

## Chapter 2

# Non-Invasive Mechanical Ventilation in Children: An Overview

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### Hypoventilation

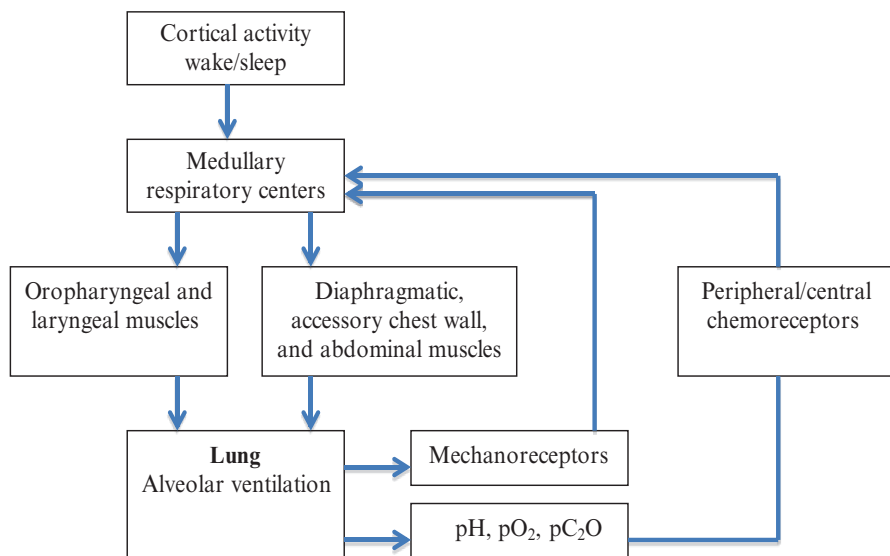
Ventilatory control is a precisely tuned physiologic process that maintains systemic oxygen and carbon dioxide levels within very narrow ranges required for appropriate cellular function. This delicate balance has resulted in a complex system that senses changes in oxygen ( $O_2$ ), carbon dioxide ( $CO_2$ ), and pH in arterial blood and in the brain and responds to these changes through compensatory responses in the upper airway and respiratory pump muscles to maintain ventilation (see Fig. 2.1). Oxygen levels are primarily sensed by the peripheral chemoreceptors, the carotid bodies, and the aortic bodies.  $CO_2$  is sensed mainly by central chemoreceptors that are widely distributed in the brainstem and, along with the peripheral chemoreceptors, input to the medullary respiratory centers in the brainstem. Perturbations in  $O_2$ ,  $CO_2$ , and pH will prompt precise changes in the depth of respiration (tidal volume), respiratory rate, and/or the breathing pattern via diaphragmatic, accessory chest wall and abdominal muscular contraction. Upper airway musculature also receives input from central and peripheral chemoreceptors resulting in contraction to maintain patency.

When alveolar ventilation is insufficient and oxygen levels become too low and/or carbon dioxide levels too high, cellular function is impaired. The alveolar ventilation equation is useful in understanding the physiologic processes leading to hypoventilation and indicates that systemic carbon dioxide levels ( $pCO_2$ ) are proportional to the ratio between systemic carbon dioxide production ( $VCO_2$ ) and alveolar ventilation (VA) as follows:

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**Fig. 2.1** Ventilatory control

$$pCO_2 \propto \frac{VCO_2}{VA}$$

Children who hypoventilate can usually be divided into one of two general categories, as follows: children with lung disease, abnormal upper airway, and/or respiratory pump impairment but normal respiratory drive versus children with normal lung, upper airway, and respiratory pump function but abnormal respiratory drive. The first category (abnormal lungs/airways/respiratory pump, normal drive) includes those with upper airway obstruction (e.g., obstructive sleep apnea), insufficient respiratory pump strength to maintain adequate minute ventilation (e.g., Duchenne muscular dystrophy), and severe lung disease (e.g., end-stage cystic fibrosis). In contrast, the second category (normal lungs/upper airway/respiratory pump, abnormal drive) includes those with inadequate sensation or responses to perturbations of CO<sub>2</sub>, O<sub>2</sub>, or pH, which commonly manifest as central sleep apnea. This group includes children with peripheral or central nervous system impairment and children given medications that decrease respiratory drive (see Table 2.1). It is important to note that some patients may fall into both categories of hypoventilation mechanisms, having impaired pulmonary/respiratory pump function and abnormal respiratory drive. For example, blunting of respiratory drive may occur in patients with long-standing muscle weakness and chronic CO<sub>2</sub> retention.

