Pediatric Noninvasive Ventilation

Cathy Haut[1]

[1] Department of Pediatric Critical Care, Pediatrix Medical Group at Sinai Hospital, Baltimore, Maryland, United States

Address for correspondence Cathy Haut, DNP, CPNP-AC, CCRN, 18544 Rose Ct Lewes, DE 19958, United States (e-mail: cathyhaut@gmail.com).

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Abstract

Noninvasive ventilation has been available for many years for use in the pediatric population. Historically, continuous positive airway pressure and bilevel positive airway pressure modes were used for respiratory diseases, including neonatal apnea, bronchiolitis, asthma, and pneumonia. Newer studies suggest that noninvasive ventilation is also an effective and safe mode for support of children with acute respiratory distress syndrome and respiratory failure. The newest type of noninvasive respiratory support is high flow nasal cannula, which has gained popularity in the past few years and its use is being justified in the literature. Studies have shown that these therapies can decrease the need for intubation and ventilation, decrease length of intensive care days, and increase patient comfort. Additional research is needed to support optimal setting selection and recommendations for the use of noninvasive therapies for infants and children.

Keywords

- noninvasive ventilation
- pediatric noninvasive ventilation
- heated high flow nasal cannula

Introduction

Respiratory illnesses are more common in children than are any other system-based problems and also accompany many disease processes including sepsis, trauma, neurologic, oncologic, and gastrointestinal conditions. Intubation and mechanical ventilation have been associated with many problems including airway complications, barotrauma, volutrauma, and the development of ventilator-associated pneumonia. Additionally, sedation, analgesia, and in some cases, neuromuscular blocking agents are necessary to facilitate mechanical ventilation synchrony, which can contribute to the incidence of adverse events. Noninvasive ventilation (NIV) offers a means of providing respiratory support without the complications of intubation and ventilation, making it an attractive alternative, and increasing evidence is available to justify its use.

The purpose of this article is to describe pathophysiology involved with acute respiratory illness in infants and children that results in a need for ventilation support, review the history of NIV, and examine the available evidence for the use of noninvasive support modalities. In addition, a discussion of interprofessional roles and management of children receiving NIV in the acute care setting is included along with prevention of potential complications.

Case Report

An infant born at 37-week gestation is seen by the primary care provider on day 15 of life for nasal congestion and cough. Two days later, he is taken to the emergency department after experiencing two episodes of apnea. He has been afebrile with a history of poor feeding for 24 hours and congested cough. Chest radiograph demonstrates patchy infiltrates and mild hyperinflation without any focal findings. A respiratory viral panel is obtained and the infant is found to be positive for respiratory syncytial virus. In the emergency department, he has another episode of apnea without any associated color change but a decrease in oxygen saturation to 85%, responding well to oxygen supplied by blow-by methods. He is extremely congested and breathing at a rate of 80 to 100 breaths per minute. The decision is made to admit the infant for further respiratory support and monitoring. A heated, high flow oxygen system (Vapotherm, Exeter, New Hampshire, United States), is used for respiratory support initiated at a flow of 8 L/minute.

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In the past, options for ventilatory support for this infant would have included intubation and ventilation or continuous positive airway pressure (CPAP) provided by nasal prongs. Even though effective, both methods pose potential complications and implications for management. Vapotherm allows for easy suctioning and is comfortable for the infant, allowing rest and ultimately a decrease in respiratory rate and oxygen requirement occurs over the next 2 to 3 days. The parents are allowed to remain at the bedside, hold their infant, and engage in skin-to-skin contact to continue their bonding process.

Background

Brief Respiratory Physiology and Diseases Managed with Noninvasive Ventilation

To understand the mechanism of noninvasive therapy in disease processes, it is important to understand the basics of ventilation, which refer to the process of air or gas exchange between the environment and the alveoli. Inspiration and expiration control the lung volume with air moving from high to low pressures in and out of the lungs depending on the pressure in the alveoli. As volume increases, pressure decreases and as volume decreases, pressure increases. Altered intrapulmonary pressures occur as a result of elasticity of the chest wall and diaphragmatic muscles, which contract during inspiration and relax during expiration.

