

NIV **NON-INVASIVE VENTILATION** **IN PEDIATRICS** *2nd edition*

A. Medina, M. Pons, F. Martín-Torres

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*We dedicate this book
to our wives and children
for keeping us up all night
after we get off of duty*

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Prologue

Reading medical texts that are more than ten years old usually provokes one of two reactions: we either laugh at the inaccuracy of the author's hypotheses, or we are taken aback by the author's prescience.

The aim of this second edition of "Non-invasive Ventilation in Pediatrics" was to incorporate all of the knowledge accumulated in the past four years. Nonetheless, due to the limited body of literature on NIV, there are many aspects of this treatment

that are dictated primarily by experience and by each author's opinion.

We hope that the colleague that reads this text now, does so with a critical eye, remembering that history repeats itself and that, consequently, many of the opinions published in this text will be scientifically refuted in the future. Nonetheless, with all humility, we hope that some of the hypotheses presented here will ultimately be confirmed.

Abbreviations

AF: Assisted flow	ventilation
ARDS: Acute respiratory difficulty syndrome	NIV: Non-invasive ventilation
ARF: Acute respiratory failure	n-SIPPV: Nasal synchronized intermittent positive pressure ventilation
AV: assisted volume	NMD: Neuromuscular disease
AVAPS: Average volume assured pressure support	NNPV: Non-invasive negative pressure ventilation
BiPAP: Bi-level positive airway pressure	NRDS: Neonatal respiratory difficulty syndrome
CCHS: Congenital central hypoventilation syndrome	OSAS: Obstructive sleep apnea syndrome
Cm: centimeters	PaO₂: Arterial oxygen pressure
CNS: Central nervous system	PaCO₂: Arterial carbond dioxide pressure
COPD: Chronic obstructive pulmonary disease	PACV: Pressure-assisted/controlled ventilation
CPAP: Continuous positive airway pressure	PAV: Proportional assisted ventilation
CRF: Chronic respiratory failure	PCV: Pressure-controlled ventilation
E: Elasticity	PEEP: Positive-end expiratory pressure
EPAP: Expiratory positive airway pressure	PEP: positive expiratory pressure
F: Flow	PICU: Pediatric intensive care unit
Fig: Figure	PIP: Peak inspiratory pressure
FiO₂: Fraction of inspired oxygen	P_{musc}: Respiratory muscle pressure
HMV: Home mechanical ventilation	PP: Positive pressure
Hz: Hertz	PS: Pressure support
IFD: Infant Flow Driv	R: Resistance
IFDA: Infant Flow Drive Advance	RF: Respiratory frequency
IPAP: Inspiratory positive airway pressure	RPM: Respirations per minute
IPPV: intermittent positive pressure ventilation	S: Spontaneous mode
IV: Intravenous	SaO₂: Trancutaneous oxygen saturation
FRC: Functional residual capacity	Sec: Second(s)
FVC: Functional vital capacity	SMA: Spinal muscular atrophy
L: Liters	S/T: Spontaneous/timed mode
LPM: Liters per minute	T: Timed mode
MI-E: Mechanical insufflation-exsufflation	Ti: Inspiratory time
Min: minutes (s)	V: Volume of air that enters the lungs
n-CPAP: Nasal continuous positive airway pressure	VCV: Volume-controlled ventilation
n-IPPV: Nasal intermittent positive pressure	V/Q: Ratio of ventilation to perfusion
	Vt: Tidal volume

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History and clinical use of non-invasive ventilation

C. Rey, M. Pons, J. Mayordomo and M. Los Arcos

INTRODUCTION

Non-invasive ventilation (NIV) can be defined as ventilation which does not require artificial entry—via tracheotomy or endotracheal intubation—beyond the vocal chords of the patient’s respiratory track. Various mechanisms have been used to deliver NIV, and different eras have witnessed the predominance of certain devices and techniques over others. Galeno was the first to describe experimental ventilation, observing how inflation of a dead animal with air via the larynx caused its bronchi to fill and its lungs to expand. Vesalio is believed to have later performed the first ever artificial ventilation during the autopsy of a Spanish nobleman whose lungs he inflated with air.

This chapter provides a historical summary of negative pressure ventilation, ventilation using rocking beds and pneumatic belts, and ventilation via nasal masks and face masks. Current clinical use of NIV in Spain is then reviewed.

NEGATIVE PRESSURE VENTILATION

The first techniques used for mechanical ventilation were based on non-invasive systems that generated negative pressure over the chest wall. The first “tank” negative pressure respirator was developed by Dalziel in Scotland in 1832. Jones patented an apparatus similar to Dalziel’s, in Kentucky in 1864, recommending its use for the treatment of asthma, bronchitis, paralysis, neuralgias,

rheumatism, seminal weakness and dyspepsia. Figure 1 shows a negative pressure respirator presented by Woillez at the French Academy of Medicine in 1876. The patient was placed into a cylindrical container with their head sticking out. An adjustable elastic rubber collar was used around the patient’s neck to obtain a perfect seal. Manual expansion of the pump created a sub-atmospheric pressure in the tank, whereas pressure on the pump caused the pressure of the tank to return to atmospheric level. Negative extrathoracic pressure was transmitted via the chest wall, and analogously to the action of negative pleural pressure during spontaneous respiration, the system generated a flow of air from the mouth to the lung.

Substitution of an electric source for manual pressure, and a leather diaphragm for the pump, provided so-called “tank” respirators, or “iron lungs”, whose use peaked during the polio epidemic of the 1930’s to the 1950’s. The first negative pressure respirator to be widely used in the clinic was the Drinker-Shaw iron lung, developed in 1928. A major polio epidemic in 1931 led Emerson to manufacture a smaller and simpler respirator. This apparatus was cheaper and easier to operate than its predecessors and boasted several technological improvements; hence, it was widely used and enabled several lives to be saved during epidemics of respiratory paralysis caused by polio.

From the 1960’s to the 1970’s, a negative pressure ventilator similar to iron lungs was used to

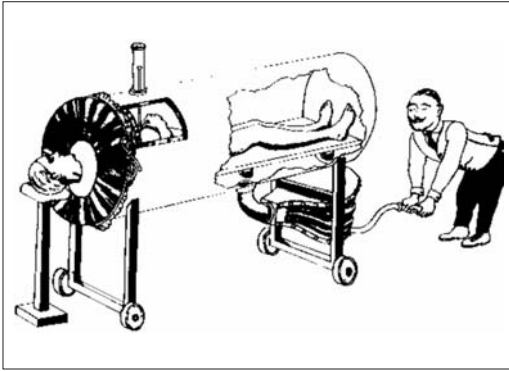


Figure 1. Manually operated negative pressure ventilator.

treat hyaline membrane disease in neonates. In this respirator, the neonate's head was placed inside of a chamber into which humidified oxygen could be added, while the rest of its body was maintained in a hermetically sealed chamber to which negative pressure was applied.

The aforementioned systems had numerous limitations: they easily led to obstructions of the upper airway through closure of the glottis, interfered with physical examination of the patient, caused skeletomuscular disorders, and were burdened by their large size, among other factors. Due to these problems, use of these respirators was eventually abandoned, as new forms of mechanical ventilation were sought.

ROCKING BEDS AND PNEUMATIC BELTS

Rocking beds and pneumatic belts, or pneumobelts, are NIV tools that were developed and that reached their peak use during the final period of the polio epidemic. Both are based on exploiting gravity to help the movements of the diaphragm and were especially utile for patients with a paralytic or very weak diaphragm.

In the early 1930's Eve described the use of manual rocking to favor ventilation in two patients with acute respiratory paralysis. The technique consisted of positioning the patient in a bed that rocked 45° up and down. The change in weight of the abdominal viscera moved the diaphragm up and down alternately, creating a new method of artificial respiration. The technique was later accepted by the

British Navy as a recommended way of reviving victims of near-drowning. Subsequent studies demonstrated the utility of this type of artificial respiration as compared to other methods. Indeed, it remained in the revival protocols until the 1960's, when mouth to mouth resuscitation took over as the initial form of artificial respiration. Automatic rocking beds were introduced in the 1940's as a type of ventilatory aid. In 1950, the American Council on Physical Medicine and Rehabilitation accepted a rocking bed designed by McKesson as a tool for weaning polio patients off of iron lungs. This bed facilitated nursing care and provided the patient with more freedom; however, it was very noisy and heavy. The Emerson rocking bed, used extensively during the 1950's and 1960's, was quieter and lighter. Nonetheless, control of the polio epidemic through vaccination led to a drastic fall in demand for these beds. It is estimated that in the United States only 80 rocking beds are still in use; they are employed for polio survivors. The majority of patients have sought other forms of ventilation assistance.

Pneumobelts deliver intermittent abdominal pressure by assisting diaphragmatic movements. They also arose in the final period of the polio epidemic, and were designed to overcome the limitations of the ventilators available at that time. Pneumobelts enabled total freedom of the upper extremities and the mouth, making it easier for the patient to remain seated. A diurnal ventilator was for patients in wheelchairs. As in the case of rocking beds, once the polio epidemic had come under control, pneumobelts lost their primary indication. Albeit several modifications were eventually made to the original mechanism, including a combination of pneumatic belt and intermittent positive pressure ventilation, pneumobelts are now very rarely used.

NASAL MASKS AND FACE MASKS

The first non-invasive positive pressure ventilation (NPPV) systems were used at the beginning of the 20th century by surgeons to perform operations that implied opening of the thorax. Brauer is considered the first surgeon to have used a positive pressure system, which consisted of a small cabin into which the patient's head was introduced. As alternatives to these small cabins, other surgeons designed face masks and hermetically sealed helmets

to generate positive pressure in the airway. However, with the advent of translaryngeal intubation techniques, these NPPV systems were abandoned.

Outside of surgery, the limitations of negative pressure NIV systems, coupled with the technological advances made during WWII, led to standard use of positive pressure mechanical ventilation via endotracheal or tracheotomy tubes. In 1907 the company Dräger developed one of the first NIV ventilators, the Pulmotor (Fig. 2.), which was used for resuscitation. In 1935 Barach reported the use of a respirator that provided continuous positive airway pressure (CPAP) via a mask for patients suffering from various forms of acute respiratory failure (ARF). Nonetheless, it was not until the 1970's that NVPP began to emerge as a slightly less aggressive alternative, simultaneously circumventing the complications associated with endotracheal tubes while improving the quality of life of the patient—namely, by preserving the defense mechanisms of the airway and enabling patients to speak and swallow. This type of ventilation assistance employed intermittent positive pressure via a mouthpiece. Initial experiences with this method appeared favorable: it had been reported that NIV could control hypercapnia in patients with acute respiratory failure. However, in subsequent studies, including a multicenter study by the US National Institutes of Health (NIH), it was found that NIV combined with nebulizer therapy for patients with chronic obstructive pulmonary disease did not provide any added advantage compared to the nebulizer therapy alone.

In the 1980's continuous positive airway pressure via the nasal passage (nasal CPAP, or n-CPAP) was first used for patients with sleep apnea and afforded good results. Intermittent positive pressure ventilation via the nasal passage (nasal IPPV, or n-IPPV) was soon employed, improving ventilation in patients with chronic respiratory failure (CRF), especially during sleep. Multiple studies on NVPP were subsequently performed in patients with ARF or CRF, sleep apnea, or respiratory difficulty after extubation, with increasingly positive results obtained.

CLINICAL USE OF NIV (Spain)

Use of NVPP has undergone surges in the past 5 years. In 2002 a survey in Spain that was



Figure 2. The Pulmotor.

performed using an electronic hospital mailing list (UCIP-net) revealed that only four pediatric intensive care units (PICUs) were equipped with NIV-specific ventilators and had written NIV protocols, and therefore, performed NIV for their patients. However, in the past 5 years, there has been an exponential increase in the use of NIV in pediatrics; hence, a large percentage of Spanish PICUs now perform this type of ventilation assistance.

From October 2004 to February 2004, an epidemiological study on pediatric NIV was performed by eight PICUs in Spain. The study encompassed 109 cases of NIV use in 104 patients (mean age: 12 months) in which the overall efficacy was 78%. In the PICU of Hospital Universitario Central de Asturias (HUCA), which has seven beds and averages approximately 300 annual admissions, during the past 3 years there have been 119 cases of NIV use in 93 patients (mean age: 3 years; age range: 1 month to 16 years). NIV was indicated for type I respiratory failure (RF) in 25% of the cases, for type II RF in 50%, and for post-extubation RF in the remaining 25%. NIV-specific ventilators were used in 95% of the cases. The primary interface used was oral-nasal (74%); in one case, a full face mask was employed. The average duration of the NIV was 35 hours. Favorable progress was obtained: mechanical ventilation was not required in 80% of the cases. Failure of NIV was greater in post-extubation RF (36%) and type I RF (27%) than in type II RF (8%). There were no complications in 80% of the cases; the complications in the remaining 20% were principally minor: self-limited skin lesions (16%),

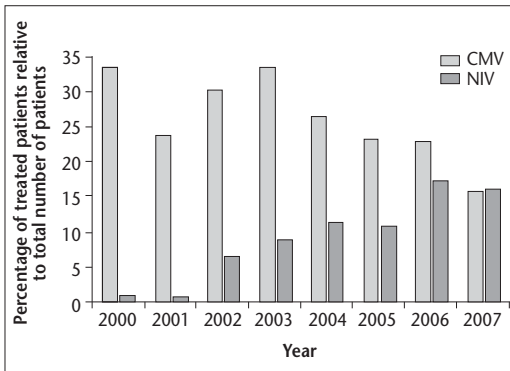


Figure 3. Change in use of conventional mechanical ventilation and non-invasive ventilation in the Pediatric Intensive Care Unit of Hospital Universitario Central de Asturias, 2000 to 2007. Data are presented as percentages relative to the total number of admitted patients. CMV: conventional mechanical ventilation; NIV: non-invasive ventilation

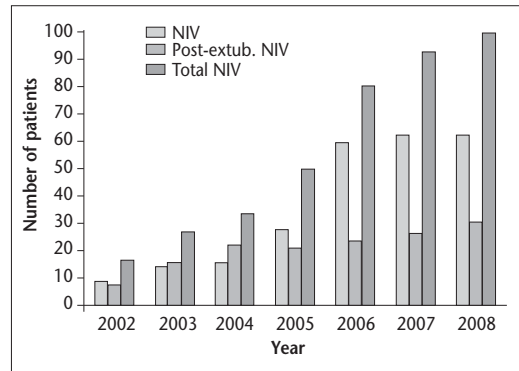


Figure 4. Change in use of non-invasive ventilation in the Pediatric Intensive Care Unit of Hospital Universitario Sant Joan de Déu de Barcelona, 2000 to 2008. NIV: non-invasive ventilation; post-extub: post-extubation.

pneumothorax (3%) and upper airway bleeding (1%).

Figure 3 shows an important trend: the change in the use of NIV compared to conventional mechanical ventilation (CMV) in the PICU at HUCA. As observed in the Figure, use of NIV has risen while use of CMV has steadily decreased, leading the former to surpass the latter for the first time ever in 2007.

Figure 4 reveals a similar trend at the PICU of Hospital Universitario Sant Joan de Déu de Barcelona, based on data collected from 287 cases between 2002 and 2006. Note that there is a major difference in the mean age of the two treatment groups (NIV group: 7.6 years; CMV group: 2.5 years). Moreover, the NIV group exhibited a lower rate of nosocomial infection as well as a shorter mean hospital stay.

In the past decade NIV has been the subject of over 1,500 scientific articles, including 14 meta-analyses. There is growing interest in pediatric NIV, as demonstrated at the 5th World Congress on Pediatric Critical Care, held in June 2007, which featured a roundtable discussion and fifteen communications on NIV.

In summary, NIV has represented a major advance in the treatment of ARF, and its utility has been well established in several clinical research publications. When properly applied, NIV is a non-aggressive respiratory support method with few side effects. Nonetheless, it has yet to be systematically

employed for all children with ARF. Several more years will be needed until all patients for whom NIV would be useful will be able to receive it.

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Physiology of respiratory dynamics. Application to non-invasive ventilation

V. Modesto, S. Vidal and E. Ibiza

INTRODUCTION

Unfortunately, physicians do not have the opportunity to administer non-invasive ventilation (NIV) until nearly a decade after having studied physiology. Hence, the authors of this chapter thought it would be apropos to review the basics of how humans breathe, how the body adjusts to situations of respiratory failure (RF), and how NIV can reverse RF.

RESPIRATORY PHYSIOLOGY

In order to deliver air to the lungs during inspiration, the respiratory musculature must create sufficient pressure to overcome two forces: the increase in the recoil pressure of the lung once it is filled, which is a static force, and the friction associated with airway flow, which is a dynamic force. During expiration, air exits the lungs passively.

To enable better understanding of how NIV with pressure support (PS) functions, this chapter first reviews the static properties of respiratory mechanics, and then reviews the dynamic properties: how the flow of air is produced from the atmosphere towards the alveoli during inspiration and in the opposite direction during expiration.

Static properties of respiratory mechanics

The static properties of respiratory mechanics are studied in conditions of airflow equal to 0 L/s

(liters per second). The pressure inside of the mouth corresponds to the atmospheric pressure (P_{atm}), which at sea level is equal to 760 mm Hg; however, for pulmonary physiology calculations, its value is taken as 0 cm H₂O (the reference pressure). The interior pressure in the alveoli (P_{alv}) and the interior pressure in the pleural space (P_{pl}) are static pressures and must be measured in the absence of airflow. The static difference between these two pressures is defined here as the transpulmonary pressure (P_{TP}), or pressure of pulmonary retraction, such that $P_{TP} = P_{alv} - P_{pl}$. The static difference between the interior pressure in the pleural space and the atmospheric pressure is defined here as the elastic recoil pressure of the chest wall (P_W), such that $P_W = P_{pl} - P_{atm}$. The sum of P_{TP} and P_W is called the total recoil pressure of the respiratory system.