**Table 2.1** Factors and diseases that may result in hypercapnia

Disturbance of respiratory mechanics	Causes and diseases
<i>Normal respiratory system but abnormal respiratory drive</i>	
Reductions in respiratory drive	Sedation/anesthesia and sleep
	Prematurity
	Congenital central hypoventilation syndrome
	Obesity hypoventilation syndrome
	Cerebral blood flow disturbance
	Chiari malformation
	Metabolic alkalosis
	Prader-Willi syndrome
	Hypothyroidism
	Sedation/anesthesia and sleep
<i>Lung, airway, or respiratory pump impairment with normal respiratory control</i>	
Disorders of oropharyngeal and laryngeal muscles	Obstructive sleep apnea
	Vocal cord dysfunction
Respiratory muscles	Muscular dystrophy
	Spinal muscular atrophy
	Spinal trauma
	Diaphragmatic paresis
	Myasthenia gravis
	Poliomyelitis
	Amyotrophic lateral sclerosis
Chest wall	Kyphoscoliosis
	Postthoracotomy, spondyloplastic
Lungs	Rheumatic diseases
	Cystic fibrosis
	Bronchopulmonary dysplasia
	Chronic lung disease
	Asthma
	Kartagener syndrome
Increased CO <sub>2</sub> production (relevant in advanced respiratory disease)	Fever
	Excess carbohydrate intake

***Children with Normal Lung and Respiratory Pump Function with Abnormal Respiratory Drive***

When central chemoreceptors and the brainstem respiratory controller are not intact, perturbations in O<sub>2</sub> and CO<sub>2</sub> will arise due to decreased respiratory drive and most commonly manifest during sleep. Examples are children administered sedating medications, infants with apnea of prematurity, and patients with congenital central hypoventilation syndrome (CCHS), metabolic alkalosis,

Prader-Willi syndrome, and CNS disorders such as a Chiari malformation. Mechanisms underlying the association of hypoventilation with sleep state in this group are numerous and vary by disorder. For example, patients with CCHS have genetically determined abnormalities in central CO<sub>2</sub> sensing, with profound effects on central chemoreceptor function and breathing rhythm generation during sleep [1]. Children with Prader-Willi syndrome may hypoventilate during sleep due to obstructive sleep apnea, abnormal ventilatory sensitivity to CO<sub>2</sub>, and/or obesity-related hypoventilation [2].

Obesity hypoventilation is defined as a weight and/or BMI greater than the 95th percentile associated with daytime symptoms of sleepiness, daytime hypercapnia with CO<sub>2</sub> greater than 45 mmHg, or serum bicarbonate greater than or equal to 27 meq/L and/or oxygen saturation less than 92 % on room air during wakefulness in the absence of other causes of hypoventilation [3]. Obesity hypoventilation is associated with decreased quality of life, cardiovascular comorbidity, pulmonary hypertension, and increased mortality.

### ***Children with Lung Disease and/or Respiratory Pump Impairment with Normal Respiratory Drive***

For children in this category, hypoventilation also most commonly manifests during sleep. The transition from wake to sleep is associated with a number of physiologic changes that result in a fall in minute ventilation. Specifically, sleep as compared to wake is associated with decreased ventilation predominantly through a reduction in tidal volume [4]. Additionally, during sleep when neuromuscular tone wanes, the upper airway is prone to collapse leading to obstructive sleep apnea [5–8]. Taken together, sleep compared to wake is a more vulnerable state for hypoventilation.

Decreased neuromuscular strength, underlying lung disease, and cardiac disease independently contribute to hypoventilation and are included in the group of children who typically have normal respiratory drive but respiratory system impairment. Children with neuromuscular disease have an increased incidence of upper airway obstruction and are also susceptible to pathophysiologic processes in the lungs that compromise minute ventilation. While diaphragm strength is retained in most neuromuscular disorders, the progressive loss of skeletal muscle tone in the intercostal and expiratory respiratory muscles results in a slow onset of hypoventilation in many patients that often manifests first during sleep [9]. The development of scoliosis, which is common in children with neuromuscular disease, further worsens hypoventilation as a result of decreases in both lung volumes and chest wall compliance [10]. Children with neuromuscular weakness who lose the ability to cough effectively are vulnerable to increased mucous impaction and resultant atelectasis. Finally, lower lung volumes have been shown to increase pharyngeal collapsibility

during sleep, posited to be largely a result of decreased caudal traction on the pharynx [11]. These factors individually or in combination can lead to an inability to meet ventilatory requirements over time.