In addition to elasticity and pressure regulation, neurologic control of breathing involves both voluntary and involuntary processes occurring through different parts of the brain and spinal cord. Essentially, breathing is controlled by neurologic function and elastic properties of the chest wall including resistance, along with the patency of the structures of the upper airway, which allows the free movement of oxygen and carbon dioxide in and out of the lungs. In children, specifically, the airway diameter is small, which significantly impacts flow and resistance to airflow. Pediatric respiratory illness alters the usual flow of air and the dynamic pressure and volume exchanges of breathing. Obstructive or resistive processes of asthma, bronchiolitis, and pneumonia; neurologic responses such as apnea of prematurity or increased intracranial pressure; and decreased elasticity of the chest wall owing to chronic neuromuscular illness such as spinal muscular atrophy or muscular dystrophy are some examples of impaired airflow and pulmonary mechanics. NIV provides positive pressure applied to the airway throughout the respiratory cycle in conditions of altered airflow or breathing. See ►**Table 1** for information on specific disease processes.

Mechanics of Noninvasive Ventilation and High Flow Systems

CPAP and bilevel positive airway pressure (BiPAP) are the most commonly recognized NIV systems, both deliver positive pressure through a noninvasive interface such as a facemask, a nasal mask or nasal pillows.[1] CPAP has relatively simple mechanics; setting an expiratory pressure to distend the lower airways, based on the age and size of the child. CPAP provides a steady pressure mode throughout all phases of respiration and assists in preventing atelectasis. It can also be used to "'stent" open an upper airway in cases of obstruction.[1] BiPAP uses two pressure settings, inspiratory pressure and expiratory pressure. Often, a back-up rate is set in BiPAP mode to support an infant with apnea of prematurity or a child with hypopnea. Both types of NIV assist in distending the airways to maintain lung volume and oxygenation at the alveolar level, supporting elasticity of the chest wall and ultimately decreasing breathing effort and accessory muscle use while improving functional residual capacity.[2] NIV also assists in maintaining airway patency and oxygenation.

There are different manufacturers of CPAP and BiPAP devices, intended only for the delivery of noninvasive ventilation. Conventional ventilators also can be used to deliver CPAP and BiPAP. In addition to the device, an interface between the device and patient is needed, which may be nasal or oronasal masks, nasal prongs, nasal pillows, or helmets. Nasal pillows can provide less aspiration risk and may stay in place easier than a tight-fitting mask; however, their disadvantages include air leakage through the mouth, nasal irritation, and higher resistance through nasal passages.[3] Oronasal masks offer pressure delivery through both the nose and the mouth, less opportunity for leaks or pressure delivered to the patient, and are better for children who are mouth breathers. Disadvantages of oronasal masks include difficult fit for some children, higher risk for aspiration, difficulty for child to communicate effectively, and potential need for sedation. Determining settings for CPAP and BiPAP is based on the amount of pressure required to overcome the child's work of breathing or improve pulmonary mechanics and oxygenation, and child's size and age.[4] Typically, CPAP settings would begin with expiratory positive airway pressure of 4 to 6 cm H_2O. This pressure is delivered to the patient continuously through the respiratory cycle on inspiration and expiration. Common BiPAP settings on initiation of therapy include an inspiratory positive airway pressure of 10 to 12 cm H_2O and expiratory positive airway pressure of 5 to 6 cm H_2O. Inspiratory positive airway pressure is similar to pressure support delivered through a conventional ventilator and this level of pressure is delivered to the patient when the device senses that the patient is initiating a breath and is terminated at the end of inspiration. Patients with hypopnea may have respirations that do not "trigger" the BiPAP device. In such cases, the expiratory positive airway pressure is delivered during respirations initiated by the patients that the device does not "sense." Oxygen and humidity are blended into the system to the requirements of the patient.

High flow nasal cannula (HFNC) systems originally were used in the neonatal intensive care unit (NICU) and consisted of delivery of heated nasal cannula air at high flow rates (e.g., 4– 6 L flow per minute). Vapotherm is the manufacturer of the first commercially available high flow oxygen delivery device, which was developed in 1998, used in the care of neonates initially in 2004, and now accompanied on the market by several other brands.[5] The mechanism of this therapy is somewhat unclear, but it is hypothesized that the high flow assists in minimizing dead space of the