Within the scope of this chapter, there is only one main concept of interest from static respiratory mechanics: the volume of the lung only changes when the magnitude of P_{TP} changes. Though it seems counterintuitive, it is not the value of P_{alv} that causes the volume of lung to change, but rather the value of P_{TP} . As the lung fills with air each value of pulmonary volume corresponds to a specific value of P_{TP} . Regardless of the values of P_{alv} and P_{pl} , at a P_{TP} value of +5 cm H₂O, the lung will fill with air to a volume equal to its functional residual capacity (FRC); at a P_{TP} value of +30 cm H₂O, the lung will be at total lung capacity (TLC); and at a P_{TP} value of +3 cm H₂O, the lung will be at its residual volume (RV).

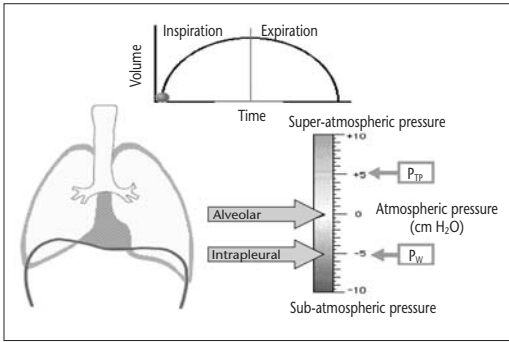


Figure 1. Phase of apnea before inspiration. P_{TP} : transpulmonary pressure; P_W : elastic recoil pressure of the chest wall.

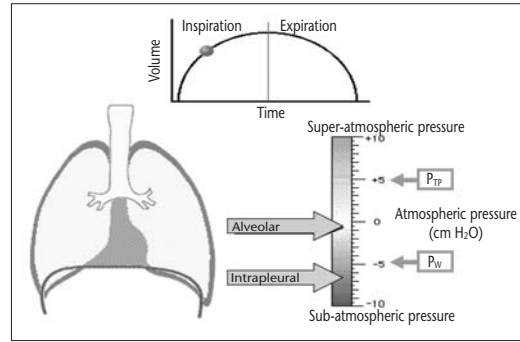


Figure 2. Initial phase of inspiration: contraction of the diaphragm. P_{TP} : transpulmonary pressure; P_W : elastic recoil pressure of the chest wall.

For greater detail on this concept, the reader is referred to other sources⁽¹⁾.

Respiratory dynamics

To enable a more detailed study of the dynamic behavior of the respiratory system, two types of diagrams are used in this chapter (shown in Figures 1 to 7 below). The first type shows a graduated vertical bar which reflects the pressure values of the system (in cm H₂O), whereby positive values correspond to super-atmospheric pressure, and negative values, to sub-atmospheric pressure. The second type shows volume plotted against time; in this plot, a point on the curve shows the position of the respiratory cycle with respect to time for each of the phases.

Analogously to fluid dynamics, respiratory dynamics is governed by the general principle that air always moves along the pressure gradient. If there is no gradient between the mouth and the alveoli, then there is no flow of air. If the P_{alv} is lower than the P_{atm} , then air enters the alveoli, whereas if P_{alv} is higher than P_{atm} , then air exits the alveoli. Once P_{alv} and P_{atm} balance out, the flow of air stops.

Before an inspiration, the respiratory musculature (i.e. the diaphragm and supporting muscles) is at rest (Fig. 1). The natural tendency of the chest wall to retract leads to a sub-atmospheric pressure in the pleural space (P_{ip}) of ca. -5 cm H₂O; however, at this point $P_{alv} = P_{atm} = 0$ cm H₂O, so there is no flow of air. Hence, the transpulmonary pressure (P_{TP}) = 0 cm H₂O - (-5 cm H₂O) = +5 cm H₂O, which drives the lung volume to FRC, the volume of the respiratory system at rest.

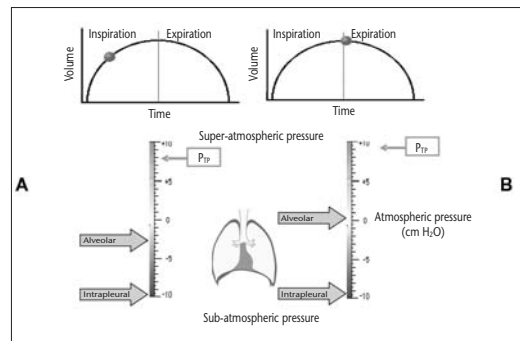


Figure 3 A and B. Final phase of inspiration. A) The drop in alveolar pressure begins the flow of air inwards. The lung gains volume, which causes the transpulmonary pressure (P_{TP}) to increase until B), the moment of maximum muscular contraction. The maximum P_{TP} coincides with the maximum lung volume, but P_{alv} balances out with the atmospheric pressure, so no more air enters.

Inspiration begins with contraction of the inspiratory muscles immediately before air enters the body (Fig. 2). This leads to a decrease in pressure in the pleural space (P_{ip}). At this initial instant, no air has yet entered the body: the volume of the lung has not changed, meaning that, as explained above, the P_{TP} initially remains constant. This can only happen if, immediately before air begins to enter, the drop in P_{ip} causes a drop in P_{alv} of equal magnitude. It is this decrease in P_{alv} at levels lower than P_{atm} that establishes the gradient which causes air to enter.

The decrease in P_{alv} generates a flow of air into the system, causing the lungs to fill with air and

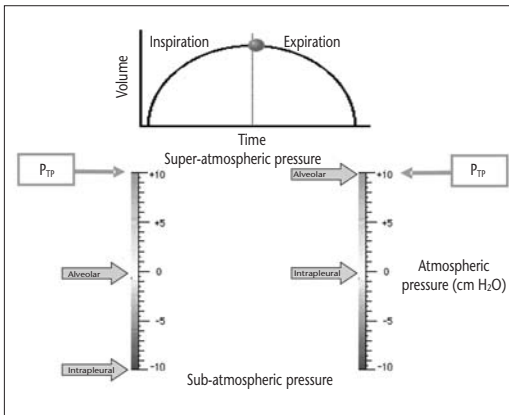


Figure 4. Abrupt stop in muscular contraction. The volume and the transpulmonary pressure remain constant, but the alveolar pressure reaches its maximum value. P_{TP} : transpulmonary pressure.

consequently, increase in volume (Fig. 3A). The change in lung volume leads the P_{TP} to gradually increase: contraction of the muscles causes a further drop in P_{pl} , but, as air enters the alveoli, the decrease in P_{alv} is not substantial. This situation remains steady during the entire inspiration until, in the final phase, muscular contraction peaks, pulmonary volume and P_{TP} reach their maximum values, and P_{alv} and P_{atm} balance out, causing the flow of air to stop and producing the inspiratory pause.

After the inspiratory pause there is a brief total stop in respiratory muscle contraction (Fig. 4). The lung remains at maximum volume, meaning that the value of P_{TP} is equal to that during the inspiratory pause (i.e. no volume has yet been lost); however, the stop in contraction causes the value of P_{pl} to reach zero. At this point, P_{TP} is entirely the result of P_{alv} , which reaches its maximum value due to the tendency of lung tissue to passively retract. The increase in P_{alv} to levels above P_{atm} establishes the gradient which causes air to exit (Fig. 5).

Once all of the air has left (Fig. 6), the flow stops: P_{alv} and P_{atm} balance out to 0 cm H₂O, P_{pl} returns to its rest level of -5 cm H₂O, P_{TP} reaches 5 cm H₂O, and lung volume is equal to FRC. The process then begins again.

The physiological basis of pressure support

If upon inspiration the patient is unable to generate sufficient force to contract the muscles in order for P_{pl} to reach a given value (e.g. < -7 cm

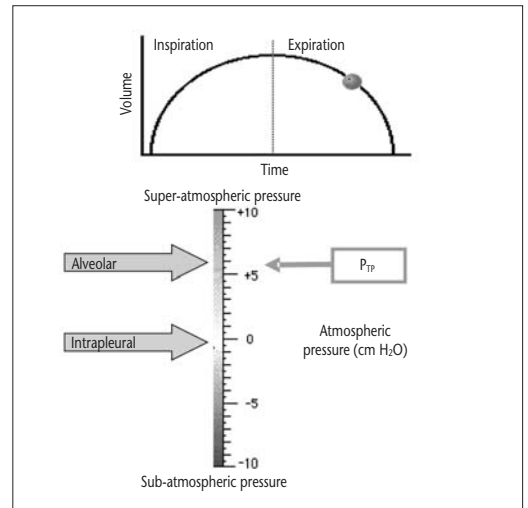


Figure 5. Exiting of air during passive expiration. P_{TP} : transpulmonary pressure.

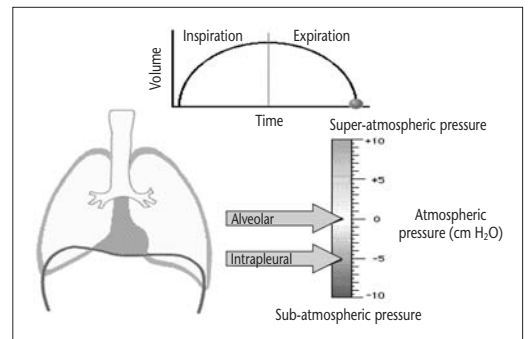


Figure 6. Pre-inspiratory apnea.

H₂O), then the situation shown in Figure 7A arises. As P_{alv} is equal to P_{atm} , the maximum P_{TP} will be +7 cm H₂O, and the lung will barely be able to fill with air. This is the clinical scenario of a patient entering into respiratory failure. If at this point, and only for the duration of the inspiration, the airway can be quickly pressurized to enable P_{alv} to rise up to a pre-established value (known as pressure support, or SP), then with the same level of muscle effort ($P_{pl} = -7$ cm H₂O) a much higher value of P_{TP} can be reached, and the lung can reach a much greater inspiratory volume (Fig. 7B). When the inspiration stops, the airway depressurizes just as in spontaneous ventilation: the stop in muscular contraction drives

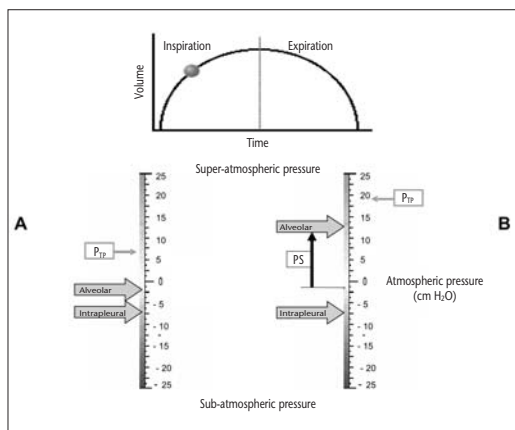


Figure 7 A and B. A) Respiratory failure: the patient is not capable of generating transpulmonary pressure (P_{TP}) greater than +7 cm H₂O. B) Use of pressure support (PS): with the same effort, the patient reaches a higher P_{TP} , and the lung fills to a greater volume.

the value of P_{pl} to zero. Again, at this point P_{TP} is governed by P_{alv} , which reaches its maximum value due to the tendency of lung tissue to passively retract. As explained above, the increase in P_{alv} to values above P_{atm} generates the gradient which enables air to exit the body.

Ventilation with pressure support requires a way of knowing when the inspiration begins (i.e. the inspiratory trigger), establishment of a pressure value at which to pressurize the airway during inspiration only, and a way of knowing when the inspiration ends (i.e. the expiratory trigger). Hence, use of pressure support, in what is known as spontaneous/timed (S/T) mode in NIV-specific ventilators, is dictated by the following key factors:

- Inspiratory synchrony
- Expiratory synchrony
- Rapid compensation for leaks in the system, in order to reach pre-established pressure values during inspiration. Obtaining good results depends on the specific characteristics of each ventilator, especially for patients with high physiological requirements (e.g. high respiratory frequency, short inspiratory time, and weak peak inspiratory flow), including infants, premature neonates, and patients suffering from neuromuscular diseases.

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Indications and contra-indications of non-invasive ventilation in patients with acute respiratory failure

M. Gáboli and M. Pons

INDICATIONS

Non-invasive ventilation in acute respiratory failure

The indications of non-invasive ventilation (NIV) in acute respiratory failure (ARF) are being increasingly better defined; consequently, it is becoming safer and more successful. As with other medical procedures, NIV was first used in adult patients, and then based on these experiences, it was gradually extended to specific areas in pediatrics. The rise in NIV use stems from a desire to avoid the complications inherent to invasive ventilation as well as an aim to better use resources. NIV can reduce hospital stays and the costs of hospital admissions and improve patient comfort. However, careful selection of candidate patients, availability of adequate material, and physician and nursing care continue to be the determinant factors for successful treatment of ARF with NIV—much more so than in the case of chronic respiratory failure (CRF).

The objectives for NIV in ARF comprise: ameliorating patient symptoms, reducing the workload of respiratory muscles, and improving gas exchange in patients who do not require intubation and conventional mechanical ventilation (CMV); however, NIV is never intended for substituting these techniques if they are clearly required. NIV is maintained while the patient is treated for the cause (e.g. infection or surgery) of respiratory failure (RF).

When selecting an ARF patient for NIV treatment, the following factors should be considered:

- a. *Clinical criteria:* symptoms and signs of respiratory difficulty (e.g. moderate or severe dyspnea, high respiratory frequency, use of accessory respiratory muscles, and paradoxical breathing).
 - b. *Blood gas criteria:* $\text{PaCO}_2 > 45$ mm Hg and $\text{pH} < 7.35$; or $(\text{PaO}_2/\text{FiO}_2) < 250$; or, if arterial blood gas test is not available, the ratio of peripheral saturation (SatO_2) to $\text{FiO}_2 < 320$, when $\text{SatO}_2 < 98\%$, which is the criterion used in the PALIVE (Pediatric Acute Lung Injury Mechanical Ventilation) multi-center study on acute respiratory distress syndrome (ARDS), which used criteria from an article on adult patients.
 - c. *The cause of ARF.*
 - d. *Lack of contra-indications* (see separate section below). In the case of any doubts, a one-hour test treatment of NIV could be administered, in which the patient is closely monitored in order not to delay intubation (if required).
- The following factors are predictors of success for use of NIV in ARF:
- a. The process or condition triggering the ARF is relatively mild.
 - b. A high level of cooperation from the patient and a high level of patient-ventilator coordination.
 - c. Optimal adaptation of the interface to the patient (i.e. in size and shape).
 - d. Improved gas exchange, heart rate and respiratory frequency in the first two hours of NIV.

- e. A moderate level of initial hypercapnia (PaCO_2 between 45 and 90 mm Hg).
 - f. A moderate level of respiratory acidosis (pH between 7.20 and 7.35).
 - g. Acute respiratory distress syndrome (ARDS) in which $(\text{PaO}_2/\text{FiO}_2) > 150$. The clearest sign of success of NIV is a drop in respiratory frequency. Contrariwise, agitation, worsening of respiratory difficulties, and worsening of gas exchange are all indicative of failure of NIV. Hence, monitoring of vital signs and blood gases (when indicated) should be prioritized in the first few hours of treatment (see Chapter 10).
- Indication of NIV to facilitate extubation and prevent reintubation in adult patients is currently accepted by the majority of authors. Patients who could most benefit from use of NIV after extubation or even after decannulation are those with chronic lung disease. Hence, the typical pediatric patient who could benefit from NIV would be a preterm infant who has undergone tracheal intubation for administration of surfactant, for whom extubation may be advised to diminish any side effects of mechanical ventilation on their immature lungs.
 - In patients with acute airway obstruction, such as that which occurs in laryngitis and in certain pharyngeal-tonsillar infections, NIV can markedly reduce the muscle effort required for breathing and improve gas exchange. It must be noted that use of NIV here is not free of risks and should be performed in the presence of experts in managing complicated airways, with adequate material available for establishing a definitive airway and only if the patient maintains their physiological reflexes for airway protection.
 - For ARF related to bronchiolitis, NIV can be indicated at different moments and for different reasons. For the youngest patients, who present with apneas, CPAP tends to be indicated as in the case of apneas in preterm infants. Patients tend to respond favorably, except in the case of severe apneas and/or if the infection develops into pneumonia. NIV then takes on the same indications and limitations described for severe cases of hypoxemia. For patients with obstructive respiratory failure, with an increase in respiratory muscle effort as well as secondary retention of CO_2 , NIV with two levels of pressure (bi-level positive pressure airway ventilation, or BiPAP) tends to be indicated, namely for improving gas exchange and reducing respiratory effort. Nonetheless, a recent random study which demonstrated that use of CPAP alone was sufficient to improve hypercapnia warrants mention. The benefits of NIV employing mixtures of helium and oxygen (which are less dense than air) are also noteworthy; these are detailed in Chapter 14. The greatest challenge in this type of pathology resides in the fact that adequate material is often difficult to find for these patients (typically, infants younger than 3 months).