Evaluation of Ventilation and CO<sub>2</sub> Homeostasis

Evaluation of ventilation during sleep should begin with a detailed history and physical examination. Symptoms of hypoventilation during sleep include frequent awakenings, headaches on awakening, difficulty concentrating, decreased energy, fatigue, and sleepiness during the day. It is recommended that a discussion of these symptoms occurs at clinic visits for children with suspected obstructive sleep apnea and for all children with neuromuscular disease or other conditions associated with hypoventilation. It should be noted that symptoms obtained during history and physical exam can underestimate polysomnography findings [12]. Thus, there should be a low threshold to perform polysomnography in children at high risk for hypoventilation.

When suspicion for hypoventilation during sleep arises, polysomnography is recommended to assess for the presence and severity of sleep disordered breathing and if present to differentiate between potential etiologies such as upper airway obstruction, decreased respiratory drive, or lung disease leading to gas exchange abnormalities. Hypoventilation during sleep in children is defined as CO<sub>2</sub> greater than 50 mmHg for greater than 25 % of total sleep time [13]. Figure 2.2 shows a 12-year-old male with achondroplasia and severe obstructive sleep apnea (apnea-hypopnea index of 112 events/h of sleep) following adenotonsillectomy. As can be seen the patient exhibited ongoing thoracic and abdominal effort associated with an absence of inspiratory airflow associated with oxyhemoglobin desaturations to 83 %

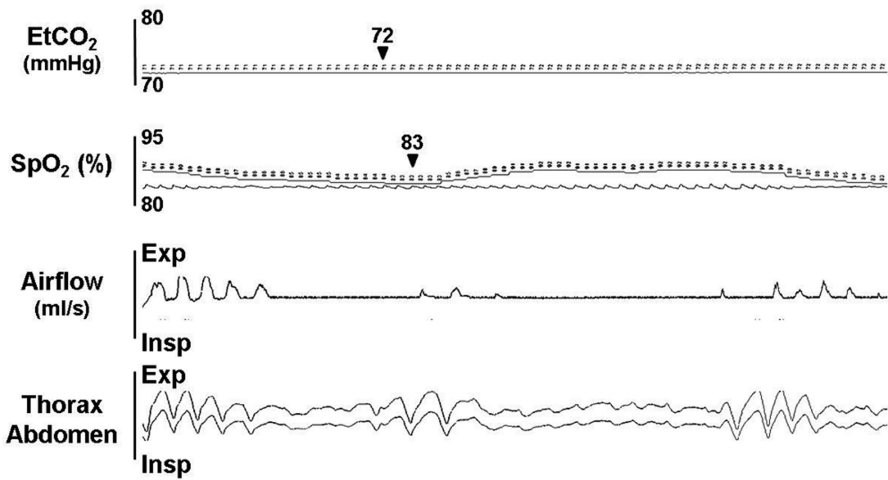
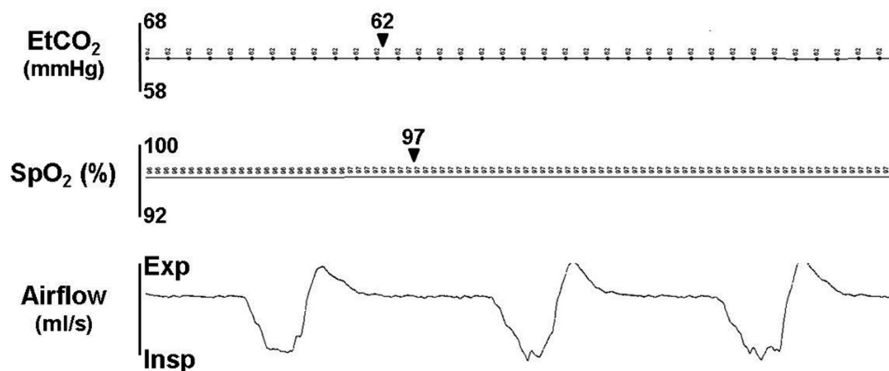


Fig. 2.2 Obstructive sleep apnea on polysomnography



**Fig. 2.3** Central hypoventilation on polysomnography

indicating obstructive apneas. The high rate of obstructive apneas in this patient was associated with transcutaneous CO<sub>2</sub> levels that were greater than 50 mmHg for approximately 70 % of the total sleep time and were as high as 72 mmHg.

In contrast, Fig. 2.3 shows a polysomnographic tracing of the breathing pattern during sleep of a 12-year-old female with a Chiari malformation who complained of headaches on awakening. Her apnea-hypopnea index was 0 events/h. Her end-tidal CO<sub>2</sub> levels, however, were greater than 50 mmHg for 50 % of her sleep time and were as high as 62 mmHg. The patient had a respiratory rate of eight breaths per minute and the inspiratory flow contour was round consistent with a non-obstructed breathing pattern. These findings are consistent with hypoventilation secondary to a decreased respiratory drive.