Table 1 Noninvasive ventilation for specific disease processes in children

Diagnosis	Respiratory involvement/ definition	Respiratory findings/ symptoms	Recommended therapies
Asthma	Increased resistance to airflow, decreased expiratory flow rates, airway over distention, hyperinflation of lungs, alveolar hypoinflation with hypoxia, ventilation–perfusion mismatch, hypercarbia is possible	Tachypnea, hypoxemia, cough, increased work of breathing, wheezing	BiPAP CPAP HFNC
Bronchiolitis	Inflammatory injury of the bronchioles, typically caused by viral processes, airway over distention, hyperinflation, reduced ventilation, hypoxia is possible	Cough, increased secretions, wheezing, increased work of breathing, visible retractions	BiPAP CPAP HFNC
Pneumonia	Obstructive process characterized by exudates and inflammatory changes, typically involving the interstitial tissue of the lung, alveolar septal edema and infiltrates, atelectasis and reduced ventilation based on location of infiltrate	Cough, tachypnea, increased work of breathing, hypoxemia	BiPAP CPAP HFNC
Acute respiratory distress syndrome	Acute bilateral infiltrates on chest radiograph, ratio of partial arterial pressure of oxygen: fraction of inspired oxygen < 200, noncardiogenic pulmonary edema	Severe hypoxemia, bradypnea, tachypnea	BiPAP
Respiratory failure	Rate of gas exchange between the atmosphere and blood cannot keep up with metabolic demand	Bradypnea, tachypnea, apnea, hypoxemia, stridor, and wheezing are possible	BiPAP
Chronic neuromuscular problems, muscular dystrophy, spinal muscular atrophy	Progressive loss of neuromuscular function, muscle weakness	Hypoxemia, bradypnea, declining respiratory function	BiPAP CPAP

Abbreviations: BiPAP, bilevel positive airway pressure; CPAP, continuous positive airway pressure; HFNC, high flow nasal cannula.

nasopharyngeal cavity resulting in improved alveolar ventilation, also providing some amount of positive pressure, which cannot accurately be determined but is known to assist in overcoming upper airway obstruction, improving ventilation.[6] Heated, HFNC systems have been successfully used in preterm infants and in older children for a variety of clinical respiratory problems, including bronchiolitis and asthma. Settings for HFNC are considered based on age and size of patient and disease process. Approximately 4 to 10 L flow for young infants and up to 20 L for older children and adolescents have been documented.[6,7]

Noninvasive Ventilation Contraindications and Complications

Contraindications for the use of NIV can include hemodynamic instability, recent pneumothorax, facial burns or trauma, altered level of consciousness, loss of cough/gag, and recent upper airway or gastric surgery.[8] Appropriate-sized equipment is an important consideration for this therapy to be effective, so another contraindication would be incorrect mask or nasal cannula sizing. Complications of NIV therapies of CPAP, BiPAP, and HFNC include both mechanical and physiological components. Maintaining CPAP nasal prongs, pillows or masks involve patient cooperation; if not left in place, therapy is not effective, although sedation may be considered in some cases to facilitate interface with the device.[4] Frequent dislodgement of facial or nasal interface can also be concerning for the patient, parents, and nurses who are taking care of the child. Other complications include hypotension, gastric distention and potential aspiration, lung hyperinflation, and pneumothorax along with skin breakdown with potential for infection.

Hypotension may be experienced as a result of positive intrathoracic pressure especially upon initiation of therapy and is managed with fluid bolus administration. Risk of barotrauma exists with the use of NIV, though not as severe as that from invasive ventilation.[9] Airway overdistention and pneumothorax are additional complications, which can result from high inspiratory pressure. These are rare occurrences, but again, using the minimal pressure to support the child without contributing to complications is the goal. Obviously, a child with deteriorating condition would prompt the

decision to obtain a chest radiograph, but the question of routine X-rays to evaluate for air leak or gastric distention is not documented in the literature.

Gastric distention and aspiration have not been identified as significant problems with the use of NIV, but there are theoretical risks, especially for patients with primary gastroenterologic problems. Children often have to refrain from oral intake due to the risk of gastric distention and associated aspiration risk resulting in potential nutritional concerns. Gastric distention can be associated with higher inspiratory pressures or higher nasal cannula liter flow. Limiting peak inspiratory pressures, using nasogastric tubes and nothing by mouth status, can be helpful in preventing gastric distention. Obviously, additional tubing under a CPAP or BiPAP mask can interfere with the seal of the mask, so consideration of this effect must be a part of the decision to use a nasogastric or orogastric tube. Nutrition remains an important part of the healing process, so if the child can tolerate periods off the devices to eat, attempts can be made to address nutritional needs through the oral route. Using HFNC may be a better option for a child to optimize opportunities for nutritional intake.