Indications of NIV in the acute patient

- During the course of neuromuscular diseases (NMDs), affectation of respiratory muscles leads to progressive chronic respiratory failure, although this still allows the patient to maintain a certain minimum quality of life. However, in the presence of a precipitating factor—typically a respiratory infection, convulsions, or medical intervention, or an intercurrent illness which limits daily physical activity or demands greater muscle effort—ARF arises, primarily via alveolar hypoventilation. In a recent study, NIV was shown to be a safe and effective first line of treatment for infants and children suffering from NMD. The authors of the study emphasize the importance of recognizing patients who can maintain sufficient respiration without use of a ventilator, whom they consider as ideal candidates for NIV, given that conventional mechanical ventilation (CMV) via endotracheal intubation with sedation and analgesia would further weaken respiratory muscles, complicate weaning and often imply definitive tracheotomy. They even propose that use of conscious sedation to facilitate coupling of the NIV interface to the patient should be considered before ruling out NIV.
- Analogously to the case of NMDs, diseases of the chest wall and of the spinal cord imply a restrictive form of respiratory failure and a high propensity to atelectasis. In these cases, NIV is not only utile during flare-ups, but also during the perioperative period of surgery to correct thoracic defects, in which it facilitates weaning from mechanical ventilation.

- Indication of NIV in pediatric patients with severe hypoxemia due to asthma remains highly controversial. The complications implied in CMV for this pathology have led to the search for alternate ventilatory strategies. NIV has been shown to improve oxygenation in patients during severe asthmatic attacks. NIV treatment of children with this pathology has scarcely been studied, and the few existing reports deal with small patient populations: 33 (Mayordomo-Colunga), five (Carroll) and three (Akingbola). Nonetheless, in the study by Mayordomo-Colunga, NIV only failed in one case. This is accomplished through a minor adjustment of the V/Q mismatch, whereby using a PEEP which does not exceed 80 to 90% of the auto-PEEP in combination with an inspiratory positive airway pressure (IPAP) or a pressure support (PS) lowers the level of respiratory effort required to maintain an adequate flow volume for gas exchange. The greatest challenge in clinical practice is to ensure that the patient couples well to the ventilator, without any agitation; this often requires light sedation (see Chapter 12). However, in respiratory failure with hypercapnia due to an asthmatic attack, NIV has not proven superior to CMV, nor does it lead to a lower number of required intubations. Early administration of NIV (i.e. before total respiratory failure), and use of ventilators that are very sensitive to the respiratory efforts of the patient, and that consequently enable good synchronization, may be important factors in the success of the treatment.
- Indication of NIV in severe hypoxemic respiratory failure (i.e. $[\text{PaO}_2/\text{FiO}_2] < 300$), such as that which occurs in ARDS or in acute pulmonary lesions (ALI), is also the subject of intense debate. The majority of studies on adult patients do not differentiate among the different causes of ARDS (i.e. whether it is primarily pulmonary or systemic), nor do they distinguish between ALI of infectious or traumatic origins. Currently, the most widely accepted conclusion is that NIV can not be recommended universally for ARDS patients ($[\text{PaO}_2/\text{FiO}_2] < 150$); rather, it should be reserved for hemodynamically stable patients without metabolic acidosis, and should only be administered in an ICU by staff with NIV expertise. In a recent study of adults, the authors observed that up to 54% of patients with ARDS that had initially been treated with NIV did not require intubation. They also reported that a $(\text{PaO}_2/\text{FiO}_2)$ value > 175 after one hour of NIV is indicative that the treatment will be successful and stated that for patients with $(\text{PaO}_2/\text{FiO}_2) < 175$, NIV must be considered even if all the intubation criteria are not strictly met. Patients who benefitted from NIV had significantly less complications, especially those of an infectious nature, and required fewer days in the ICU compared to patients treated from the beginning with endotracheal intubation and mechanical ventilation. Few promising studies on severely hypoxemic pediatric patients exist, and no universal guidelines have yet been established for this pathology. It seems reasonable to extrapolate the findings from adult patients and then proceed cautiously in the most severe pediatric patients (according to the level of severity upon admission), without delaying intubation in those patients who, after one hour of treatment, do not exhibit any clinical or blood gas improvement (see Chapters 13 and 23).
- Among situations of ARF in adult patients, use of NIV is probably most well-documented for acute pulmonary edema (APE). NIV, in either CPAP or BiPAP modes, has been shown to rapidly improve gas exchange and lead to lower intubation and mortality rates and is relatively cost-effective. NIV in APE currently tends to begin in the ER and is even used during extra-hospital transport. APE is much less frequent in pediatric patients than in adult patients, owing to the rarity of cardiac ischemia in the pediatric age. Cardiogenic APE (CAPE) may be the first sign of severe cardiac insufficiency (e.g. myocarditis, cardiomyopathy or a congenital deformation). In this case, if there is any clear cause of hemodynamic instability, then NIV must be used cautiously, in the PICU and with strict monitoring. Contrariwise, if the APE is due to hypervolemia and a periodic decompensation of a known and controlled cardiac condition that arises in the post-operative period of corrective cardiac surgery, then NIV, owing to its mildness, should be attempted as the first treatment option in tandem with the specific medical treatment. Among non-cardiogenic edema, a noteworthy type is that of

APE due to negative intrathoracic pressure, which is caused by a spontaneous forced respiration against an obstruction in the upper airway. This scenario has been reported in patients after ear, nose and throat (ENT) surgery. In these cases, in which the mechanism appears to be an increase in permeability due to a change in pressure in the pulmonary arterioles and capillaries, if the airway is permeable and safe, then the response to NIV tends to be very good and the patient tends to improve within a few hours. Lastly, if the edema is found within the context of an ALI (e.g. due to inhalation of toxic material, infection or trauma), then the level to which the pulmonary parenchyma has been affected and the grade of the hypoxemia should be evaluated as described above for ARDS.

- NIV has also proven effective for ARF in patients who have undergone autologous bone marrow transplant. The efficacy of NIV for this patient group is limited to certain etiologies such as APE following hyperhydration before a chemotherapy session. More severe etiologies (e.g. pulmonary hemorrhage) call for intubation and CMV. NIV seems to involve fewer complications than CMV. NIV has likewise proven utile in pediatric ARF patients affected by oncological pathology.
- Albeit anecdotal, NIV has been used in one case in which intubation was impossible. Although this application can not be considered a true indication of NIV, it should nonetheless be considered in extreme situations.
- Finally, the palliative indication of NIV in oncology and neurology patients should not be forgotten. In these patients NIV can improve an intercurrent process or ease symptoms of respiratory difficulty.

CONTRA-INDICATIONS

All techniques, regardless of their novelty or sophistication, have their respective limitations and contra-indications. The main contra-indications of NIV are described below (Table IV, chapter 23).

When protection of the airway is required

For situations in which ventilation is indicated for protection of the airway (e.g. coma or active

digestive hemorrhage) NIV is absolutely contra-indicated, since, as with use of a laryngeal mask, it can not guarantee this protection. The only exception to this rule is for patients with hypercapnic encephalopathy, who can derive neurological benefits from a short (2 to 3 hours) test treatment of NIV.

Severe respiratory failure

Contra-indication of NIV in severe RF is supported by data on adult patients: a higher mortality rate has been observed in patients that received intubation after preliminary NIV treatment. However, patients for whom intubation is not a valid option due to the causative disease are an exception. As previously mentioned, in ARDS with $(\text{PaO}_2/\text{FiO}_2) < 150$ indicates a high risk of technical failure of NIV; hence, NIV should generally be considered contra-indicated for severe RF.

Fixed obstruction of the airway

NIV is contra-indicated in these situations, which take too long to resolve for it to be effective.

Abundant and thick secretions

Restricted access to cleaning the airway –especially in the case of an oral-nasal interface in patients with limited coughing ability– is a high risk factor for NIV failure.

Vomiting

As with abundant secretions, the presence of vomit makes maintaining a well-positioned interface for continuous administration of NIV nearly impossible.

Hemodynamic instability: shock

For patients in this severe state, the concept of energy conservation should be applied: respiratory effort is eliminated, and therefore, NIV should not be used. In post-operative cardiac patients, the presence of arrhythmias can often be considered a contra-indication for NIV.

Craniofacial malformations, trauma and burns

NIV is impossible to administer in patients with lesions in the area where the NIV interface would be positioned. Moreover, positive pressure in the presence of ethmoidal fractures has been associated

Table I. Causative processes of acute respiratory failure (ARF) for which use of non-invasive ventilation (NIV) should be considered

Decompensated diseases of the central nervous system

- Congenital (e.g. respiratory sequelae in infantile cerebral paralysis)
- Acquired (nearly always palliative indication: e.g. cerebral tumors)
- Central hypoventilation with hypercapnia
- Apneas in preterm infants
- Apneas in infants

Decompensated abnormalities of the chest wall and of the spinal column

- Malformations of the chest wall
- Ankylosing spondylitis
- Kyphoscoliosis
- Achondroplasia
- Obesity hypoventilation syndrome

Decompensated neuromuscular diseases in which respiratory muscles are affected

- Diseases of the second motor neuron (e.g. spinal muscle atrophy)
- Guillain-Barré syndrome without signs of bulbar affection
- Diseases of, or damage to, the phrenic nerve
- Myasthenia gravis and other congenital myasthenic syndromes
- Myopathies (e.g. congenital, mitochondrial, metabolic or inflammatory, or deposition diseases)
- Muscular dystrophies
- Myotonic dystrophy
- Polio and its after-effects
- Botulism (Use NIV with caution)

Diseases of the upper respiratory tract

- Obstruction of the upper airway (e.g. laryngitis or laryngotracheitis)

Decompensated pulmonary diseases

- Acute pulmonary edema
- Pneumonia
- Atelectasis
- Bronchiolitis
- Cystic fibrosis
- Asthma
- Neonatal acute respiratory distress syndrome

Other scenarios

- Apnea after adenotonsillectomy
- Post-operative period after surgical correction of scoliosis
- Pulmonary complications caused by sickle cell anemia
- Early extubation
- As support in procedures involving sedation
- Severe respiratory failure in terminal illness (palliative indication)

with orbital herniation. Some authors have postulated that application of NIV in patients with cerebrospinal fluid (CSF) fistulae implies an increased risk of post-traumatic meningitis.

Pneumothorax

Regardless of how it is delivered, positive pressure always has negative consequences for lungs with pneumothorax. However, experience with adult patients does not contra-indicate use of NIV in drained pneumothorax.

Recent gastrointestinal surgery

Dehiscence of esophageal sutures has been described in patients who received NIV during the post-operative period. The entry of a large volume of air into the digestive tract with esophageal and/or gastric distension implies a risk during the immediate post-operative period. However, currently there are publications that demonstrate the efficacy of NIV at low pressure without complications.

Despite the existence of certain contra-indications, in the Guidelines of the British Thoracic Society, use of NIV is accepted as long as intubation is planned or the indication is palliative.

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Conditions and settings for delivering non-invasive ventilation

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INTRODUCTION

When considering the conditions and settings required for administering non-invasive ventilation (NIV), the first aspect to evaluate is the limitations of the equipment to be used.

Firstly, as with other apparatuses, fixed NIV ventilators require AC power and gas tanks (oxygen and medicinal air) and can only be used in hospitals (and only in designated areas). Portable NIV ventilators enable greater flexibility, although the majority of them do not have an oxygen blender, and therefore, have limited use for treatment of severely hypoxemic patients. Moreover, appropriate ventilators and interfaces must be available for each type of patient, which in pediatrics implies maintaining a broad array of materials and accessories.

Secondly, personnel caring for the pediatric patient must have a certain level of expertise in NIV. Although NIV-specific ventilators tend to be relatively easy to operate, no personnel should initiate NIV or change any NIV parameter if they lack fundamental knowledge of the method, do not have experience in treating acute patients, or are not qualified to detect and treat any possible complications.

Lastly, hospital staff must consider the availability of materials for cardio-respiratory monitoring (in principle, non-invasive) of patients and for performing CPR.

If all of the aforementioned conditions have been met, then NIV can basically be performed anywhere by using a portable ventilator. However, it is preferable to maintain acute patients, and to perform any changes in the ventilatory parameters for chronic patients, in a hospital. Application of NIV outside of the hospital should be reserved for pre-established treatment of chronic patients.

The following sections provide an overview of NIV in the pediatric intensive care unit (PICU), general ward, intermediate care areas, ER, delivery room and other hospital areas (e.g. sleep laboratories, diagnostic radiology and the operating room), during transport, and lastly, at home.

It should be underscored that factors such as ventilator type, and the availability of trained, experienced personnel on hand 24 hours a day, can have greater influence on the outcome of NIV than the location where it is performed.

NIV IN THE PEDIATRIC INTENSIVE CARE UNIT

The location which best ensures successful NIV of acute patients is the PICU, where patients can most quickly be rescued via intubation and conventional mechanical ventilation (CMV). Some authors recommend initiating NIV in the PICU for patients with acute respiratory failure (ARF), while recognizing its potential efficacy for patients with stable chronic respiratory failure (CRF).

Whenever NIV is performed outside of the PICU, it should be treated as an early form of intervention, but never with the same criteria as those with which CMV is indicated, since the risk of failure—and consequently, any risks for the patient—can be extremely high. In contrast to the case of adults who are not in the ICU, NIV is not used as respiratory support for children who are not in the PICU.

Only one prospective randomized controlled trial study on the efficacy of NIV in pediatric acute respiratory failure have been performed.

Criteria for initiating NIV in the pediatric intensive care unit

Initiation of NIV in the PICU is recommended for patients presenting with respiratory acidosis, respiratory failure pathology (e.g. pneumonia, acute lung injury [ALI], acute respiratory distress syndrome [ARDS] and asthma). Patients who do not show signs of improvement within the first 2 hours of NIV treatment in the general ward should be transferred to the PICU to continue NIV under closer observation. The criteria for starting NIV in the PICU comprise:

- Respiratory insufficiency which requires $\text{FiO}_2 > 0.4$.
- Apneas.
- $\text{pH} < 7.30$, either initially or after 2 hours of ineffective NIV treatment in the general ward.
- Respiratory therapist, medical or nursing staff in the general ward has limited experience with NIV.
- Patient or family are not cooperating.

Material

- NIV-specific ventilator equipped with an oxygen blender.
- Conventional ventilator with an NIV option.
- Interface (preferably oral-nasal).
- Assisted cough for neuromuscular disease patients.

Personnel

Administration of NIV requires trained medical and nursing staff, plus respiratory physical therapists for neuromuscular disease (NMD) patients. If the latter are not available, they can be replaced with nurses to perform physical therapy.

NIV IN THE GENERAL WARD AND IN INTERMEDIATE CARE AREAS

Recent studies on adult patients show that NIV performed in the general ward reduces the need for intubation and shortens hospital stay. One multi-center study reported a lower hospital mortality rate. Nonetheless, this technique requires close monitoring of the patient and a clearly established protocol for transferring the patient to the ICU. The criteria may vary among hospitals in function of the availability of nursing staff and the level of training of the personnel. Another factor to consider for pediatric patients is the amount of stress that admission into the PICU could imply.

Intermediate respiratory care units (IRCUs), which exist in countries such as the United States and Italy, have been shown to be cost-effective and can even improve patient life expectancy.

NIV in acute pediatric patients can rarely be started in the general ward, although some centers have reported periodic experiences in cancer and NMD patients with heightened ARF or CRF. This type of administration requires qualified personnel who are available 24 hours a day.

The ideal option for patients in these areas is to provide an intermediate care unit staffed with trained personnel. The criteria for initiating NIV in the general ward or in intermediate care areas comprise:

- Respiratory insufficiency which requires $\text{FiO}_2 < 0.4$.
- Initial $\text{pH} > 7.3$
- Expert staff available 24 hours a day
- Patient and family are cooperating

Material

- NIV-specific ventilator (no blender required).
- Assisted cough for neuromuscular disease patients.

Personnel

Medical and nursing staff, respiratory therapists must be trained in NIV use.

NIV IN PEDIATRIC EMERGENCIES

To date, in most hospitals NIV in pediatric patients has generally been administered in the PICU. The ever growing body of evidence on the efficacy of NIV for ARF (primarily Type II), and the

increasing amount of experience with it at many hospitals, has led to administration of this technique in less ideal scenarios, such as pediatric emergencies. Moreover, better results have been reported for early initiation of NIV; hence, the child who is to receive NIV should be transported to the PICU as quickly as possible.

Several articles on adult patients have been published that demonstrate that NIV can be safely administered in the ER to select ARF or CRF patients, such as those suffering from heightened chronic obstructive pulmonary disease (COPD) or acute pulmonary edema (APE), terminal patients, or those who have rejected more advanced support methods. Indication of NIV in the ER is less established for asthma and for pneumonia and other types of hypoxemic or Type I ARF.

All of the aforementioned articles underscore that the expertise of hospital staff is key to the success of NIV. Given that ER staff may not be ideally suited to the task, or that the ER may provide less than optimal conditions for patient monitoring, NIV in the ER should only be administered to patients with the least severe diagnoses.

The NIV mode (CPAP or BiPAP) to be employed in the ER should be the same one used in the ICU. Albeit the recent literature does not clearly favor one mode over the other, certain publications have described CPAP as being simpler.

Indications and Modes

As there is no published list of indications of NIV for pediatric emergencies, the authors of this chapter have compiled one here. It must be emphasized that despite the fact that NIV in the ER is not performed for severe ARF patients, hospital staff must always have the material required for emergency intubation prepared and at hand.

1. Asthmatic patients with marked respiratory effort who do not respond sufficiently to conventional inhalation therapy and oral or parenteral corticosteroids: These patients can benefit from NIV in BiPAP mode. The ideal patient for NIV in the ER would be an older child capable of cooperating who is suffering a moderate to severe asthmatic attack.
2. NMD patients with ARF, above all, those with upper airway respiratory infections: These patients can respond very well to NIV, given that

their lack of muscle force enables good patient-ventilator synchrony. Some of these patients may receive NIV at home, which can facilitate cooperation on their part or the part of their families.