If polysomnography is not available, additional methods to evaluate ventilation during sleep include pulse oximetry, end-tidal or transcutaneous CO<sub>2</sub> devices, or blood gas performed during wake or sleep. It should be noted that while recommendations for the assessment of CO<sub>2</sub> during polysomnography by the American Academy of Sleep Medicine do not distinguish between end-tidal and transcutaneous devices, there are potential shortcomings with both devices [13]. Both end-tidal and transcutaneous CO<sub>2</sub> measurements are well tolerated by children during sleep, readily available, and commonly employed to assess CO<sub>2</sub> during polysomnography. Sidestream end-tidal CO<sub>2</sub> accurately reflects arterial CO<sub>2</sub> under normal breathing conditions when adequate expiratory airflows are entrained, which can be seen when the CO<sub>2</sub> waveform plateaus reflecting exhalation of gas from the alveoli. The sidestream end-tidal method can underestimate CO<sub>2</sub> levels, however, when the plateau in CO<sub>2</sub> concentration is not attained [14]. Underestimation of CO<sub>2</sub> with the end-tidal device will occur during rapid shallow breathing, when nasal airflow is reduced or absent such as when the cannula is removed or if the patient is mouth breathing. The transcutaneous CO<sub>2</sub> method has also been used to assess arterial CO<sub>2</sub> levels during sleep. There are well-described gradients between arterial and transcutaneous levels during sleep; however, transcutaneous measurements of CO<sub>2</sub> may underestimate systemic levels if contact with skin is impaired or overestimate if the heated probe

is in contact with the same area of skin for a prolonged period leading to elevated localized temperature and thereby local increases in  $\text{CO}_2$  production [15, 16].

In children with lung disease or neuromuscular disorders, lung function tests should also be considered as a part of their routine assessment. Lung volumes can be particularly helpful identifying patients at risk for hypoventilation. Decreases in residual volume are commonly seen prior to a reduction in total lung capacity. Lung function in patients with Duchenne muscular dystrophy has been correlated with findings of gas exchange perturbations during polysomnography [9]. In general, ventilation during sleep should be evaluated when FVC falls below 60 % predicted [17]. If the patient has additional comorbidities such as heart disease or lung disease, ventilatory failure might occur with milder degrees of neuromuscular weakness.

## Noninvasive Treatment of Hypoventilation

Noninvasive positive pressure ventilation is the delivery of air from a compressor to the patient without use of an endotracheal tube, with patient interfaces that include nasal or full face mask, nasal prongs, nasal cannula, or mouthpiece. The most common noninvasive ventilation modalities are continuous positive airway pressure (CPAP) and bi-level positive airway pressure. For both modalities air is delivered from a compressor via tightly fitting nasal or full face mask attached by headgear or straps that fit around the head and increases pressure in the upper airway. Noninvasive ventilation treatment during wake can be effectively achieved with the use of a ventilator that delivers large tidal volumes to the patient by a mouthpiece often referred to as sip and puff ventilation. A relatively new noninvasive ventilation positive pressure modality is high-flow nasal therapy (HFNT), which delivers air at high flow rates via nasal cannula and can be used during wake and sleep [18, 19]. Effective treatment of hypoventilation requires an understanding of the underlying pathophysiology responsible for an elevation of systemic  $\text{CO}_2$  and the mechanisms of different noninvasive positive pressure ventilation modalities on gas exchange.

The goal of ventilatory support is to increase minute ventilation and thereby reduce systemic  $\text{CO}_2$  levels. As discussed above systemic  $\text{CO}_2$  is proportional to the ratio of  $\text{CO}_2$  production ( $\text{VCO}_2$ ) to alveolar ventilation, which is equivalent to tidal volume ( $\text{Vt}$ ) minus physiologic dead space ( $\text{Ds}$ ). Thus, reducing systemic  $\text{CO}_2$  levels can be achieved by increasing tidal volumes and/or decreasing physiologic dead space as follows:

$$p\text{CO}_2 \propto \frac{\text{VCO}_2}{\text{Vt} - \text{Ds}}$$

For children with obstructive sleep apnea who hypoventilate due to upper airway obstruction, CPAP can effectively alleviate upper airway obstruction, and when respiratory drive is intact, inspiratory tidal volumes increase and gas exchange improves [20]. For children with insufficient respiratory pump strength or lung

disease as well as for children with decreased respiratory drive, bi-level positive airway pressure can augment tidal volumes to normalize gas exchange during sleep. High-flow nasal therapy produces a small amount of positive pressure in the upper airway, thereby decreasing upper airway obstruction [21]. The high flow of air also washes out gas in the upper airway decreasing dead space. It should be noted that while correction of hypoxia can be achieved with supplemental oxygen, caution must be used in children who hypoventilate such as children with neuromuscular disease because of the potential for worsening hypercapnia when hypoxic ventilatory drive is decreased. Thus, when supplemental oxygen is administered to children who hypoventilate,  $\text{CO}_2$  levels should always be monitored.