Skin, especially that of small infants and children who are on prolonged therapy, can be compromised under the interface (e.g., mask, prongs) due to pressure on the skin. Prevention of skin breakdown can be accomplished by minimizing pressure with the use of intermittent application, providing breaks for the child, and skin protectant use. The incidence of pressure ulcers in critically ill infants and children is documented to be 18 to 27%, breakdown associated with many factors including nutrition and the use of medical devices, which comprise facial CPAP or BiPAP.[10] The Braden Q scoring tool provides a framework for identifying children at risk for pressure ulcers and has been found useful in the assessment of patients at risk for skin breakdown.[10] This tool assigns a score for mobility, activity, sensory perception, moisture, friction, nutrition, and tissue oxygenation. Using this type of tool along with a plan for breaks in the schedule for children on CPAP or BiPAP can assist in minimizing skin breakdown as well as gastric distention and aspiration.

If skin does break down, risks of nosocomial infections increase. In 2005, an outbreak of *Ralstonia mannitolilytica*, a rare bacteria attracted to water, was associated with the use of Vapotherm 2000i equipment, which was subsequently recalled. New information about Vapotherm parts use and replacement has been published; no further outbreaks have occurred and it is again being used.[11]

Review of Literature

History and Evidence for Practice

The history of noninvasive NIV extends back to the 1940s when it was first documented in the treatment of respiratory illnesses such as pneumonia, pulmonary edema, near-drowning, Guillain–Barré syndrome, and acute asthma, although primarily in adult patients.[8,12] From this time and into the 1950s, negative pressure ventilation in the form of the "iron lung" was also used, especially for adult patients with polio.[8,13] In the 1960s, providers had a greater understanding of gas exchange, so the use of intermittent positive pressure breathing and volume ventilation became more widespread.[12] Ventilator sophistication with the availability of varied settings changed the focus of ventilation therapy to primarily invasive methods. Even though hospitals for the care of preterm neonates were documented at the turn of the 20th century, the first official U.S. NICU was established in 1965 when positive pressure ventilation for preterm infants improved survival, but resulted in persistent lung disease.[14,15] Neonatal CPAP was then used in the 1970s with attempts to limit invasive ventilation in this population.[16] The first pediatric intensive care unit (PICU) was also established in 1965 at Children's National Medical Center in Washington, District of Columbia, United States, 20 years before the development and popularity of BiPAP.[15] In adults with obstructive sleep apnea, NIV was first discussed in 1980s, followed by its use for patients with chronic obstructive pulmonary disease.[8] The U.S. NICU was the first to use HFNC therapy to replace nasal CPAP, which has now become more popular in older pediatric patients.[16]

Available literature regarding the use of NIV, including CPAP and BiPAP, has increased in the past 20 years with recent studies supporting effectiveness of NIV for the treatment of various respiratory disease states including chronic lung disease, cardiac surgical support, acute respiratory distress syndrome (ARDS), and respiratory failure in adults.[17] Evidence also supports the use of NIV in pediatric patients with status asthmaticus, bronchiolitis, successful decannulation or early decannulation from tracheostomy.[9,18,19] NIV has been successfully used in the treatment of pulmonary edema, in postoperative care and as a therapy for palliation when intubation is not an option.[9,20] The most recent discussion in the literature is the use of NIV for ARDS and respiratory failure, although in these situations conservative management is needed to react when the patient does require intubation and ventilation.[20]