3. Infants suffering from bronchiolitis (Type I or II): These patients should initially be treated with CPAP via nasal prongs or nasal tube, which can afford better adaptation and less air leakage than do nasal or oral-nasal masks.
4. Immunodepressed ARF patients for whom eventual intubation could imply serious complications and for whom rapid administration of NIV can prevent worsening of respiratory failure.
5. Older children with pneumonia and associated marked respiratory effort: These patients require even closer monitoring than those cited above, as Type I ARF implies much greater risk of NIV failure than does Type II ARF. CPAP provides better gas exchange, although BiPAP decreases the load on inspiratory muscles. These patients should only be treated by ER personnel with broad experience in NIV and should be immediately transferred to the PICU. Patients with ALI—and of course, those with ARDS—as well as infants with pneumonia or some other cause of Type I ARF should be immediately transferred to the PICU for initiation of NIV or CMV.

Potential problems

The main problems that can arise with use of NIV in pediatric emergencies comprise:

- Lack of experience or training among hospital personnel
- Rejection of NIV by hospital personnel, above all, if it fails
- Insufficient monitoring
- Excessive workload for medical and nursing staff, namely due to the close monitoring required for these patients, especially at the onset of NIV administration

NIV DURING TRANSPORT OF PEDIATRIC PATIENTS

Mechanical ventilation during transport of critically ill children has improved substantially,

especially due to advances in portable ventilators and monitoring systems, which now provide similar performance to that typically obtained in the ICU. Although the outlook for NIV during transport may be promising, there is no specific literature with strong evidence from which any recommendations on its use could be made.

One of the first things to ensure before transport begins is that the patient has a permeable airway; if there is any doubt, then the patient should be intubated. This would be the principal limitation on the application of NIV during transport. One of the major risks implied in using NIV is a delay in intubation, which must be avoided at all costs before and during transport.

Types of transport

Transport can be classified into two main groups: intra-hospital and extra-hospital. NIV is much easier to administer inside the hospital, since it enables much greater safety in terms of controlling the patient's airway.

Portable ventilators and ventilation systems

A broad range of commercially available portable ventilators is now available. However, few of these are specifically adapted for NIV. Although the Osiris 2[®] and 3[®], and the Oxylog 3000[®], can perform leak compensation for adaptation to NIV, use of these devices during transport of pediatric patients is problematic. The Osiris 2[®] and 3[®] are only equipped for positive pressure ventilation with mixtures of air: they can not be used with 100% O₂. The Oxylog 3000[®] features a flow sensor with a minimum threshold of 3 liters per minute (lpm), which is inadequate for young pediatric patients with reduced inspiratory strength. Other ventilators which can be made portable are not specific for NIV and are not amenable to the difficult working conditions implied in transporting patients. Conventional ventilators (e.g. Servo-i[®] and Savina[®]) can be used, although they are excessively large and are very susceptible to damage from continuous use in inadequate conditions.

Home ventilators (e.g. VS Ultra[®] and Legend Air[®]) meet several of the requisites for use of NIV during transport of pediatric patients: they are small, flexible, and easy to program. However, they are severely limited by their lack of an oxygen blender;

hence, their use implies incorporation an oxygen T-piece in line with the tubing and the flow meter. The maximum flow of O₂ supplied is 15 lpm and the FiO₂ does not exceed 50%. As such, these ventilators can not be used in hypoxemic patients whose O₂ requirements exceed said value or whose condition is highly likely to worsen during transport. Some of these ventilators are equipped with oxygen enriching systems that enable FiO₂ levels near 80%.

There are now NIV ventilators that can be used as both conventional and portable ventilators (e.g. Elisée[®] and Carina[®]). They feature oxygen blenders, graphic monitoring, and highly sensitive triggering systems and are small and light. Although these ventilators are very expensive—which limits their practicality for use exclusively during transport—they remain an attractive option due to their multifunctionality (i.e. CMV, NIV and portable ventilation).

Ventilators that feature continuous flow (e.g. Babylog 2000[®], CF120[®] and BabyPac 100[®]) can be used to administer CPAP in neonates and infants. These are practical for initial treatment of patients in early phases of Type I ARF (i.e. hyaline membrane disease [HMD], Type I-pattern bronchiolitis, etc.) or Type II ARF (i.e. apneas in neonatals or secondary to bronchiolitis) who can benefit from early CPAP treatment instead of administration of pure O₂. Use of BiPAP with these ventilators is difficult, given that none of them are equipped with a trigger, and therefore, can only perform intermittent mandatory ventilation (IMV). Consequently, these ventilators may suffer from a high level of desynchronization; hence, they are not the best devices for use during transport.

Another option is the Boussignac CPAP system, which is now used in the pre-hospital stabilization and transport of adult patients with acute Type I ARF. Albeit no studies on its efficacy in children have been published, the authors of this chapter believe that it could prove highly utile, as it is cheap, simple (it does not require a respirator) and comfortable and enables pulmonary recruitment while simultaneously providing effective oxygen therapy.

Indications and ventilation modes

Patients should be diligently selected, as the priority during transport is to maintain permeability of the airway. In terms of choosing the ventilation mode, the easiest option seems to be CPAP used

either with ventilators featuring continuous flow or with systems that are directly adaptable to flow meters (e.g. Boussignac CPAP or Vygon® CPAP), as this enables faster adaptation to the patient than use of BiPAP, which demands more careful monitoring and longer adaptation time. Furthermore, systems for administering BiPAP generally do not feature an oxygen blender; therefore, they have limited use in situations in which patient control is difficult, such as in transport.

Based on the premises outlined above, NIV in transport may be easier for patients with Type I ARF (e.g. HMD, near drowning, and meconium aspiration) than those with Type II. Nonetheless, in Type I patients, NIV should only be administered to those who do not have major respiratory difficulties or heightened oxygen requirements and who are not hemodynamically compromised; it is contraindicated for patients with ALI or ARDS. In Type II patients, NIV should be limited to patients whose oxygen needs are less than 50%. In any case, when evaluating NIV for use during transport of a pediatric patient, the contra-indications of NIV, and the specific risks implied in transporting the patient, should always be very carefully considered.

NIV AT HOME

Indications

NIV at home is primarily indicated for CRF that demands intermittent mechanical ventilation and for respiratory sleep disorders.

Objectives

- Improve the patient's quality of life: avoiding flare-ups, preserving cardiopulmonary function, maintaining adequate growth and development at each age, and improving the chances of academic and social integration.
- Increasing survival rate.

Modes

NIV can be performed at home with either positive pressure (NPPV) or negative pressure (NNPV). The former is typically preferred as it is more effective, easier to use during transport and does not imply obstruction of the upper airway (an occasional consequence of NNPV).

Conditions

NIV can be performed at home for patients who have maintained respiratory autonomy and the ability to expectorate and who do not have any difficulty swallowing. The upper airway must be permeable, without any fixed obstruction or deformation that substantially alters its morphology.

In order for parents to care for their children at home, it is crucial that they receive a detailed explanation of the objectives sought with NIV and that they give their full approval and cooperation. Patients must also be taught about the specific NIV treatment that they are to receive and its benefits in a manner appropriate to their age, cognitive level and emotional state, and must understand that the success of the treatment will be greatly facilitated by their cooperation.

Family members and others who are to care for the child must also be trained in home use of the apparatuses, rapid detection of major problems that could arise during NIV administration (e.g. disconnection of the apparatus, mask leaks, sores, and hypoventilation with hypoxia), and maneuvers to solve said problems, and must know how to quickly alert emergency services in the event that these maneuvers prove insufficient.

It is absolutely critical that there be a team of hospital personnel to periodically monitor the patient's progress, evaluate any required changes in the NIV parameters, quickly solve any complications that may arise, and maintain close contact with equipment providers. This team would preferably have at least one doctor with expertise in respiratory pathology and critical pediatric illnesses, as well as nursing staff, a rehabilitation physician and a physical therapist that is trained in respiratory pathology. The team and the patient (or family or care provider) must be able to contact each other by telephone at any time.

If the patient can not be easily transferred to the team, or if the level of home care can not be guaranteed to meet that provided in the hospital, then home administration of NIV should be seriously reconsidered.

Control guidelines: Initially, it would be advisable for the team to visit the patient at 2 to 4 weeks after the start of home NIV, and then at 2 to 6 months (according to the stability of the patient), as well as anytime that the patient suffers from some type of intercurrent condition that affects the NIV.

NIV IN OTHER LOCATIONS

NIV in sleep laboratories

Respiratory sleep disorders in pediatrics encompass a broad array of clinical situations such as obstructive sleep apnea (OSA) and sleep apnea hypopnea syndrome (SAHS), increased resistance in the upper airway, nocturnal asthma symptoms, and other conditions involving chronic alteration of respiratory function.

Sleep laboratories outfitted for children provide the ideal environment to diagnose the respiratory changes that arise during this period, and can also serve as the ideal location to begin NIV (if indicated).

NIV in diagnostic radiology

One of the latest areas to which NIV has been adapted is the radiology ward. Radiological examination can be affected as the patient breathes. As infants and small children can not cooperate during radiological exams by pausing at the end of each deep breath, they must often be sedated to ensure that they do not move during chest CTs (whether standard or high-resolution). Some authors have suggested using NIV (administered via facial mask) to induce a controlled respiratory pause of 8 to 12 seconds, during which the images can be captured. The pause is achieved by increasing pressure in the airway in synch with the patient's inspiration. NIV can afford better quality radiological exams and avoids the interference caused by endotracheal tubes during exploration of the larynx or trachea. This indication of NIV demands close monitoring of the sedated patient.

NIV in the operating room

NIV can be used in the operating room for procedures which are brief, relatively painless and do not directly compromise the airway in children who can not cooperate. There have been reports of cases in which intubation was impossible where NIV was used for ventilation until spontaneous breathing was achieved.

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Non-invasive ventilation interfaces

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INTRODUCTION

In non-invasive ventilation (NIV), interfaces are devices used as a bridge between the patient and the tubing of the mechanical ventilator. They are positioned in or around the nose or mouth and adjusted to obtain a semi-hermetic seal.

Successful NIV requires an NIV-compatible interface (i.e. features and material) and fastening system. Indeed, failure of NIV within the first few hours of treatment is usually due to patient discomfort with the interface or to a lack of patient-ventilator synchronization.

The type of interface chosen for each situation depends on two main factors: the patient's age and type of respiratory failure (RF). The availability of materials in each ward (see Table I) is also influential.

There are various types of interfaces, the most well-known of which are nasal and oral-nasal masks. Other systems include nasal pillows, nasal prongs, pharyngeal cannulae, full face masks, and helmets.

Although pediatric use of NIV has increased, no general guidelines on its use have yet been established, nor have any studies been published in which strong evidence could be used to support specific recommendations. Hence, physicians must develop their pediatric clinical practices according to the pediatric consensus and data on adult patients.

CLASSIFICATION OF NIV INTERFACES

NIV interfaces can be classified according to various characteristics:

- Material: silicone, silicone gel or a mixture of both.
- Location: nasal, nasal prong, intranasal, oral-nasal, or oral.
- Safety: with or without an anti-asphyxia valve
- Exhalation: vented or non-vented.
- Use: single use or reusable.

CONVENTIONAL INTERFACES: MASKS

The most popular masks in pediatric NIV are nasal and oral-nasal masks. These must be fabricated with non-allergenic materials and should be adapted to the patients face to minimize the possibility of leaks. In neonatal NIV, masks are no longer widely used due to their tendency to obstruct the nasal airway as well as the difficulty they present in obtaining an adequate seal. There are new mask designs which can be effective alternatives to other nasal interfaces that are more complicated to attach or that cause local lesions.

Nasal masks are generally indicated for Type II chronic respiratory failure (CRF) or Type I acute respiratory failure (ARF), but only for patients that are not very dyspneic, and can cooperate and keep their mouth closed—otherwise, leak compensation would make the mask intolerable. Oral-nasal masks are best suited for Type I and advanced Type II ARF, in which the patient can not breathe through the nose alone, especially for dyspneic patients that tend to breathe through the mouth. They are also indicated for cases in which it is impossible to keep

Table I. General recommendations for choosing an NIV interface. ARF: acute respiratory failure

ARF	Age	Choice	Alternatives
TYPE I	Neonates	Short double nasal prongs	Nasal-pharyngeal tube Nasal mask
	Infants	Large nasal mask used an oral-nasal mask	Nasal mask Short nasal prongs
	4 to 6 years	Oral-nasal mask	Nasal mask Nasal-pharyngeal tube
	6 to 12 years	Oral-nasal mask	Nasal mask Helmet
	> 12 years	Oral-nasal mask	Full face mask Helmet Nasal mask
TYPE II	Neonates	Short double nasal prongs	Nasal-pharyngeal tube
	Infants	If $FiO_2 < 0.5$: nasal mask, nasal prongs If $FiO_2 > 0.5$: large nasal mask used as oral-nasal mask	Short nasal prongs Nasal-pharyngeal tube Nasal-pharyngeal tube
	1 to 6 years	Oral-nasal mask	Nasal mask Nasal-pharyngeal tube
	6 to 12 years	If $FiO_2 < 0.5$: nasal mask If $FiO_2 > 0.5$: oral-nasal mask	Oral-nasal mask
	> 12 years	If $FiO_2 < 0.5$: nasal mask If $FiO_2 > 0.5$: oral-nasal mask	Oral-nasal mask Full face mask

the patient's mouth closed during use of a nasal mask.

No studies on the efficiency of each system for pediatric patients have been published; hence, use of these interfaces depends on personal experience and on the tolerance and efficacy in each patient.

Given that pediatric ARF patients that meet intubation criteria currently tend to be admitted into the PICU, the most widely used—and possibly, the most effective—interface is the oral-nasal mask, as in the case of adults, indicated above.

Use of nasal and oral-nasal masks in neonates and infants is difficult due to the limited selection of materials available for these ages (Fig. 1) as well as to the challenges encountered in maintaining these systems during feeding, crying, movement, etc.

Each type of interface has its respective advantages and disadvantages (see Table II).

Masks tend to be fabricated primarily from silicone mixed with plastic. The former is used to provide better comfort and tolerance, although in



Figure 1. Respirationics® oral-nasal mask used on an infant.

some cases adaptation to the patient may still be insufficient. Some interfaces are moldable, which facilitates adaptation to the patient's face (Figs. 2 and 4). For example, once run under hot water, silicone gel (Fig. 2) interfaces can be molded to achieve better coupling to the patient's nose.

Table II. Advantages and disadvantages of oral-nasal and nasal masks

Type	Advantages	Disadvantages
Oral-nasal	<ul style="list-style-type: none"> • More effective than nasal masks (dyspneic patients tend to breathe through the mouth) • Avoids nasal resistance 	<ul style="list-style-type: none"> • Higher incidence of claustrophobia • More complicated maintenance in the event of coughing or vomiting • Less comfortable in the long-term • More dead space
Nasal	<ul style="list-style-type: none"> • More comfortable and tolerable in the long-term • Lower incidence of leakage • Less dead space • Lower incidence of claustrophobia • Lower risk in the event of vomiting • Enables expectoration and feeding without removal of the mask 	<ul style="list-style-type: none"> • Loss of efficacy when the mouth is open, requiring greater work by the diaphragm <i>implica mayor trabajo diafragmático</i> • Leakage via the mouth. Increased flow to compensate for leaks causes de-adaptation.

**Figure 2.** SleepNet nasal interface used as an oral-nasal interface on an infant.

Regardless of the interface material, one of the most common complications encountered in administration of NIV is skin irritation caused by pressure, which can lead to sores and skin necrosis. This effect can be minimized through pre-application of special dressings (e.g. Comfeel®, Askina® and Duoderma®), a practice that should be made standard in all acute patients before beginning NIV.

If required, nasal masks can be custom made, although this can be difficult as it requires the patient's cooperation. This is generally done for chronic patients for whom adequate masks are not commercially available.

Masks may have ports for pressure lines, CO₂ measurement or other uses; these must remain

**Figure 3.** Resmed® vented interface.

closed when not in use. Said connectors can also be used to administer O₂, although this is not an ideal method since it generates a turbulent flow inside of the mask, which increases discomfort.

Masks may be vented (Fig. 3), whereby the exhaled air is eliminated through a vent in the mask itself, or non-vented (Fig. 4), whereby the exhaled



Figure 4. Draeger Novastar non-vented oral nasal interface.



Figure 5. Hans-Rudolph oral-nasal interface with anti-asphyxia valve.

air is eliminated through the tubing and the mask does not have any vents. Both types of masks can be used with NIV-specific ventilators. However, if a conventional ventilator with double tubing is used, then non-vented masks should be employed and all of the ports should be closed to minimize any leaks that the ventilator is not able to offset.

Some masks are equipped with an anti-asphyxia valve (Fig. 5). These valves are intended to capture air outside of the tubing to prevent re-inhalation by the patient in the event of ventilator failure or power outage. These valves act as gates which are opened by the flow of air emitted by the ventilator. Should this flow of air prove insufficient, the gate closes, enabling the patient to breathe ambient air. If the expiratory positive airway pressure (EPAP) is too low or a conventional ventilator with discontinuous flow is being used, the anti-asphyxia valve can open and close intermittently; in this case, the preferred option is to use a different mask, otherwise, the EPAP must be increased. These interfaces should not be used in conventional ventilators equipped with an NIV option, since these ventilators do not compensate for leaks well, and



Figure 6. Respironics oral-nasal mask without anti-asphyxia valve.

therefore, should only be used with masks without an anti-asphyxia valve (Fig. 6).