### ***Continuous Positive Airway Pressure***

The most common indication for noninvasive positive pressure ventilation in children is obstructive sleep apnea. Obstructive sleep apnea is the result of pharyngeal collapse during sleep due to the combination of increased mechanical loads (anatomic upper airway properties) and insufficient compensatory neuromuscular responses to obstruction [8, 22–26]. During sleep when neuromuscular tone falls, the upper airway is prone to collapse [5, 27, 28]. Manipulations of nasal CPAP to assess nasal pressure maximal flow relationships are considered the gold standard to assess upper airway collapsibility, termed the critical closing pressure or Pcrit. Utilizing the Starling resistor to model airflow through a collapsible tube, airflow through the pharynx is dependent on the relationships between the surrounding pressure of the pharynx and pressure downstream in the lower airways and upstream at the nose. When Pcrit is more positive than upstream pressure, complete collapse occurs and there is no airflow (apnea). When pressure downstream falls below Pcrit, partial airway occlusion occurs and airflow is dependent on the gradient between pressure upstream and the collapsible segment in the pharynx. To alleviate upper airway obstruction, either the Pcrit must be lowered (more negative) or nasal pressure increased. Adenotonsillectomy is the first line of treatment recommended by the American Academy of Pediatrics for children for obstructive sleep apnea children, which reduces mechanical loads in the pharynx and decreases Pcrit [29]. Additional factors that can reduce Pcrit include a change in body position, for example, from supine to side, and weight loss [30]. Following adenotonsillectomy approximately 35 % of children have residual sleep apnea [31]. For children with residual sleep apnea, children who refuse surgery, or children who are not deemed appropriate surgical candidates, noninvasive positive pressure ventilation is recommended. The primary effect of CPAP is to increase nasal pressure and create a positive pressure gradient upstream between the nose and the point of airway collapse in the pharynx. In addition to improving pharyngeal patency, CPAP also has been shown to improve gas exchange by increasing lung volumes and decreasing atelectasis [32].



Because patient comfort is correlated with adherence with noninvasive positive pressure ventilation [32–34], selecting an appropriately sized mask the patient finds comfortable is important. There are a number of patient interfaces including nasal masks, full face masks, and nasal pillows. If treatment of upper airway obstruction is the goal, caution should be used with a full face mask. At the same level of pressure, a full face mask compared to a nasal mask is often associated with decreased efficacy in restoring upper patency and in some cases will not restore upper airway patency at high pressure levels or require increased pressure levels resulting in discomfort to the patient [26]. The mechanisms that decrease the efficacy of a full face mask for treating obstructive sleep apnea are not clear; however, investigators speculate that when breathing through the nose and mouth, a full face mask does not create an adequate pressure gradient across the oropharynx or hypopharynx to restore patency and that increased pressure applied to the chin may force the mandible and tongue posteriorly and increase pharyngeal collapse. Moreover, a full face mask should be used with great caution in young patients and those with neuromuscular weakness because the patient has to be able to remove the mask in event of emesis to avoid aspiration or during machine or power failure to prevent an asphyxic event. Polysomnography is recommended to assess the appropriate pressure settings because it effectively demonstrates the relationship between nasal pressure on upper airway obstruction, gas exchange, and sleep quality [35].

