volume during the expiratory phase. This mode is also called *Negative Pressure with CNEP*. This is particularly useful in children with parenchymal lung disease with decreased FRC. When the expiratory pressure is set to be positive, the chest is compressed during the expiratory phase providing active exhalation. This is also referred to as *Negative/Positive Pressure Ventilation.* The positive expiratory pressure can facilitate exhalation and CO_2 removal. Conversely, exhalation of the lungs is passive due to chest and lung recoil when the expiratory pressure is set to be zero or negative. When the expiratory pressure is set to be zero, it is also called *Cyclical Negative Pressure ventilation*

2. Synchronized mandatory ventilation—Some devices are capable of providing synchronized mandatory ventilation. The Hayek ventilator can sense patient's breathing efforts both in the cuirass as well as a nasal cannula. The Pegaso V ventilator can sense the patient's efforts using a nasal cannula or a facemask. Just as with the unsynchronized mode, the ventilator needs to have a preset rate, I:E ratio, inspiratory and expiratory pressures. If the patient is apneic or is unable to trigger, then the ventilator will deliver the set number of breaths. If the patient is breathing spontaneously and can trigger a breath, the ventilator will deliver a breath with the preset inspiratory and expiratory pressures with fixed inspiratory and expiratory times. This mode is similar to the Assist-Control mode with positive pressure ventilation. This is referred to as *Synchro-Timed* mode by the Pegaso V ventilator and *Respiratory Triggered* mode by the Hayek ventilator.
3. Synchronized assisted ventilation—Some devices are capable of providing synchronized, assisted ventilation similar to pressure support in positive pressure ventilation. When a patient's effort is sensed, the ventilator delivers a breath with the preset inspiratory and expiratory pressures. The inspiratory and expiratory times that determine the I:E ratio will depend on the patient's own efforts. When the patient makes an expiratory effort, machine inspiration is terminated and exhalation is initiated. During the succeeding exhalation phase, if an inspiratory effort is sensed, a mechanical breath is delivered. Unlike pressure-support ventilation, this mode has a back-up mode which is the unsynchronized mandatory mode with a preset rate, inspiratory and expiratory pressures, and a fixed I:E ratio. The inspiratory and expiratory pressures are the same whether the breath is synchronized and assisted or unsynchronized and mandatory.

Patient-triggered and synchronized pressure control require the use of an interface such as a nasal cannula or a direct trigger line connected to the chamber. The trigger is pressure and ranges from 0.6 to 3.0 cm H_2O. The proximal interface (e.g., nasal cannula or a mouth-piece near the patient's airway) are more sensitive than the direct cuirass pressure sensing line.

4. CNEP—*CNEP* refers to a spontaneous mode where a constant sub-atmospheric pressure is provided throughout the respiratory cycle. CNEP is like CPAP and is used to support conditions with increased work of breathing associated with small airway disease and V/Q mismatching. Initiation of CNEP usually begin at –7 to –10 cm H_2O and is adjusted as necessary based on gas exchange and work of breathing. Occasionally a more negative setting may be needed. Improvement is identified by better oxygenation and ventilation, a decrease in expiratory muscle use and metabolic acidosis.
5. High frequency oscillator mode—The Hayek ventilator can function as a high frequency ventilator at a frequency between 2 and 15 Hz. The expiratory pressure is set to be a positive pressure of the same magnitude as the negative inspiratory pressure. The total pressure deflection between peak inspiration and peak expiration is called the *Span* similar to the amplitude/power of the high frequency oscillatory ventilators used from invasive ventilation. The high frequency mode is not approved for use as a ventilator in the US.
6. Machine Failure and Alarms Machine failure is indicated by both audio and visual alarms and occur when the device is deemed inoperable. These alarms vary with device. Reasons leading to machine failure include but are not limited to (1) AC power failure, (2) unrecognized hardware failure, (3) pressure sensor fault or failure, (4) faulty pressure valve, (5) software failure, and (6) tank pressure being too low. Both high and low alarms can be set for pressure and rate.
7. Monitoring Clinically, NPV has been associated with improvement in ventilation and oxygenation in a number of clinical situations. Most commonly the modality has been used as an adjunctive support device in conjunction with supplemental oxygen devices. Standard physiologic monitoring should be used to identify clinical improvement or decline during therapy. Clinical evaluation should include a systematic assessment of the upper airway patency, cardiovascular, respiratory, and neurologic status. Respiratory rate and pattern changes are helpful in identifying clinical improvement or worsening. Pulse-oximetry will identify changes in SpO_2, facilitating oxygen titration and identifying need for escalation in therapy. Institutionally accepted oxygen titration guidelines should be used to manage support. Additionally, end-tidal carbon dioxide ($ETCO_2$) monitoring through a commercially available system using a nasal cannula interface may help recognize changing in expired CO_2. Clinicians should be aware of any changes in $ETCO_2$, as it is a key indicator of muscle fatigue or increasing intrapulmonary shutting. If changes in vital sign, SpO_2, or $ETCO_2$ are seen, blood gas measurements should be obtained (Table 10.5).

Table 10.5 Negative pressure generator devices and characteristics of operation

Device	Inspiratory pressure (cm H_2O)	Expiratory pressure (cm H_2O)	CNEP maximum (cm H_2O)	Rate (breaths/min)	I:E Ratio	Modes	Trigger	Alarm
Hayek® United Hayek	−50	10 cm above the inspiratory pressure up to +50	−50	6–150	1:6	C, CNEP	Pressure	Apnea High RR MF
Negavent DA-3 Plus Pegaso V Dima Italia	−5 to −99	−25 to + 99	−25	1–50	1:6	C, A/C, CNEP, A + Plat	Pressure, Flow	P_{max} P_{min} MF

C: Control; A/C: Assist Control; CNEP: continuous negative extrathoracic pressure; A + Plat: Assisted with Plateau pause; P max: Maximum Pressure; P Min: minimum pressure; MF: Machine failure

Additionally, understanding of the operational characteristics (Table 10.5), interface sizing, and device limitations will facilitate the therapeutic effect of NPV. Both the devices are capable using inverse I:E ratios. These are used mainly for secretion clearance purposes and not for ventilatory support.

10.2.6 Secretion Clearance and Cough Assist

High frequency chest wall oscillations using the cuirass ventilators can be used for secretion clearance in patients. It can be used alone or in combination with sigh breaths following which the airway can be cleared of any secretions that are brought up. The sequence of high frequency oscillations followed by the sigh breaths can be programmed into the ventilator. Cuirass ventilators can also be used as cough assist devices with a simulated cough that has a prolonged inspiratory phase with a pressure of –20 to –60 cm H_2O followed by a very short expiratory phase with a positive pressure of the same magnitude as the inspiratory phase.

Suggested Readings

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