However, masks with an anti-asphyxia valve are suitable for home NIV patients who cannot adapt to nasal interfaces: in the event of a power outage



Figure 7. Nasal and oral-nasal masks. Choosing the best mask for each child requires having a wide variety of models and sizes available.

they prevent asphyxiation, as many home NIV ventilators are not equipped with an internal battery.

Pediatric care providers should have a broad array of interfaces (Fig. 7) on hand in order to choose the best mask for each child and allow for the possibility of changing the interface over the course of the day to eliminate pressure points in the same area of the child's face. It should be mentioned that nasal and oral-nasal masks designed for adults are often used for children.

The number of brands of masks continues to rise (see Table III). Resmed® and Resmed® are the two brands in Spain that currently offer the greatest variety of sizes for pediatric patients.

Respironics provides a wide selection of reusable masks: nasal, nasal gel and oral-nasal, including for different nose widths. It also has small nasal masks for infants and toddlers. Its Comfort Flap® adaptors, used on the cushion of its nasal masks (Fig. 8), create an air cushion that enables greater patient comfort by facilitating adaptability and reducing tension in the straps. Respironics also offers a mask (Contour Deluxe™) whose cushion has dual flaps.

Resmed® offers masks (Infant Mask System) which are designed for patients aged 0 to 6 years. These masks feature a rigid pediatric frame that can adapt to two different sized cushions, a frontal T-support that provides greater stability and a larger contact surface area while lessening the risk of pressure sores, and a five-point head strap. Resmed® used to offer the smallest commercially available nasal mask for infants; however, they stopped manufacturing it because the cushion was so soft



Figure 8. Respironics nasal mask with adaptor. Top: Mask and adaptor. Bottom: Adaptor coupled to the mask (Comfort Flap®).

that it blocked the nostrils. Their Mirage Kidsta® nasal mask is useful for patients over 6 years old. Its special harness is primarily supported by the cheeks and the lower nose, thereby reducing pressure on the nasal bridge and forehead. Moreover, it affords extremely low levels of leakage, thanks to its double-wall cushion, which inflates upon entry of air into the mask. Its design provides patients with a clear field of vision, allowing them to read and helping them to acclimate (see Chapter 11, Figure 3).

Lastly, there are oral interfaces, available in two mouth sizes (small and large), indicated for patients with mouth-breathing or chronic nasal obstruction (see Chapter 19, Figure 5).

ALTERNATIVE INTERFACES

For cases in which NIV can not be administered via mask, alternative—albeit less effective—interfaces are available.

Table III. The most widely used nasal and oral-nasal masks. Models available in pediatric sizes are listed in bold.

Brand	Type	Brand	Sizes*	Sizing by age (years)
Respironics®	Oral-nasal	<ul style="list-style-type: none"> • Spectrum • Comfort Full 2 • Image3, Image3 SE vented/novented 	<ul style="list-style-type: none"> • P, S, M, L • S, M, L • S, M, L 	Lite profile <1 Petite 1-3 Small 3- 6 Medium 7-14 Large > 14
	Nasal	<ul style="list-style-type: none"> • Profile Lite (modeable gel, vented) • ComfortGel (modeable + comfort flap) • Comfort Classic® • Contour Deluxe (no vented) • ComfortLite 1 and 2 (3 interfaces: pillow cushions, simple cushions or direct seal cushions) • ComfortCurve (3 seals) • Comfort Select • Nasal Gold Seal (7 sizes) • Simplicity 	<ul style="list-style-type: none"> • P, S, MS, M, MW, L, LN • P, S, M, L • S, M • P, S, M-L • P, S, M, L + 6 sizes • direct seal cushions • S, M, L • S, M, SW • P, S, MS, M, MW, L, LN • S, M 	
Resmed®	Oro-nasal	<ul style="list-style-type: none"> • Mirage Quattro • Ultra Mirage (vented or non-vented) • Mirage serie 2 (vented or non-vented) • Mirage Liberty (oral and nasal pillows) 	<ul style="list-style-type: none"> • XS, S, M, L • S, M, L shallow or standard • S, M, L shallow or standard • Oral: S, L + Nasal: S, M, L 	S: 1 to 4 M: 4 to 10 L: 10 to adult
	Nasal	<ul style="list-style-type: none"> • Infant mask system • Mirage Kidsta • Sullivan Mirage (vented or non-vented) • Ultra Mirage II (vented or non-vented) • Mirage Activa • Mirage Vista 2 	<ul style="list-style-type: none"> • Size < 2 y, cushion: S, L • S (> 6 years) • S, M, L shallow o S • St, L, shallow, wide • St, L, shallow • St or deep 	Infant mask system < 2 S: 1-4t M: 4-10 L: > 10
Hans Rudolph®	Oro-nasal	<ul style="list-style-type: none"> • Hans Rudolph VIP 7500, 7600 	<ul style="list-style-type: none"> • P, XS, S, M, L 	
	Nasal	<ul style="list-style-type: none"> • Alizes (vented or non-vented) 	<ul style="list-style-type: none"> • S M, L 	
Dräger®	Oro-nasal	<ul style="list-style-type: none"> • ClassicStar (vented or non-vented) • NovaStar (vented or non-vented) 	<ul style="list-style-type: none"> • S, M, L • S, M, L 	>30 kg
	Oro-nasal	<ul style="list-style-type: none"> • FlexiFit 431, 432 (vented or non-vented) 	<ul style="list-style-type: none"> • S, M, L 	
Fisher & Paykel®	Nasal	<ul style="list-style-type: none"> • Infinity 481 • Acclaim2 • FlexiFit 405 • FlexiFit 406 "Petite" (vented) • FlexiFit 407 (vented or non-vented) 	<ul style="list-style-type: none"> • L • 1 size 2 silicone seals • 1 size, 2 seals: S/M-M/L • 1 size P • 1 size, silicone seal 	
	Oro-nasal	<ul style="list-style-type: none"> • Bluestar, Bluestar Plus, inflatable 	<ul style="list-style-type: none"> • Child, S, M, L, Ultra L 	
Koo Medical®	Nasal	<ul style="list-style-type: none"> • Moonlight Deluxe 	<ul style="list-style-type: none"> • S, M, L 	
	Oro-nasal	<ul style="list-style-type: none"> • YARA (vented or non-vented) 	<ul style="list-style-type: none"> • S, M, L 	
Weinmann®	Nasal	<ul style="list-style-type: none"> • Joyce (vented or non-vented) 	<ul style="list-style-type: none"> • S, M, L 	
	Oro-nasal	<ul style="list-style-type: none"> • MOJO gel 	<ul style="list-style-type: none"> • S, M, L 	
SleepNet Corp.®	Nasal	<ul style="list-style-type: none"> • IQ (vented or non-vented) • MiniME (vented or 3 caps P, S, XS) 	<ul style="list-style-type: none"> • S, M, L • Single size 	
	Oro-nasal	<ul style="list-style-type: none"> • Breeze SleepGear with nasal pillows or Dream Seal masck • DreamFit® (vented) • SoftFit Ultra Nasal 	<ul style="list-style-type: none"> • 7 pillows-3 nasal masks • St, L, Plana • 6 siezes 	
Tyco® Healthcare	Nasal	<ul style="list-style-type: none"> • SoftFit Ultra Nasal 	<ul style="list-style-type: none"> • 6 siezes 	
Vygon®	Oro-nasal	<ul style="list-style-type: none"> • CPAP Boussignac 	<ul style="list-style-type: none"> • 6 type: neonate, infant, child, adult S, M, L 	

*Sizes: P = petite; XS = extra small; S = small; M = medium; MN = medium-narrow; MW = medium-wide; L = large, LN = large-narrow; Std. = standar



Figure 9. Adams circuit used for an adolescent patient.

Nasal pillow systems (Adams-type)

Nasal pillow systems arose as an alternative to nasal masks for treating patients with sleeping disorders. They provide patients with better vision and greater comfort (Fig. 9). They can also be used as an alternative interface for patients with pressure sores on the nasal bridge. There are several models

of these systems available, some of which are listed in Table IV.

A noteworthy example of Adams circuits is the airway delivery and management (ADAM) interface from Puritan Bennett®. This system is coupled to the nostrils through nasal pillows (available in seven sizes) and supported by the head, over which the tube is fastened via Velcro® straps to avoid pressure on the nasal bridge.

Helmet

Helmets were initially designed for maintenance of respiratory failure in hypoxemic adults. Although they are employed as an alternative to conventional masks in patients with ARF, to date few experiences with them in pediatric patients have been reported.

Helmets are transparent PVC cylinders that cover the patient’s head. They have a strap at neck level and are fastened at armpit level via an abdominal belt or a harness. These systems are advantageous in that they do not imply any points of facial contact and feature ports for nasal-gastric exploration and for catheters. Given their large dead space, use of helmets in NIV requires a high flow (> 35 liters per minute [lpm]) to reduce the risk of CO₂ re-inhalation.

There are currently two models of helmets on the market, both of which are made by StarMed®. These are available in various sizes according to the circumference of the patient's neck:

- A model (Castar R®) for bi-level positive airway pressure (BiPAP) ventilation (available in small, medium, large and extra-large). It features two

Table IV. An overview of various nasal pillow masks

Brand	Name	Sizes
Respironics®	<ul style="list-style-type: none"> • ComfortLite 1 and 2 (3 interfaces: pillow cushions, simple cushions or direct seal cushions) • OptiLife (with chin-support band) 	<ul style="list-style-type: none"> • Pillow cushions P, S, M, L + simple cushions: P, S, M, L + 6 direct seal cushions • P, S, M, L
Resmed®	<ul style="list-style-type: none"> • Mirage Liberty (nasal pillows or oral pillow) • Mirage Swift I y II 	<ul style="list-style-type: none"> • Nasal pillows: S, M, L + oral pillow: , L • 3 pillows: S, M, L
Fisher & Paykel®	<ul style="list-style-type: none"> • Infinity 481 • Opus 482 	<ul style="list-style-type: none"> • 4 seal sizes: XS, S, M, L • 3 silicone seal sizes: S,M,L
Tyco® Healthcare Puritan Bennett®	<ul style="list-style-type: none"> • Breeze® SleepGear® CPAP (with nasal pillow or Dream Seal mask) • Adam Circuit 	<ul style="list-style-type: none"> • 30 kg. 7 pillow sizes and 3 mask sizes • 7 pillows

*Sizes: P = petite; XS = extra small; S = small; M = medium; L = large.



Figure 10. Helmet interface for administering CPAP to an infant. Model: Castar®.



Figure 11. Full face mask used for NIV during weaning from conventional mechanical ventilation of a patient suffering from ARDS secondary to a hemophagocytic syndrome.

inflatable nasal pillows at its base and top that are designed to reduce internal volume.

- A model (Castar®) for continuous positive airway pressure (CPAP) ventilation and oxygen therapy. CPAP is generated through a PEEP valve connected to the expiratory circuit. In contrast to its BiPAP counterpart, this model comes in specific pediatric sizes. The Infant Low helmet (Fig. 10) is indicated for children weighing 3 to 10 kg, and the Infant High, for 10 to 15 kg. The system has an anatomically moldable pillow to help support the child's head. The adult helmet weighs 400 g, and the pediatric one, 260 g.

Full face masks

Full face masks are only available in adult sizes; hence, their use in pediatric medicine is limited to adolescent patients (Fig. 11). They are a good alternative for patients in whom a good seal can not be achieved with oral-nasal masks; patients with pressure sores; and patients who suffer from claustrophobia, as they do not obstruct the patient's field of vision. These masks minimize the risk of leaks, but have similar disadvantages as oral-nasal masks.

Alternative systems for neonates

Currently, neonatal NIV is almost exclusively administered through nasal devices or interfaces. Masks that are strongly fastened to the face, and devices that require sealing at neck level, have been rejected in pediatric medicine due to serious

complications associated with their use, including an increase in intracerebral hemorrhage (ICH) and post-hemorrhagic hydrocephalus. Noteworthy examples of alternative interfaces for neonates and infants are listed below:

Nasal prongs

Nasal prongs (tubes) are indicated for neonates and small infants with Type I and Type II RF. Single nasal prongs are simple and widely-used, although the majority of authors consider them to be inferior to double nasal prongs.

Double nasal prongs

Double nasal (bi-nasal) prongs are the preferred interface for neonatal NIV. Several models are now commercially available (e.g. Argyle®, Hudson®, Vygon®, Inca®, BabyFlow®, Alladin/Infant Flow® and Giulia®). They are simple, safe and effective. However, they carry a risk of causing nasal trauma, and some models may imply a significant increase in the patient's breathing work. Hence, new nasal interfaces have been designed to minimize these effects and to reduce any additional resistance in the airway due to the device as well as any fluctuations in the pressure delivered to the airway. Noteworthy examples of new nasal prong systems include:

- BabyFlow® (Dräger®): Employs a set of adaptors that substitute the flow sensor of the Babylog 8000 ventilator and that contain a silicone double nasal prong available in different sizes. Eliminating



Figure 12. BabyFlow® system used with the Evita XL® respirator for an infant.

the flow sensor means that when BabyFlow® is used with the Babylog 8000, only CPAP can be administered; however, if it is used with the Evita ventilator (which contains an internal flow sensor), then BiPAP can be administered (Fig. 12).

- **Infant Flow®:** Designed to maintain sufficient flow during patient inspiration (i.e. the Bernoulli and Venturi effects) while minimizing resistance to expiration (i.e. the Coanda effect, and fluidic flip). For more information on Infant Flow®, the reader is referred to Chapter 17, “Neonatal non-invasive ventilation”. This system can be used with short double nasal prongs, or soft silicone nasal masks of various sizes, to enable the exhaust flow to exit as gas enters. This increases its effective internal diameter, thereby decreasing leaks around the prongs (Fig. 13). The larger effective diameter and fine walls of the prongs, and the fact that no gas enters during expiration (due to fluidic flip), together reduce added breathing work normally implied by this type of interface. The Infant Flow® is D-shaped, whereby the area supported by the septum is flat—a design intended to minimize pressure sores and prevent septal necrosis, which are the main complications encountered with nasal CPAP. It includes a guide for selecting the appropriate tube in function of the patient’s nostrils (the largest tolerated diameter should be applied).

Nasal cannulae

For treatment of apnea in premature infants, CPAP administered via nasal cannulae with a flow

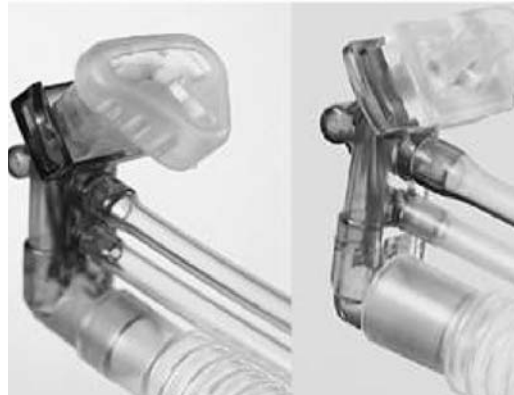


Figure 13. Top: Infant Flow® system used for an infant. Bottom: interfaces that are compatible with the system (nasal mask and nasal prongs).

of up to 2.5 L/min can provide comparable results to those obtained with conventional CPAP via nasal prongs. It has been shown that cannulae with an external diameter of 3 mm and a flow of up to 2 L/min can increase intra-esophageal pressure and reduce asynchrony in thoracoabdominal movements. Nevertheless, optimal parameters of flow, cannula size and humidification level have yet to be established.

Nasal-pharyngeal tubes

Nasal-pharyngeal tubes have been used to deliver CPAP for over 30 years and can be useful for neonates and infants. They enable feeding through nasal-gastric tubes without interruption of ventilation. However, they have their disadvantages: compared to other interfaces they are less tolerant, less effective (they are prone to leakage from the mouth and the



Figure 14. NIV administered with the Respironics BiPAP® Vision® system via a nasal-pharyngeal tube (shortened endotracheal tube) in an infant with pneumonia.



Figure 15. NIV administered using the Benveniste device.

contra-lateral nostril), and harder to fasten. Leakage from the mouth can be minimized through the use of a pacifier. A shortened endotracheal tube inserted through a nostril can be used as a nasal-pharyngeal tube (Fig. 14). The depth of insertion should be calculated externally from the patient, such that the tube is positioned in the oropharynx without causing discomfort. The reason for cutting the tube is to reduce dead space. It is attached to the nose using surgical tape. This system has primarily been used for delivering CPAP, although it can also be employed for intermittent positive pressure ventilation. These tubes can be used in tandem with either Benveniste-type devices (Fig. 15) with pre-warmed and pre-humidified airflow or ventilators with highly sensitive trigger systems that are capable of detecting these patients' small variations in flow, which can be made even smaller by major leaks.

FASTENING SYSTEMS

The majority of interfaces are adapted to the child's face through elastic straps or caps (Fig. 16), which are adjusted tightly enough to prevent air leaks but loosely enough to avoid generating excessive pressure. Caps are easier and faster to position than straps, but allow less perspiration and therefore, are uncomfortable in warm environments. Straps require more effort to achieve a good fit, but they enable better perspiration, thereby allowing the patient to stay cooler. Just as in the case of masks, choosing the best fastening system for each child and each interface requires having a wide variety of systems on hand. The BabyFlow® and Infant Flow®



Figure 16. Different fastening systems on young patients: cap; elastic straps; and a ventilation cap designed for the Infant Flow® system.

systems each feature specific fastening systems in different sizes. Respironics and Resmed® offer various caps and strap systems (Fig. 17) that are adaptable to different masks. However, most masks now incorporate their own fastening system (Fig. 18), which eliminates the difficulties of coupling interfaces to fastening equipment. Helmets are fastened either under the armpits (for adolescents) or through an integrated piece of cloth that passes under the body (for infants) (see Fig. 19).