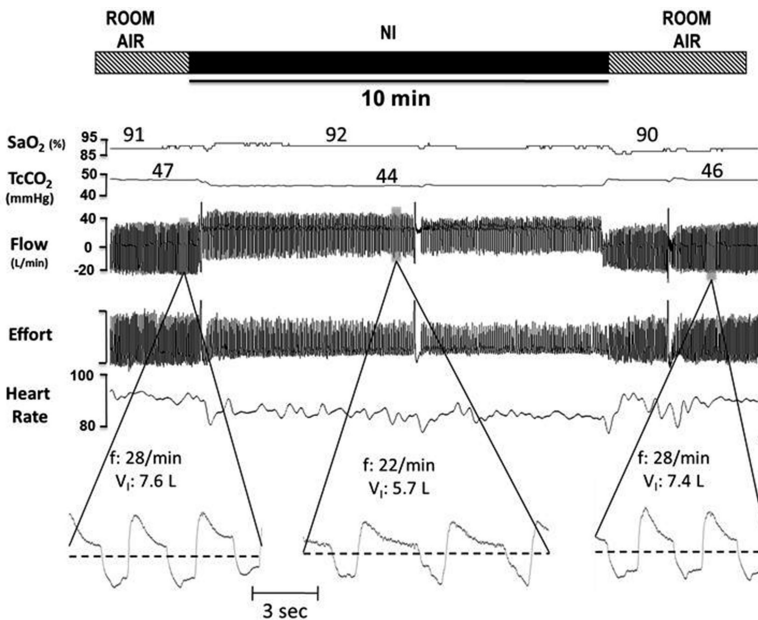
### ***Bi-level Positive Airway Pressure***

For patients who hypoventilate without evidence of upper airway obstruction or have ongoing impairment in gas exchange after upper obstruction is alleviated with CPAP, bi-level positive airway pressure has been shown to effectively restore appropriate oxygen and carbon dioxide levels in children. The therapeutic mechanisms to increase minute ventilation are similar to invasive mechanical ventilation; most bi-level devices provide an ability to alter expiratory pressure, inspiratory pressure, respiratory rate, and inspiratory time. In contrast to invasive mechanical ventilation, when using noninvasive positive pressure ventilation to increase minute ventilation, the upper airway must be taken into consideration. If upper airway obstruction is present, expiratory positive airway pressure (EPAP) should be adjusted first to restore upper airway patency so that adjustments of inspiratory positive airway pressure (IPAP), respiratory rate, and inspiratory times can effectively increase minute ventilation and restore normal gas exchange. In patients without upper airway obstruction, a full face mask can be used effectively to restore ventilation; however, the same concerns for young patients and patients with neuromuscular disease above persist. The bi-level settings required to restore gas exchange should be assessed while monitoring oxygen and carbon dioxide levels using the lowest pressures that effectively alleviate upper airway obstruction and normalize gas exchange, which like CPAP are best assessed with polysomnography

[35]. Once noninvasive positive pressure ventilation is established during sleep, reevaluation with polysomnography should occur regularly, with intervals dependent on age and clinical features. For example, the evaluation of ventilation during sleep in older children can occur yearly if stable, while reevaluation of ventilation during sleep in younger children might be scheduled more frequently as requirements may change with growth.

### *High-Flow Nasal Therapy*

High-flow nasal therapy (HFNT) has been used in the hospital setting particularly on pediatric intensive care units and has recently become commercially available for home use. High-flow nasal therapy delivers air through a nasal cannula that is heated and humidified at flow rates ranging from 5 to 50 L/min. In contrast to CPAP or bi-level airway pressure devices, high-flow nasal therapy does not require formation of a seal at the nose and/or mouth. High-flow nasal therapy has proven efficacious in the treatment of children and adults with mild to moderate OSA [21, 36]. While there is a slight increase in nasal pressure, the lack of a seal limits the amount of nasal pressure to approximately 2 cm H<sub>2</sub>O at 20 L/min in adults, suggesting that there are additional mechanisms of action that stabilize the breathing pattern and normalize gas exchange [21]. Figure 2.4 is a 15-year-old female with cystic fibrosis who underwent



**Fig. 2.4** Trial of high-flow nasal therapy in a patient with cystic fibrosis

trial off and on HFNT at 20 L/min alternating over 10 min periods. HFNT at 20 L/min was associated with a reduction in both  $\text{CO}_2$  from 47 to 44 mmHg and minute ventilation from 7.6 to 5.7 L/min. The alveolar ventilation equation (see “Children with Normal Lung and Respiratory Pump Function with Abnormal Respiratory Drive”) indicates that the reduction in systemic  $\text{CO}_2$  associated with a decrease in minute ventilation is due to either decreased dead space ventilation by washing  $\text{CO}_2$  out of the upper airway or decreased production of  $\text{CO}_2$  suggesting decreased energy expenditure from the work of breathing. The effects of HFNT on  $\text{CO}_2$  levels in children without upper airway obstruction suggest a potential role for children with lung disease and neuromuscular disorders, including those with mild disease, or as a bridging therapy until more aggressive noninvasive ventilatory support (e.g., bi-level positive airway pressure) or tracheostomy is required. HFNT might also be particularly helpful for young children including infants with OSA and children who have significant difficulty tolerating CPAP or bi-level noninvasive ventilation due to the patient interface. Studies evaluating effectiveness of HFNT in the home setting have not been performed, and the role of HFNT in both children with OSA and children who hypoventilate without OSA has not been adequately determined.