The literature regarding HFNC is conflicting and lacks robust research, despite increased use and clinical popularity in both neonates and children. A 2014 Cochrane review attempted to determine if HFNC systems were more effective than other forms of NIV.[21] Eleven studies were evaluated to identify effectiveness and also to consider the safety and efficacy of respiratory modes. There were no randomized control trials in this HFNC use and the overall quality of the studies could not document superior effectiveness over other forms of NIV.[21] Safety and efficacy also could not be determined. Outcomes such as escalation of therapy to CPAP or intubation as well as length of stay or intensive care days could not be determined with the limited data. Another review of the literature published in 2013 could not demonstrate effectiveness of HFNC over other NIV therapies, also indicating the need for more robust studies.[16] However, in a retrospective study, 489 children with a primary diagnosis of bronchiolitis, or diagnosed with pneumonia or asthma, were managed with HFNC in the emergency department over a 2-year period of time.[22] Forty-two children required intubation following a trial of HFNC, but the majority were managed successfully with HFNC and only one infant sustained a superficial burn from the plastic

cannula, thus documenting safety in a large cohort. This study used vital signs and blood gas results for inclusion in the analysis and since many of the patients did not have blood gases obtained, they were excluded from the results. A respiratory rate $>$ 90th percentile, $pCO_2 > 50$, and pH < 7.3 were independently associated with higher incidence of intubation, providing some information helpful in anticipating or predicting NIV failure.[22]

Noninvasive Ventilation Guidelines in Developing Countries

Available literature from many sources supports the use of NIV in most developing countries.[23] The National Institute for Health and Clinical Excellence provides guidelines for adult use of NIV, which encounter two levels, I and II.[24] For patients who are included under level II or with more complicated illness, the risk of failure of NIV is much higher, therefore demonstrating little differences in outcomes including mortality and morbidity and intubation and ventilation after the NIV trial. In 2002, the British Thoracic Society published guidelines for NIV in acute respiratory failure, also in the adult population.[25] Impaired consciousness, presence of excessive secretions, and severe hypoxemia were contraindications for the use of NIV in patients with respiratory failure.[25] Despite specific use in adult patients, there are currently no available national or international pediatric guidelines that can provide evidence-based recommendations for the use of NIV, but research does exist to support trials for many system-based problems.

Asthma, Bronchiolitis, and Pneumonia

Asthma and bronchiolitis continue to cause significant illness with a need for children to be admitted to pediatric inpatient and critical care beds. BiPAP has been used as the mode of NIV to support children with obstructive lung disease, such as asthma and bronchiolitis. Basnet completed a pilot study with 10 children receiving BiPAP for status asthmaticus.[26] Findings indicate that 9 of 10 children had reduced oxygen requirements and did not have a need for sedation or anxiolytics.[26] NIV has also been studied in children with bronchiolitis. Both Ganu et al[27] and Lazner et al[28] demonstrated a shorter length of intensive care stay in children with bronchiolitis with the use of NIV.

Acute Respiratory Distress Syndrome and Respiratory Failure

Evidence indicates benefits of NIV in treating respiratory failure and ARDS. Muñoz-Bonet et al[29] demonstrated a statistically significant difference in avoiding intubation in a study of 37 children between the ages of 1 month and 16 years when treated with BiPAP or CPAP with pressure support for acute respiratory failure. Cavari et al[30] attempted the use of NIV for infants with impending respiratory failure and demonstrated a 73% success rate in preventing intubation in a group of 22 infants. In a retrospective study of 239 children with cancer who were admitted to a PICU over an 8-year period of time, Pancera et al[31] evaluated the success rate of NIV use for respiratory failure. Despite varying degrees of severity of illness in this population of children with malignancies, the study was encouraging with 57% of the population successfully managed on NIV. Finally, Yañez et al[32] published a randomized control trial in 2008 with 50 children randomized to receive oxygen therapy alone or therapy with BiPAP. NIV significantly reduced the need for intubation and ventilation when compared with the control group. A randomized controlled trial in Ghana evaluated the use of CPAP based on respiratory rate of children ages 3 months to 5 years with acute respiratory presentations. The mean respiratory rate was reduced by 16 breaths per minute as compared with no change in the control group.[33]

Noninvasive Ventilation in the Postoperative Period and after Extubation

NIV has been successful for children used immediately following extubation or at a later time after extubation if a child develops respiratory difficulty. A prospective, observational study of PICU patients intubated for at least 12 hours and considered to be at risk for extubation failure was studied.[23] The authors attempted to identify risk factors for reintubation based on whether NIV was used immediately after extubation or with signs of respiratory failure within 48 hours following extubation.[23] Despite the overall success with the use of NIV, there were no specific characteristics or outcomes determined to be related to extubation failure.[23] In a study of 163 children in a PICU in the United Kingdom treated with NIV either instead of intubation or following planned extubation, success of remaining extubated could be somewhat predicted by blood pressure and also by disease process. Children with more severe illness associated with acidosis, tachypnea, and the need for higher levels of oxygen were more likely to require intubation or reintubation.[34]