DISADVANTAGES AND COMPLICATIONS

Pediatric NIV has its drawbacks. Above all:

- It puts high demands on medical and nursing staff in terms of attending to the patient, namely,



Figure 17. Bonnet that incorporates a strap to facilitate closing of the mouth.

for adjusting the interface to minimize leaks and obtain good adaptation to the ventilator.

- There is a limited selection of commercially available masks, which leads to a low rate of success with, and a lack of confidence in, the technique.
- Due to factors such as age and pathology NIV is only suitable for a relatively small population of RF patients. This makes obtaining experience for more complex cases difficult. The primary complications associated with NIV interfaces are covered in Chapter 11, “Complications and technical problems in non-invasive ventilation”.

RECOMMENDATIONS FOR STARTING NIV

The following recommendations are intended as a guide to starting NIV and should be adapted to each patient’s situation (i.e. comfort level, technical options, etc.):

- A. The choice of interface depends on various factors, which are listed below in order of importance:
1. Size and age of the patient.
 2. Phase of the disease and/or blood gas levels.
 3. Type of respiratory failure (RF).
 4. Availability of material.
 5. The patient’s level of cooperation.

Table II lists major interfaces NIV. These are to be chosen according to the patient’s age, type of RF, and specific needs as well as in function of the capacities of each ward.

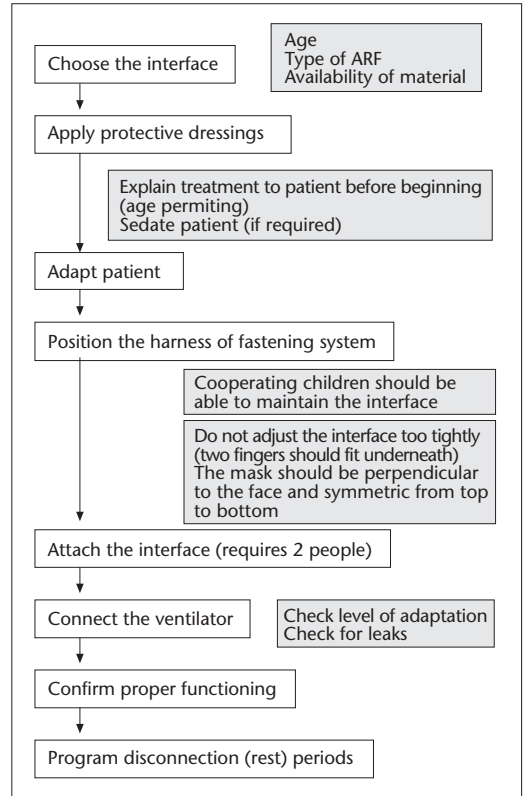


Figure 18. Initial protocol for starting NIV in function of the interface.



Figure 19. A helmet fastened to an infant.

- B. One or more alternatives should be made ready for patients whose facial profile, pathology (e.g. insufficient strength to activate the inspiratory trigger, and pressure sores) or comfort level are not compatible with the first interface chosen.

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Non-invasive ventilation devices

S. Menéndez, A. Medina, F. Martín-Torres and C. Rey

A broad array of devices for non-invasive ventilation (NIV) is now available. For example, invasive ventilators used in the pediatric intensive care unit (PICU), designed for intubated patients with little or no leakage, now increasingly feature an NIV option. There are also ventilators which are specifically developed for NIV. Some of these are intended for the hospital use, whereas others are intended for home use; the former tend to be more complex than the latter. Furthermore, there are ventilators designed for neonatal NIV, and ventilators designed for use during transport, which also increasingly feature the option to administer NIV.

This chapter provides a broad overview of various NIV systems and ventilators. Due to the constant technological advances in the field, only certain models have been described here.

NEGATIVE PRESSURE NIV SYSTEMS

Non-invasive negative pressure ventilation (NNPV) systems are based on the classic iron lung. They work by applying a sub-atmospheric pressure around the chest wall of the patient, which generates a pressure gradient from the mouth to the alveoli, and consequently, a flow of air into the lungs during inspiration. During expiration the externally produced negative pressure stops, allowing air to exit the alveoli. This flow usually occurs passively, although some devices apply a positive pressure to drive expiration.

There are three main modes of NNPV: negative pressure applied during inspiration; negative pressure during inspiration and positive pressure during expiration; and continuous negative pressure, which is analogous to continuous positive airway pressure (CPAP). All of these methods tend to involve a lot of equipment and are therefore difficult to use during transport. The main complication with NNPV is that it can cause obstructive sleep apnea through collapse of the upper airway. One of the advantages of NNPV is that it increases the venous flow to the heart; hence it may be indicated in acute respiratory failure (ARF) patients with low cardiac output after right heart surgery. These methods can be used individually or in combination with positive pressure ventilation delivered through an endotracheal tube. However, NNPV systems have generally been replaced by modern positive pressure systems.

There are various types of NNPV systems:

Iron lungs or tank ventilators

These are the most mechanically effective systems for guaranteeing a total seal of the chest wall area. However, they are bulky and therefore difficult to transport.

Cuirasses and jackets

Cuirasses (shells) and jackets (ponchos) tend to be made of plastic which adapts to the front and lateral areas of the chest wall and the abdomen. Jackets also feature nylon cords that

reach the neck, wrists and elbows to aid in sealing the system. Both cuirasses and jackets connect to a central unit equipped with a pump that generates a negative inspiratory pressure and in some cases, a positive expiratory pressure. Continuous negative pressure is sometimes used to prevent alveolar collapse. Compared to iron lungs, cuirasses and jackets are more comfortable and manageable but less effective, as they do not completely surround the patient's chest wall. Moreover, they may be difficult to adapt to patients with chest wall malformations, and therefore, may need to be custom made.



Figure 1. NIV with the Servo 900® ventilator.

POSITIVE PRESSURE NIV SYSTEMS

Non-invasive positive pressure ventilation (NPPV) consists of facilitating the entry of gas into the lungs via cyclic application of a positive pressure in the airway using extra-tracheal systems (e.g. face or nasal masks, and nasal or pharyngeal cannulae).

Conventional invasive ventilators

Any conventional mechanical ventilation (CMV) device can be used to deliver NIV, although with serious limitations. Indeed, before NIV-specific ventilators entered the market, CMV ventilators were used for NIV (Fig. 1). Using volume-controlled ventilation (VCV) modes, leaks were compensated for by increasing the tidal volume (V_t) more or less randomly. On one hand this strategy led to excessive peak inspiratory pressure (PIP) in cases of low leakage, while on the other hand, it could not sufficiently compensate for high leakage. In certain cases, this compromised the patient's tolerance. Whereas the most common modes (S, S/T) used in NIV-specific ventilators are equivalent to pressure support ventilation (PSV), the most widely used modes in CMV ventilators are those which are time-controlled or time-assisted with a predefined inspiratory time (T_i). This is because in CMV ventilators used with PSV the transition from inspiration to expiration occurs when the inspiratory flow drops below a pre-defined maximum value, which in NIV may be delayed or may not even occur when large increases in inspiratory flow are required to compensate for a high level of leakage (see Chapter 13, Fig. 1). An excessively high or never-ending T_i will not be well tolerated by patients;

hence, modes in which the T_i is specifically programmed are preferred.

CMV ventilators have other disadvantages which limit their utility for NIV. The inevitable leaks inherent to NIV can interfere with key aspects of ventilator function, diminishing patient-ventilator synchrony and increasing the possibility that endotracheal intubation will be required. Choosing an appropriate interface and attaching it tightly still can not totally eliminate leakage and may cause patient discomfort or even pressure sores. Leaks can complicate activation of the inspiratory trigger at the beginning of the cycle, thereby increasing the level of respiratory effort required for activation. Likewise, they lengthen the response time of the device, which often leads to auto-cycling. After activation and during gas delivery, leaks reduce the efficacy with which the device achieves pressurization, to the point that the programmed PIP may not be reached during the T_i . As explained above, using variable flow to compensate for leakage at the end of the cycle can delay activation of the expiratory trigger. This phenomenon tends to be especially marked in obstructive RF cases, where it causes a slower drop in inspiratory flow. Contrariwise, in restrictive RF cases, leaks tend to shorten the T_i excessively. In both cases patient-ventilator synchrony can become compromised. In contrast to CMV ventilators, NIV-specific ventilators (see below) are designed with applications that offer effective compensation for a wide array of leaks, adjusting for trigger sensitivity, response time, pressurization performance and cycling criteria to the extent of leakage.

Table I. Principal conventional mechanical ventilators featuring an NIV option.

	CMV modes	NIV modes	PTPt (cm H ₂ O/sec)	PTP500 (% ideal value)
Elisée (ResMed-Saime) (Fig. 2)	A/C, SIMV (PCV and VCV) PS ± VG		0.15-0.2	< 10%
Esprit (Respironics) (Fig. 3)	A/C, SIMV (PCV and VCV)	S, S/T	< 0.05	20 to 30%
Evita XL (Drägerwerk) (Fig. 4)	SIPPV, SIMV ± ASB, MMV± ASB, BIPAP±ASB, APRV	NIV	< 0.05	10 to 20%
Extend (Täema)	A/C, SIMV (PCV and VCV) PSV, APRV, PRVC, MRV	VCV, PCV, SIMV, PSV	0.05 to 0.1	20%
Newport e500 (Newport MI)	A/C, SIMV (PCV and VCV) PSV, VTPS, VTPC		0.15 to 0.2	20 to 30%
Servo-i (Maquet) (Fig. 5)	VCRP, PC, VC, PS, VS, BiVent, Automode and NAVA (Neurally Adjusted Ventilatory Assist)	PS, PC, PS + VNI Backup, CPAP Nasal (500 g- 10 kg)	0.15 to 0.2	10 to 20%
Servo-s (Maquet)	VCRP, PC, VC, PS, BiVent	PS, PC, PS + PC Backup	0.15 to 0.2	10 to 20%
Vela (Viasys)	A/C, SIMV (PCV and VCV) PSV, PRVC	A/C, SIMV, PSV	0,1	10 to 20%
Raphael (Hamilton)	A/C, SIMV (PCV and VCV) SPONT, ASV, APRV DuoPAP	NIV	< 0.05	40 to 50%
840 Ventilator (Tyco-Nellcor Puritan Bennett) (Fig. 6)	A/C, SIMV (PCV and VCV) PS, Bi level, VV +, PAV+	NIV	0.012	N/P

CMV: conventional mechanical ventilation; NIV: non-invasive ventilation; PTPt: inspiratory pressure-time product; PTP500: pressure-time product at 500 ms from start of inspiratory effort; PCV: pressure-controlled ventilation; VCV: volume-controlled ventilation; PS, PSV and ASB: pressure-support ventilation; N/P: information not provided by manufacturer.

Table I summarizes the main features of the CMV ventilators with NIV option that are most widely used in the PICU. The Table includes the variable of inspiratory pressure-time product (PTPt) and pressure-time product at 500 milliseconds of respiratory effort (PTP500). PTPt represents the area under the pressure-time curve from the beginning of the inspiratory effort (negative pressure) to the return to the starting value by pressurization of the system, whereas PTP500 is used to gauge the pressurization performance of the ventilator. PTPt is measured in cm H₂O per second, and its value is directly proportional to the respiratory effort required to activate the inspiratory trigger. Low PTPt values represent less work to activate the trigger in the presence of leaks. PTP500 is measured relative to an ideal pressure (i.e. the target pressure) whose value

is taken as 100%. High PTPt values in the presence of leakage indicate a high pressurization capacity.

NIV-specific ventilators

Although commercially available NIV respirators include volumetric models (see Table II), the most popular devices employ continuous flow pressometric turbines that cycle with a decelerating flow and by alternating between two preset pressure levels. These are generally labeled as bi-level positive airway pressure (BiPAP) ventilators. Despite having high levels of leakage, they provide effective and well-synchronized ventilation.

The simplest respiratory support mode offered by BiPAP ventilators is continuous positive airway pressure (CPAP). When the level of CPAP must be gradually brought above 12 cm H₂O, or when



Figure 2. Elisée®.



Figure 3. Esprit®.



Figure 4. Evita XL®.



Figure 5. NIV with the Servo-i® ventilator, delivered through nasal-pharyngeal tube.

there is a high level of respiratory effort starting from the very beginning, a high level of respiratory support is required. The two levels of pressure in BiPAP comprise the inspiratory positive airway pressure (IPAP) and the expiratory positive airway pressure (EPAP); the latter is lower than the former. BiPAP ventilators offer two distinct types of inspiratory cycles: spontaneous (S) and timed (T). S cycles are started by the patient by activating the inspiratory trigger and stopped by the patient once the virtual curve of the ventilator intersects the real curve of the patient (see Fig. 7). In contrast, T cycles are started by the ventilator at a preset frequency (Fr) and stopped after a preset Ti.

The most widely used mode in BiPAP ventilators is S/T mode, whereby spontaneous modes in which the difference between IPAP and EPAP is applied as PRESSURE SUPPORT are alternated with timed modes that, in the absence of any respiratory effort by the patient, are applied using a preset Fr. In both the S and the T cycles, the V_t obtained by the patient is a function of any difference between IPAP and EPAP as well as of any respiratory effort.

State of the art devices feature ventilation modes that support variable levels of pressure support. These



Figure 6. Puritan-Bennet 840.

modes include proportional assisted ventilation (PAV®; Resprionics) (Fig. 8), average volume assured

Table II. Principal NIV-specific ventilators

Model	NIV modes	O ₂ blender	Graphic display	Setting	Accessories
BiPAP Vision® (Respironics)	CPAP, S/T, T, PAV	Yes	Yes	Hospital	
Supportair® (Airox)	VCV (A/C, SIMV), PCV (C, A/C), PSV (S, ST)	Yes	Yes	Hospital	
Carina (Dräger) (Fig. 11)	CPAP, PS, PC BIPAP, VG	Yes	Yes	Hospital	Internal battery
LTV 1000® (Breas)	VCV (C, A/C, SIMV), PCV (PSV)	Yes	Yes	Hospital/Home	
BiPAP Synchrony® (Respironics)	CPAP, S, S/T, T	No (optional O ₂ valve)	No	Home/Hospital	
VPAP III ST-A® (Res Med)	CPAP, S, S/T, T	No	No	Home/Hospital	Attachable humidifier
VS Ultra® (Saime)	PCV (A/C), PSV (S, S/T), PS-TV, VCV (A/C)	No (optional O ₂ valve)	No	Home/Hospital	Battery
VIVO 40® (Breas) (Fig. 12)	CPAP, PSV, PCV	No	No	Home/Hospital	Internal battery
BiPAP AVAPS® (Respironics)	AVAPS	No	No	Home	
AutoSet CS 2® (Res Med)	SVA	No	No	Home	
BiPAP Serena (Saime) (Fig. 13)	S, S/T	No	No	Home	
GoodKnight 425 ST BiLevel® (Puritan Bennett)	S, APNEA	No	No	Home	

ASV: adaptive servoventilation; AVAPS: average volume-assured pressure support; PS-TV: pressure support with tidal volume; CPAP: continuous positive airway pressure; GV: guaranteed volume; PAV: proportional assisted ventilation; PCV: pressure-controlled ventilation; PSV: pressure support ventilation; S: spontaneous; S/T: spontaneous/timed; T: timed; VCV: volume-controlled ventilation.

pressure support (AVAPS®; Respironics) (Fig. 9), adaptive servo-ventilation (ASV®; ResMed®) (Fig. 10), and pressure support with tidal volume (PS-TV®; Saime). No comparative studies on the efficacy of these modes in pediatric patients have been published to date.

As with CMV ventilators, an important aspect in NIV-specific ventilators is the ability to offset the effect of leaks on the respiratory effort needed to activate the inspiratory trigger. The most effective devices are those that operate by flow, especially for patients with obstructive respiratory conditions or trapped airways, or for whom reaching the preset auto-PEEP threshold may imply additional respiratory effort. In terms of the expiratory trigger, both leakage compensation via additional flow, and obstructive airway pathologies, can delay the drop in inspiratory flow below the cycling threshold, thereby lengthening the Ti and worsening patient-ventilator synchrony. Technological advances have led to the development and patenting of various sophisticated

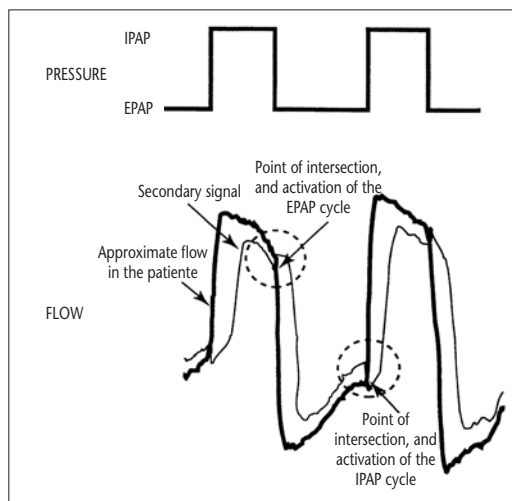


Figure 7. Auto-track® automatic triggering mechanism.

triggering systems. One example is the Autotrack® system by Respironics, which in less than 100 ms



Figure 8. BiPAP Vision® with optional PAV mode.