### *Noninvasive Positive Pressure Ventilation During Wakefulness*

Hypoventilation can develop acutely during wakefulness in patients with neuromuscular disorders or in otherwise healthy children, for example, with pneumonia or status asthmaticus. The use of noninvasive positive pressure ventilation in the intensive care unit setting for children with an acute onset of hypoventilation during wakefulness has been shown effective at reducing intubation and length of stay and should be considered as the first approach to support ventilation particularly for children with neuromuscular disorders. Treatment with noninvasive positive pressure ventilation in the critical care setting, however, is outside of the scope of this book chapter. For children with chronic hypoventilation during wakefulness, noninvasive ventilation has been shown to effectively restore oxygen and carbon dioxide levels and might decrease the need for mechanical ventilation [37]. For short periods of time, noninvasive positive pressure ventilation via mask can be well tolerated during wake without significant complication. Because noninvasive positive pressure ventilation by mask requires a tight seal and if use is required for more than 24 h consecutively, the risk of skin breakdown increases, which needs to be taken into consideration for children requiring ventilator support for prolonged periods [38].

When hypoventilation is present during wakefulness, assessing hypoventilation during sleep and if present treating can improve daytime gas exchange and reverse hypercapnia when awake [39–42]. Several studies in children with neuromuscular disease have demonstrated decreased development of hypercapnia during wakefulness and improvement in diurnal oxygenation and carbon dioxide levels when gas exchange was normalized during sleep [40, 43–45]. Reversal of daytime

hypoventilation with nocturnal noninvasive positive pressure ventilation treatment suggests that patients develop a loss of sensitivity to elevated carbon dioxide and hypoxia that can be restored and improve ventilation during wakefulness when gas exchange is normalized during sleep. In children with neuromuscular disorders, rest of respiratory musculature during sleep might also play a role in restoring daytime gas exchange.

For patients requiring chronic noninvasive positive pressure ventilation during wakefulness and sleep, a commercially available mouthpiece can be attached to a ventilator for use when awake, which is often referred to as mouthpiece ventilation or sip and puff ventilation [46, 47]. One approach is to set the ventilator in assist control cycling at high volumes in a timed mode with the alarms turned off. The mouthpiece should be placed next to the patient's mouth allowing them to place it between their lips and inhale at regular intervals to augment inspiratory tidal volumes as needed. Mouthpiece ventilation is well tolerated and does not interfere with eating or speaking. If patients have an aversion to noninvasive positive pressure ventilation, if it is contraindicated, or if hypoventilation cannot be corrected by noninvasive positive pressure ventilation, invasive mechanical ventilation should be considered.

Alternatively, high-flow nasal therapy (HFNT) when heated and humidified has been shown to improve oxygenation and comfort in children with respiratory distress in an intensive care setting [48]. In adults, HFNT during wakefulness increased tidal volumes and lowered respiratory rate [18]. These studies suggest a possible role for HFNT in children with chronic hypoventilation during wakefulness. Taken together the data suggest the use of heated and humidified air delivered through a nasal cannula has the potential for treatment of chronic hypoventilation in children during wakefulness; however, further studies assessing its specific role are needed.

### ***Introducing Noninvasive Positive Pressure Ventilation***

Initiation of noninvasive positive pressure ventilation should be considered in children with diurnal or nocturnal hypoventilation and obstructive sleep apnea as noted above. Discussion of the need for and the goals of noninvasive positive pressure ventilatory support should occur with patients and their families and the medical team on a routine basis and should begin as early as possible. For most patients with progressive and slow onset of hypoventilation, ventilatory support can be effectively initiated in the outpatient setting. Initiation of noninvasive positive pressure ventilatory support can be difficult for families and when possible should be done slowly and carefully because experience with noninvasive positive pressure ventilation in the first 1–2 weeks of use is strongly associated with long-term adherence [33, 49]. Introduction of the device during wakefulness for young children and children resistant to initiation can be helpful. One approach is to introduce the mask alone without airflow during wakefulness and when tolerated add a low level of pressure. Once airflow is tolerated during wakefulness, it can be incorporated into the bedtime routine slowly increasing the duration of use. For patients unable to tolerate the initiation of

noninvasive positive pressure ventilation, psychologists trained in cognitive behavioral therapy can be helpful [50]. Tracheostomy may be considered in children who are unable to tolerate noninvasive positive pressure ventilation or when noninvasive positive pressure ventilation is inadequate to meet the patient's ventilatory needs.