Neuromuscular Diseases

Children with chronic muscular weakness or neuromuscular conditions have been using NIV for many years. Seventy percent of these children also develop acute respiratory illness and are often intubated in the PICU due to respiratory failure.[35,36] A prospective, noncontrolled study was completed in Taiwan, which included children with underlying neuromuscular conditions who developed respiratory failure or needed support following extubation. The authors used oxygen saturation and blood gas results to define respiratory status with therapy consisting of a combination of BiPAP and mechanical cough assist device (e.g., mechanical in-exsufflator). Of the 15 patients enrolled in the study, 12 had successful treatment with NIV as BiPAP. Four patients required intubation.[35] Contrary to this study, Mayordomo-Colunga et al[23] determined that children with neurologic illness had a higher incidence of intubation or failed NIV.

Recommendations for Interprofessional Management

Making the decision to use NIV is a team choice based on supporting an infant or child with the least invasive mode of therapy determined by the underlying disease and condition.

Each health care provider in the acute care setting has a role in the assessment of the patient and in deciding the most appropriate technology/device for the child's condition, availability of appropriate interface (e.g., mask, prongs), provision of education and explanation of the therapy to the child and family, applying and initiating the therapy, and monitoring the clinical response.

Determining the appropriate setting for delivery of NIV is a consideration when initiating this therapy. If the child is being treated for ARDS or respiratory failure, the child will require PICU monitoring, but in other instances of respiratory disease, the treatment setting will be based on hospital protocols, availability of appropriate staff, such as respiratory therapists and skilled nurses, and level of monitoring desired by the interprofessional team. There are individual hospital protocols that address appropriate settings for NIV therapies, but no standard published guidelines.[4] Each child will have unique needs and each institution will offer guidelines on how and where NIV therapies can safely be administered.

Determining settings for NIV can be a medical decision, but in most cases, it is based on the response of the child with initial settings jointly identified by respiratory therapy, nursing, and medicine. Ongoing adjustments should be made by those who have closest interaction with the patient and an understanding of patient response. Oxygen requirements and weaning are often decided by clinical examination (e.g., respiratory rate, work of breathing, presence of retractions) and oxygen saturation monitoring.

Monitoring for complications of NIV, whether using CPAP, BiPAP, or HFNC, should be consistently reviewed and recorded by all members of the interprofessional team. It is very important to accurately monitor the effectiveness of noninvasive ventilation on the work of breathing and gas exchange and make changes accordingly.[4] Complications of NIV were previously discussed, but identification and management of these problems remain an interprofessional responsibility as different providers interact with the patient at different times during the therapy.

In addition to determining which type of NIV to be used, the setting for the patient, and the equipment settings, additional important monitoring is warranted. Temperature of the high flow and CPAP/BiPAP humidification system needs to be set and monitored to prevent patient burns. Regardless of the NIV system, there is a need to maintain humidification of the airway. Thick secretions and dry mucous membranes can result if adequate humidity is not available. However, too much humidity in a mask or cannula can cause obstruction to the system or discomfort for the child.

The interprofessional team providing care for children who require respiratory support can make a difference in minimizing complications of intubation and ventilation. In addition, cost savings can be identified related to shorter lengths of PICU and hospital stay, decreased ventilator-associated pneumonia incidence, and decreased use of sedation and analgesia, by using an NIV plan of care with the use of CPAP, BiPAP, or HFNC.[4,16,20] Ongoing discussions with parents about intact maintenance of the device, and assessing and addressing discomfort for the child to accomplish this task add to the care provision and complication prevention plan. Nurses, especially, as the care provider with the most contact with the patient and family can support the use of these therapies working closely with respiratory therapy and the medical team until the patient is stabilized and therapy is discontinued.

Summary

NIV in the form of CPAP, BiPAP, or HFNC can be an effective, safe, and financially responsible mode of providing respiratory support in a variety of pediatric conditions as compared with intubation and mechanical ventilation. Care of the child receiving therapy requires monitoring for complications or side effects and measuring efficacy. Determining when increased support is necessary is extremely important in the management plan. Further research studies in the form of randomized controlled trials are needed to document which mode provides the best support with the highest level of safety.

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