Figure 9. BiPAP Synchrony®.

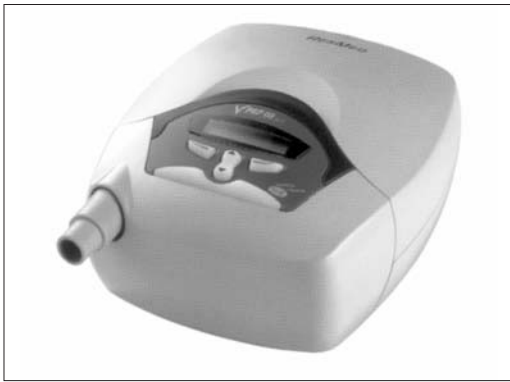


Figure 10. VPAP III.



Figure 11. Carina®.

(the threshold of conscience inspiratory effort) combines the inspiratory response with a cycling criterion that oscillates according to the respiratory resistance of each patient.

BiPAP ventilators are generally simpler and cheaper than CMV ventilators. For instance, they feature tubing with a single inspiratory circuit, which obviates quantification of the small expiratory tidal volume that escapes through the inevitable leaks between patient and interface. Expiratory gases escape the system through a constant outflow which is typically located at the patient-end of the tubing. However, this design does not totally prevent re-inhalation of expired gas. Given that the re-inhaled volume in pediatric patients can imply a large percentage of the physiological V_T , re-inhalation can have major consequences for the patient's acid-base equilibrium. These effects can be diminished through



Figure 12. Vivo 40®.

adequate positioning of the controlled outflow in the interface, by increasing the outflow itself (by increasing the EPAP), and by using expiratory valves such as Plateau (Respironics) valves.

NIV-specific ventilators designed for hospital use (see Table II) typically feature a built-in oxygen blender to facilitate treatment of hypoxemic patients that have high FiO_2 . State of the art BiPAP systems



Figure 13. Serena®.

for hospital use are generally equipped with screens for graphic monitoring of major respiratory parameters.

NIV-specific devices intended for extra-hospital use generally lack an O₂ blender but may feature specific valves for connecting to O₂ or can be equipped with an oxygen T-piece, preferably at the near end of the inspiratory handle in order to avoid turbulence that can bother the patient. However, given that these devices generally employ flows greater than 30 L/min, but that the maximum O₂ flow offered by conventional flow-meters is 15 L/min, it is difficult to achieve an FiO₂ of > 50% whether using O₂ valves or a T-piece. As such, extra-hospital NIV ventilators have limited utility for hypoxemic patients.

Neonatal NIV ventilators used with nasal cannulae

Neonatal NIV requires equipment that is specifically adapted to the functional and anatomical needs of neonatal patients. The Infant Flow® (EME) and Infant Flow Advanced® (EME) systems deliver NIV to neonates through a patented piece that simultaneously acts as nasal interface and pressure generator (Figs. 14 and 15).

In the Infant Flow® system the aforementioned piece enables high-velocity bursts of warm and humidified gas to be generated during inspiration (i.e. the Bernoulli effect), providing active assistance and nearly constant maintenance of the CPAP level. During expiration the increase in intranasal pressure, together with the pressure generator—which is based on fluid dynamics, fluidic flip and the Coanda effect—directs said bursts of gas and the expired gas towards the expiratory branch of the piece with a minimum response time and without producing any major oscillations in CPAP. The small size and long-lasting battery of the Infant

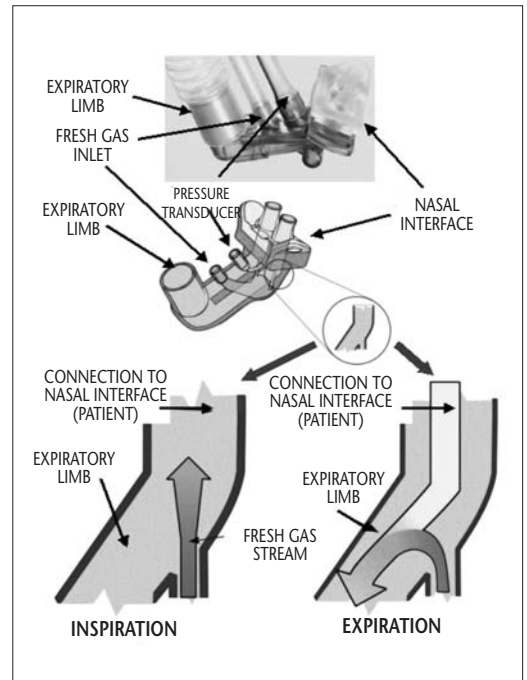


Figure 14. Top: Structure of the pressure generator used in the Infant Flow® and Infant Flow Advanced® systems. Bottom: Characteristic change in flow from inspiration to expiration (i.e. fluidic flip) of these systems (see text for more details).

Flow® system make it amenable to early perinatal use and enable uninterrupted ventilation during transport between the delivery room and the neonatology ward.

The Infant Flow Advanced® includes the option to add additional gas to the base volume at programmable values of 0 to 5 L/min (flow), 1 to 120 respirations/min (respiratory frequency, f), 0 to 11 cm H₂O (pressure) and 0.1 to 1 sec (Ti). This feature, together with the specific impedance trigger activated by the patient's abdominal muscles, extends the ventilation modes possible with the Infant Flow system to include non-synchronized and synchronized intermittent positive pressure ventilation (IPPV and SIPPV). The reliability of said triggering system is limited, given that it can be inadvertently activated by non-respiratory abdominal muscle movements. Lastly, use of the trigger as an apnea sensor enables programming of a safety mode (backup) at respiratory frequencies adjustable from 0 to 30 rpm. The latest Infant Flow model is known as SiPAP® (Fig. 16).

The Giulia® (Ginevri) ventilator (Fig. 17) provides

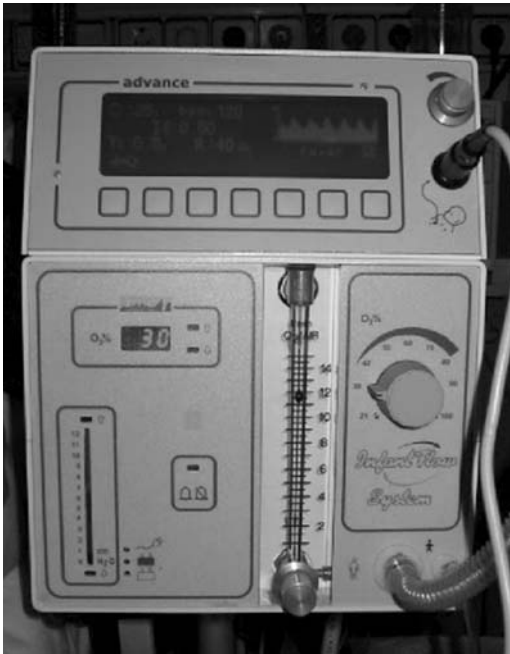


Figure 15. Infant Flow Advance®.

CPAP, SIPPV and synchronized intermittent mandatory ventilation (SIMV). It employs a flow trigger that is connected to nasal cannulae and whose activation is not interrupted by non-respiratory abdominal muscle movements. Its graphic display shows pressure and flow values and rates.

Portable ventilators with an NIV mode

Portable ventilators used during transport or emergency situations are also becoming evermore sophisticated: in some cases they now offer the same level of performance as the devices used in the PICU. Noteworthy examples include the Oxylog 3000® (Dräger), LTV1000® (Pulmonetic Systems) and Osiris 2 and 3 (Taema), whose leak alarms can be modified or turned off, and which compensate for leaks, allowing mask delivery of NIV to patients weighing approximately 5 kg. The Oxylog 3000®, which only offers NIV in the pressure-controlled modes of BIPAP, BIPAP/ASB, CPAP and CPAP/ASB, employs an inspiratory sensor with programmable flow (> 3 L/min). NIV during transport can also be administered with simple CPAP devices such as the Bousignac (see Chapter 12).



Figure 16. SiPAP®.



Figure 17. Giulia. Ginevri®.

Other NIV methods

Phrenic electrostimulation

Phrenic electrostimulation, also known as diaphragmatic tracking or diaphragmatic stimulation, can be considered as a type of NIV which does not require a permanent airway. It consists of positioning electrodes that electrically stimulate one or both of the phrenic nerves, causing the diaphragm to contract, and consequently, generating an inspiratory flow.

Abdominal compressors (pneumobelts)

Abdominal compressors, also known as pneumobelts, are inflatable belts that are placed in between the patient's pubis and navel and then connected to a positive pressure ventilator. Upon inflation, the belt generates a pressure that moves the diaphragm upwards, thereby favoring expiration; upon deflation, it favors inspiration.

Rocking beds

Rocking beds allow patients to alternate between the Trendelenburg and anti-Trendelenburg positions, facilitating passive movement of the diaphragm by gravity (alternating between the caudal and cephalic directions), thereby aiding inspiration and expiration. Rocking beds enable respiratory frequencies of approximately 30 respirations/min and V_t of approximately 500 mL.

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Non-invasive ventilation modes and methods for pediatric patients

J. López-Herce and J. Pilar

INTRODUCTION

Although non-invasive ventilation (NIV) can be delivered using either positive or negative pressure, the techniques used to administer each form are very different. This chapter provides an overview of the modes and methods for positive pressure NIV (NPPV), which is the most common type of NIV in both adult and pediatric patients.

Until only a few years ago, NIV was performed using continuous positive airway pressure (CPAP) systems or NIV-specific ventilators that offered few ventilation modes and were primarily indicated for obstructive sleep apnea (OSA). When ICU personnel did not have an NIV ventilator available, they adapted conventional invasive ventilators to administer NIV using volume-controlled or pressure-controlled methods. NIV delivered this way often failed, especially in very small children, because the ventilators and materials did not meet the specific needs of pediatric patients. However, in the past few years, new ventilation modes suitable for NIV have been developed and existing ones have been improved. Moreover, new ventilators for home ventilation of pediatric patients, capable of both invasive and non-invasive ventilation, have been introduced. Lastly, many of the latest systems for invasive ventilation now feature NIV modes. Consequently, the range of indications of pediatric NIV has expanded. The recent development of high flow oxygen therapy, together with CPAP and NPPV, has provided an array of new treatment strategies

for pediatric patients with respiratory failure (RF). Physicians can now choose among options of varying degrees of aggressiveness before resorting to intubation.

This chapter provides an overview of the current NIV methods of high flow oxygen therapy, CPAP and NPPV.

HIGH FLOW OXYGEN THERAPY

Principle

In high flow oxygen therapy a strong flow of air—ideally stronger than the peak inspiratory flow of the patient—is mixed with oxygen, and then delivered through nasal cannulae. The gas is humidified (95 to 100% relative humidity) and warmed to near body temperature (33 to 43 °C) to make it more tolerable.

Mechanism of action

The high flow is believed to create a small positive pressure (i.e. CPAP) gradient that improves oxygenation and decreases respiratory effort; however, this has yet to be fully demonstrated. Regardless of oxygen concentration, the humidity in the air has benefits the body by improving ciliary movement and removal of secretions. Lastly, using airflow similar to the insufflation of tracheal gas cleanses the anatomic dead space, thereby improving ventilation.



Figure 1. Fisher-Paykel.

Interfaces

- Nasal cannulae of different sizes (according to age). Conventional nasal cannulae can be employed as long as the same caliber and length recommended by the manufacturer are used.
- Can be used in tracheotomized patients.

Indications

- Patients with high oxygen requirements .
- Moderate respiratory failure (RF).
- Apnea in premature infants.

Commercially available systems in Spain

Of the numerous high flow oxygen systems produced, there are currently two available in Spain: Fisher-Paykel (Fig. 1) and VapoTherm (Fig. 2). The latter can deliver flows of approximately 1 to 40 L/min. These models feature two modes: low flow (1 to 8 L/min: for premature infants, neonates and small infants) and high flow (5 to 40 L/min: for children and adults). Each mode uses different cartridges for humidifying the gas. The nasal cannulae used are sized according to the patient's age.

Programming the flow

The flow is programmed according to tolerance:

Premature infants, neonates and small infants: low flow (1 to 8 L/min).



Figure 2. VapoTherm.

Children: approximately 5 to 20 L/min.
Adults: approximately 8 to 40 L/min.

Advantages

- Simple and easy to use, and well-tolerated by the patient.
- Suitable for any age.
- The air can be enriched with nitric oxide or heliox.

Risks

Infection: In order to minimize the risk of infection, hospital staff must closely follow the protocols for changing the interfaces and cleaning the system. This risk has been reduced in newer models which use disposable interfaces.

CONTINUOUS POSITIVE AIRWAY PRESSURE

Principle and mechanism of action

In CPAP, which is the simplest NIV mode, a continuous positive pressure is maintained throughout the respiratory cycle. This pressure is delivered via continuous airflow and/or a pressure valve, enabling the patient to breathe spontaneously (Fig. 3). Spontaneous breathing

- The child determines the respiratory frequency and V_t according to their breathing work.
- The continuous pressure in CPAP keeps the airway open, increases the respiratory functional capacity and reduces alveolar collapse.

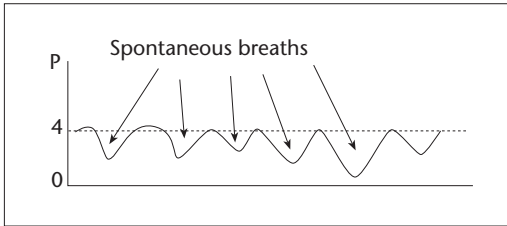


Figure 3. Plot of time vs. pressure for CPAP (P: pressure).

Interface

CPAP can be administered through any interface (e.g. nasopharyngeal tube, nasal or oral-nasal mask, nasal cannulae, and short nasal prongs).

Delivery methods

CPAP can be delivered using various systems and ventilators. However, it should be remembered that respiration and programming differ among devices.

CPAP systems: These basically comprise an air and oxygen flow source, tubing and an expiratory resistance (positive end expiratory pressure [PEEP]) valve. An air heater and humidifier are connected to the inspiratory tubing. The patient can freely draw in air. In these systems neither the volume nor the respiratory frequency are monitored; hence, a flow meter must be connected to the tubing to measure the pressure. CPAP systems can either be assembled from separate components available in the ward (Fig. 4) or purchased fully pre-assembled. There are also commercially available simplified CPAP systems which can be used during transport and which do not include an air heater and humidifier.

NIV ventilators: These generally only maintain CPAP using continuous flow in the airway. The patient can freely draw in air.

Continuous flow neonatal ventilators: These maintain CPAP with continuous flow in the airway and with a PEEP valve. The patient can freely draw in air.

Conventional invasive ventilators: These maintain continuous pressure in the airway via a PEEP valve, but generally do not maintain a continuous airflow. In order to draw in air, the patient must open the inspiratory sensitivity valve at each breath. This requires greater respiratory effort than do the other systems. This problem can be solved by introducing continuous airflow by connecting a T-piece to the



Figure 4. Benveniste system assembled from separate components.

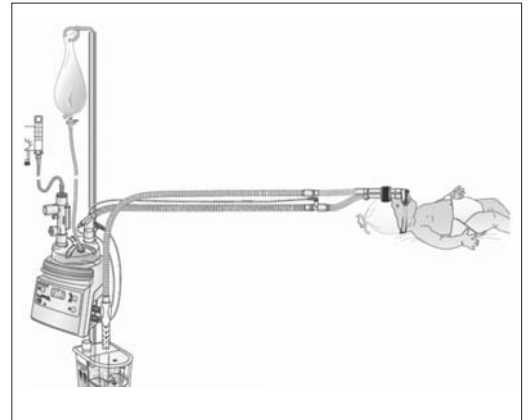


Figure 5. Bubble CPAP system.

tubing at the inspiratory loop of the ventilator. However, this modification can alter pressure and volume readings.

An ideal CPAP system would administer continuous flow, such that the patient could breathe and draw in air at will, and would monitor at least volume, respiratory frequency, and pressure. The airflow would have to be strong enough for the

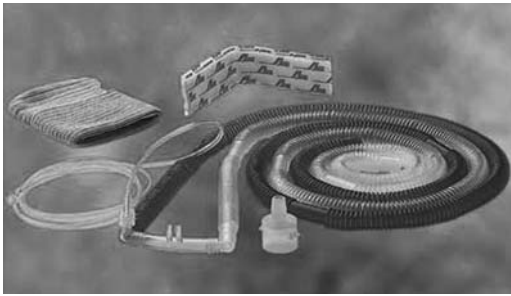


Figure 6. Hudson system.

patient to draw in air without limits (i.e. at least two to three times the normal minute volume), but not so strong as to cause the patient discomfort.

Indications

- Obstructive sleep apnea syndrome (OSAS).
- Central and/or obstructive apneas in premature infants with bronchiolitis.
- Bronchiolitis with respiratory failure.
- Respiratory failure (without alveolar hypoventilation): pneumonia, chest wall trauma, cardiogenic pulmonary edema.
- Post-extubation respiratory failure.
- Respiratory failure with weak respiratory effort (if BiPAP is not available).