### ***Benefits of Noninvasive Positive Pressure Ventilation***

In children with neuromuscular disorders, such as Duchenne muscular dystrophy, who have hypercapnia, the use of noninvasive positive pressure ventilation has been associated with improved survival [51–53]. In children with spinal muscular atrophy treatment, noninvasive positive pressure ventilation and invasive mechanical ventilation via tracheostomy were similar in regard to mortality [37]. It should be noted that most studies assessing effects of noninvasive positive pressure ventilation in children with neuromuscular disease on mortality are limited by their retrospective design and small numbers of patients studied.

In addition to effects on mortality, noninvasive positive pressure ventilation has also been associated with reduced comorbidities in children with neuromuscular disease. Specifically, noninvasive positive pressure ventilation has been associated with decreased incidence of hospital admission [45]. Use during sleep has been shown to improve quality of sleep, decrease daytime sleepiness, increase sense of well-being and independence, improve concentration, and reduce the incidence of morning headaches [40, 52–54].

Decreased neuromuscular tone is associated with impairment of chest wall shape and growth, which might also be mitigated with noninvasive positive pressure ventilation. As a result of intercostal and expiratory muscle weakness, respiratory movement can become asynchronous ultimately resulting in a bell-shaped chest wall. There is some evidence that chest wall shape can be maintained when noninvasive ventilation is introduced early in life and pressure levels are titrated to prevent asynchronous respiratory motion [55]. While underlying mechanisms responsible for maintaining chest wall shape are unclear, possibilities include alleviation of lower airway obstruction and the reduction of atelectasis. The effects of noninvasive positive pressure ventilation on chest wall shape and growth is an active area of study that has the potential to slow the rate of decline of pulmonary function and thereby significantly improve respiratory health of children with neuromuscular disorders.

### ***Complications of Noninvasive Ventilation***

The most common complication of noninvasive positive pressure ventilation is skin breakdown and ulceration. As discussed previously, the risk is increased with use over prolonged periods of time. The risk of skin breakdown also increases with excessive tightening of headgear straps and increased pressure applied to the face [38, 56]. When initiating CPAP, the medical team can be very helpful in

demonstrating appropriate amount of pressure required to create an effective seal. The mask should be cleaned daily to remove oils that adhere to the mask from the face and contribute to skin breakdown. When skin irritation begins, it can be effectively alleviated with use of hydrocolloid tape to prevent skin irritation while maintaining a good seal and minimizing air leak. These complications can be decreased with assessments of mask fit and adjustments of mask fit and type when needed. Other common complications include nasal dryness and irritation which can result in nasal bleeding. This can be effectively treated with application of heat and humidity [57–59]. If irritation continues despite adequate heat and humidity, nasal steroids can effectively reduce nasal irritation. Use of positive pressure during sleep can result in gaseous distention of the abdomen, the risk of which is increased with higher levels of pressure. If a G-tube is present, venting the abdomen through the G-tube during sleep can help to decrease the risks associated with gastric distention. As discussed previously, there is risk of aspiration associated with emesis into a full face mask. Introduction of tightly sealed mask with pressure applied to rapidly developing facial bony structures has been associated with significant maxillary hypoplasia. Fauroux et al. assessed 40 children who had been using noninvasive positive pressure ventilation for a minimum of 4 weeks and found facial flattening in 68 % of children, with severity correlated with hours per day of mask use [60]. The risk of maxillary hypoplasia might be reduced with alternative patient interfaces or by altering masks to apply pressure at different points on the face and could include use of nasal pillows when possible; however, there are no studies assessing these interventions.

### ***Future Considerations***

Noninvasive positive pressure can effectively support the ventilatory needs for many children who hypoventilate. Understanding the etiology responsible for hypoventilation and choosing the appropriate modality and settings are critical to restore ventilation. Many questions regarding noninvasive ventilation, however, remain. Adherence with noninvasive ventilation remains suboptimal in some patient populations including children with obstructive sleep apnea. While advances in patient interfaces have improved comfort, adherence has not improved markedly. Of particular concern are young children and infants, for whom options for noninvasive patient interfaces are limited. Moreover, the roles of newer non-invasive ventilation modalities including the high-flow nasal cannula system for children who hypoventilate have not been adequately determined.

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Sterni, L.M.; Carroll, J.L. (Eds.)

2016, XIV, 362 p. 49 illus., 29 illus. in color., Hardcover

ISBN: 978-1-4939-3747-9

A product of Humana Press