Programming

- Parameters to program:
 - CPAP systems: flow of air and/or oxygen and regulation of the expiratory resistance valve.
 - NIV-specific ventilators or conventional (invasive) ventilators with an NIV option: CPAP or EPAP, and FiO_2 (if available), and alarms for volume, pressure, frequency and apnea (only available in certain models)
 - Neonatal ventilators: flow, PEEP, FiO_2 , and alarms for volume, pressure, frequency and apnea. The minute volume and apnea alarms must often be set at the minimum to prevent them from continuously going off due to leakage.
 - Conventional invasive ventilators: inspiratory sensitivity, PEEP, FiO_2 , and alarms for minute volume, pressure and apnea.
- Starting parameters: Low CPAP levels (approximately 4 to 6 cm H_2O) are generally recommended for initiating ventilation.

- Adjustments: The CPAP level should be adjusted in increments of 2 cm H_2O according to the patient's tolerance and respiratory needs. Levels above 12 cm H_2O are usually not well tolerated. If the patient does not show any signs of improvement, hospital staff should consider switching to another NIV mode.

Advantages

- Simple, easy to use and adjust, and can be delivered with a simple apparatus .

Disadvantages and secondary effects

- Does not assist the patient with each breath.
- Does not provide safety breaths for patients who are hypoventilating or have constant apnea; hence, monitoring of cardio-respiratory signals and of transcutaneous oxygen levels is crucial.
- Over-inflation: Use of excessive CPAP can lead to pulmonary over-inflation (infants with bronchiolitis are at especially high risk) and diminished venous return.

NIV MODES IN CONVENTIONAL INVASIVE VENTILATORS

Types

Non-invasive mechanical ventilation can be administered using conventional invasive ventilators under volume-control or pressure-control. Nearly any ventilation method or mode can be used: controlled, assisted/controlled, intermittent mandatory ventilation (IMV), pressure support ventilation (PSV) and CPAP. The respective advantages and disadvantages of each method or mode to deliver NIV are similar to those for delivering invasive ventilation.

Programming

Programming of invasive ventilators for NIV is similar to that used for patients with endotracheal intubation, the parameters of which are summarized in Table I. However, there are certain differences that must be considered:

Volume: In volume modes, a greater V_t (up to twice as large) can be programmed for NIV than for invasive ventilation in order to compensate for the dead space of the mask and for any leaks.

Table I. Starting values of NIV parameters for invasive ventilators.**Peak pressure or pressure support*:** 8 to 10 cmH₂O

Once the patient tolerates the mask well, this value should be increased in increments of 2 cm H₂O until reaching the peak value (typically 14 to 20 cm H₂O) that provides the best improvement of respiratory failure without provoking intolerance or generating leaks.

Tidal volume:** 15-30 mL/kg.

Low values (10 to 12 mL/kg) should be used initially, and then increased according to the patient's chest wall expansion and tolerance.

PEEP: 4 cmH₂O.

For patients with hypoxemia and/or atelectasis, this value should be increased to a maximum of 6 to 10 cm H₂O.

Inspiratory time or percent: 0.2 to 0.5 sec or 33%.**Respiratory frequency:** 2 to 5 respirations/min less than the patient's respiratory frequency***.**FiO₂:** 0.21 to 1 according to the pathology

For ARF patients, high values can be used initially and then decreased in function of the saturation.

Ramp slope, flow speed, and inspiratory delay: These are adjusted based on the patient's tolerance. As a general rule, the younger the patient, the lower the flow or the slower the ramp during the adaptation phase****.

Inspiratory sensitivity: maximum sensitivity; Flow of 1 to 2 L/min or Pressure of 0.5 to 2 cm H₂O (flow trigger is preferred).

Expiratory sensitivity**:** 40 to 70% of the maximum inspiratory flow, depending on leakage.

Alarms: for apnea, respiratory frequency and pressure; The expiratory volume alarm should be turned off for very low values caused by leakage.

*For PCV, and pressure-assisted/controlled ventilation (PACV), pressure-controlled SIMV (PC-SIMV), and PSV modes.

**For volume-controlled ventilation, including volume-assisted/controlled ventilation (VACV), and volume-controlled SIMV (VC-SIMV) modes.

***For controlled, assisted/controlled, and SIMV modes.

**** Not programmable on all ventilators.

Respiratory frequency: For the patient to maintain spontaneous breathing, good synchrony is crucial: setting the respiratory frequency and the inspiratory to expiratory ratio very close to the patient's actual values indirectly provides an inspiratory time similar to that of the patient. Patients typically have very short inspiratory times (0.2 to 0.5 seconds); hence, there is no rationale for artificially extending the inspiratory time, which in turn increases the risk of asynchrony. Some ventilators feature the option to independently limit the inspiratory time.

Inspiratory sensitivity: Flow-sensitivity methods are generally better than pressure-sensitivity methods. For NIV in conventional invasive ventilators, adjusting the sensitivity is crucial: given the dead space of the mask and the existence of leaks, flow

sensors, such as those for pressure, may not detect the patient's inspiration or may detect it late. These problems could lead to ventilator-patient asynchrony with respiratory exhaustion and risk of barotrauma. Furthermore, in CPAP and PSV modes, if the patient is unable to open the ventilator valve, then they will not draw in any air, and therefore, will functionally remain in apnea with a severe risk of respiratory arrest. In assisted/controlled methods and PSV and SIMV-pressure support modes, if the trigger is too sensitive, then autocycling can occur and possibly compromise ventilation by causing patient-ventilator asynchrony.

Expiratory sensitivity: regulates the end of the ventilation cycle. Depending on the ventilator and the mode used, the end of inspiration may be:

- a. A fixed value set by the operator (e.g. by programming the inspiratory time in controlled, assisted/controlled or IMV modes).
- b. A fixed value set by the manufacturer (e.g. 25% of the inspiratory peak value in the pressure support).
- c. Hence, just as in invasive ventilation, the expiratory trigger tends to be adjusted as closely as possible to the extubated patient's physiological condition: it is programmed to approximately 5 to 25% of the achieved peak flow (provided there is no leakage). In NIV, ventilators try to compensate for constant leakage, and the decrease in peak flow is much slower. This translates into an undesired prolongation of the inspiratory time, causing the patient discomfort. Consequently, the expiratory trigger should be programmed at a higher value (40 to 70% of the achieved peak flow), according to the inspiratory time that the patient would use without NIV (see Chapter 13, Fig. 1).

Indications

Invasive ventilators in NIV mode are indicated for hospital use when volume-controlled or pressure-controlled methods are required, and when an NIV ventilator with built-in oxygen blender is either unavailable or unable to provide good ventilation or adaptation to the patient.

Advantages and disadvantages of each method and mode

- In volume-controlled methods, the pressure is variable and there is a higher risk of leakage, with lower tolerance by the patient as well as gastric distension, and skin irritation and/or necrosis.
- Pressure-controlled methods generally compensate better for leaks and are better tolerated by the patient. Moreover, the decelerating flow distributes air better. However, in these methods the V_t is variable, and therefore, if patient resistance or compliance changes, then sufficient ventilation can not be guaranteed.
- PSV can provide better adaptation to the patient. However, leakage in PSV can extend the inspiratory flow even after the patient has started expiration, thereby forcing the patient to increase their respiratory effort in order to counteract the

ventilator. This scenario can be avoided by using pressure-control, whereby the inspiratory time is limited by programming, which is the preferred method of many physicians.

Disadvantages of using invasive ventilators for NIV

- Invasive ventilators, whether used with pressure-controlled or volume-controlled methods, generally offer worse adaptation in BiPAP mode than do NIV ventilators.
- Invasive ventilators, whether used with pressure-controlled or volume-controlled methods, do not provide sufficient leak compensation.
- In invasive ventilators the alarms for low minute volume and for apnea often sound continuously due to dead space in the mask and to leaks. In some models, these alarms can not be turned off.
- Invasive ventilators are generally harder to maintain than NIV ventilators.

VENTILATION WITH CONTINUOUS FLOW AND BI-LEVEL POSITIVE AIRWAY PRESSURE

This mode is available in NIV ventilators and in some conventional ventilators that have an NIV option.

Principle

In this mode, a turbine generates pressure at two levels (inspiratory positive airway pressure [IPAP] and expiratory positive airway pressure [EPAP]) with a continuous flow throughout the respiratory cycle. Although it is traditionally known as BiPAP (bi-level positive airway pressure), there are legal issues concerning use of this acronym; hence, this mode is given a different name by each manufacturer. It is the most widely used NIV mode for all types of patients and clinical scenarios. The ventilator constantly monitors the patient's respiratory effort, using a highly sensitive flow sensor attached to the circuit, which enables synchronization with spontaneous breathing as well as compensation for any leaks in or near the mask.

Parameters to program (see Table II)

- IPAP: controls the ventilation; During the inspiratory phase a higher IPAP generates a greater tidal volume (V_t).

Table II. Starting values of NIV parameters for bi-level pressure ventilators

IPAP: 8 to 10 cm H₂O.

Once the patient tolerates the mask well, this value should be increased in increments of 2 cm H₂O until reaching the peak value (typically 10 to 20 cm H₂O) that provides the best improvement of respiratory failure without provoking intolerance or generating leaks.

EPAP: 4 cm H₂O*

Inspiratory time or percent: 0.4 to 0.5 sec or 33%**.

Respiratory frequency: 10 respirations/min less than the patient's respiratory frequency.

FiO₂:** according to pathology.

Ramp slope, flow speed, and inspiratory delay**:** ramp slope: 0.05 to 0.4 sec; or flow speed: 10 to 30 L/min according to age (in the adaptation phase: the younger the patient, the lower the flow).

Alarms: for apnea, respiratory frequency, tidal volume, minute volume, and pressure*****

**In some bi-level pressure ventilators, the minimum programmable EPAP is 4 cm H₂O.*

***Only in S or S/T modes.*

****Some bi-level pressure ventilators (e.g. BiPAP Vision®, and Carina®) feature a built-in oxygen inlet, whereas in others, the oxygen flow must be introduced through the tubing or the mask.*

***** Not programmable on all ventilators.*

****** Depends on ventilator type.*

- EPAP: improves the residual functional capacity and oxygenation.
 - Inspiratory ramp slope or flow speed: regulates the speed at which air enters; These parameters are crucial for ventilator-patient adaptation. Longer ramp times and/or slower flows lead to slower entry of air, consequently enabling the patient to better adapt at the onset of ventilation. Not all ventilators feature programmable ramp slope or flow speed.
 - FiO₂: For ventilators that are not equipped with an oxygen blender, but that do have an oxygen valve (e.g. BiPAP synchrony®, VS Ultra®), the FiO₂ delivered can be determined from the manufacturer's data table. For ventilators in which oxygen is added through the tubing or mask, the FiO₂ can be calculated based on the airflow delivered by the ventilator and the flow of added oxygen. However, it is difficult to achieve FiO₂ > 50% in these ventilators.
 - Respiratory frequency: This parameter is only activated as rescue parameter when the detected respiratory frequency falls below the programmed value. If the programmed value is too close to the patient's actual value, the ventilator could interfere with the patient's respiratory rhythm. The majority of NIV-specific ventilators can not detect the inspiratory efforts of infants, especially those younger than 3 months. This problem can be solved by setting the respiratory frequency and the inspiratory time close to the patient's actual values, in hopes that the child adapts to the programmed rhythm.
 - Inspiratory time (as time or percent): controls the duration of the IPAP in rescue breaths.
 - Alarms for apnea, volume and pressure.
- Bi-level pressure ventilation modes**
- The oldest BiPAP ventilators featured different ventilation modes:
 - CPAP: the ventilator maintains a continuous flow that allows the patient to breathe freely.
 - Spontaneous (S) mode: equivalent to pressure support with constant flow; The ventilator maintains a CPAP (EPAP) until the patient draws in, at which point it switches to a pressure support (IPAP). The frequency and duration of the inspiration are controlled by the patient. The patient triggers all inspirations, and the ventilator helps the patient with each breath.
 - Spontaneous/timed (S/T) mode: the ventilator acts as pressure support for the patient's

spontaneous breaths. If the patient does not trigger a minimum number of respirations, then the ventilator runs a cycle comprising an IPAP, an inspiratory time and an EPAP at a programmed frequency. S/T is the most widely used bi-level mode for both acute respiratory failure (ARF) and chronic respiratory failure (CRF) patients.

- Timed (T) mode: the ventilator delivers a programmed number of breaths regardless of the patient's respiratory efforts. The authors of this chapter believe that this mode should only be used if the ventilator can not detect the patient's breaths, as commented above.
- The latest NIV models and conventional ventilators with NIV option only feature two modes: CPAP and an S/T mode, which guarantee a minimum number of respirations if the respiratory frequency falls below a preset value. For spontaneous breathing, pressure support is delivered until the IPAP is reached.

Indications

S/T mode tends to be the preferred bi-level mode for initiating NIV in nearly all cases; however, certain pathologies can initially be treated with CPAP (e.g. acute pulmonary edema [APE]).

Advantages

- For invasive ventilators S/T bi-level modes generally provide better adaptation than volume-controlled or pressure-controlled methods.

Disadvantages

- Some pediatric patients, especially very young (small) children, can not tolerate the flow required to reach the required pressure.
- Certain modes and ventilators can not regulate the pressure ramp.

MIXED VENTILATION MODES

Both conventional and NIV ventilators now often feature mixed mode options for ventilation which is controlled by volume but regulated or cycled by pressure. These mixed modes include average volume assured pressure support (AVAPS), found in the Respiration BiPAP® devices, and Draeger's guaranteed volume (GV).

Principle

In this mode a target V_t is programmed. The ventilator measures the patient's expiratory V_t and then modifies the IPAP breath by breath to reach the target value. This mode can be used with S, S/T or assisted/controlled methods.

Parameters to program

- Target V_t : 200 to 1,500 mL.
- Minimum IPAP: at least 4 cm H₂O above the EPAP.
- Maximum IPAP: up to 30 cm H₂O; The ventilator automatically gradually adjusts the IPAP delivered to the patient between the minimum and maximum values to reach the target V_t . The change in IPAP between breaths is less than 1 cm H₂O.
- EPAP: improve the residual functional capacity (RFC) and oxygenation.
- Inspiratory time (as time or percent).
- Slope of the inspiratory ramp or flow.
- Expiratory tidal volume alarm (can be turned off).

Indications

Older children and adolescents with hypoventilation.

Advantages

- Ensures ventilation with low risk of hypoventilation or hyperventilation.
- Provides better adaptation to the patient.

Disadvantages

- For patients who have major leaks, the expiratory V_t does not accurately reflect the real V_t .
- Given that the minimum programmable V_t is 200 mL, this mode can only be administered to older children.
- There is very little clinical experience with this mode in NIV for adult patients and no experience with pediatric patients.

PROPORTIONAL ASSISTED VENTILATION

Principle

Proportional assisted ventilation (PAV) is a partially synchronized mode in which the ventilator

delivers a variable pressure support and flow which are instantly adjusted according to the patient's respiratory effort.

- The ventilator continuously measures the volume and flow generated by the patient through a pneumotacometer connected to the tubing and then calculates the elasticity and resistance.
- The ventilator administers a pressure and a flow to compensate for the elasticity and resistance. This support is directly proportional to the patient's inspiratory effort.
- The ventilator can amplify the patient's respiratory effort at a preset proportion, without the need for a preset volume or pressure (flow, pressure, and volume are not programmed in PAV). This mode acts as an additional muscle which is controlled by the respiratory effort of the patient, who determines the respiratory frequency and the depth of each breath.
- Just as in PSV, in PAV the patient determines the respiratory pattern (respiratory frequency and inspiratory time), and the patient's effort contributes to the entry of air.

Fundamentals

- In spontaneous breathing the pressure generated by the respiratory muscles serves to overcome the forces of elasticity (E) and resistance (R) in the respiratory system. Elasticity is proportional to the volume of air introduced into the lung (V), whereas resistance is proportional to the flow speed (F). The pressure of the respiratory muscles (P_{musc}) is equal to the product of the elasticity and volume plus the product of resistance and the flow: $P_{\text{musc}} = (E \times V) + (R \times F)$.
- PAV delivers respiratory aid through flow assistance (FA), measured in cm H₂O/L/sec, and volume assistance (VA), measured in cm H₂O/L. In PAV the pressure created by the respiratory muscles is equal to the sum of the elasticity and resistance minus the pressure by the ventilator, such that: $P_{\text{musc}} = V \times (E - VA) + F \times (R - FA)$.

Parameters to program

PAV ventilators offer an array of ventilation options to choose from according to the patient's pathology:

1. Programmed ventilation: all parameters are programmed by the operator.

- Flow assistance (FA) compensates for resistance by increasing the V_t while decreasing the respiratory frequency. The most widely used level for adults is 2 cm H₂O/L/sec (range: 0 to 12 cm H₂O/L/sec).
 - Volume assistance (VA) compensates for elasticity by increasing the V_t while reducing the patient's respiratory effort. 5 cm H₂O/L (range: 0 to 25 cm H₂O/L).
 - Percent assistance (for elasticity and resistance) delivered by the ventilator: 100%, although some devices start at 20% and then increase until reaching the maximum value tolerated by the patient.
 - PEEP: 4 cm H₂O.
 - Maximum pressure.
 - Maximum V_t .
 - Alarms for pressure and volume.
 - Sensitivity: automatically set in the BiPAP Vision®.
2. The operator chooses the patient's respiratory pattern (e.g. normal, obstructive, restrictive or mixed), the percent assistance, the PEEP, the maximum pressure, and the maximum V_t , and the ventilator automatically adapts the assisted flow and assisted volume according to the patient's respiratory effort and the measured elasticity and resistance.

Steps for programming proportional assisted ventilation

The most difficult aspect of PAV is the initial programming, since, theoretically, the elasticity and resistance of the patient's respiratory system should be measured before beginning. If these values are not known, there is a risk of overestimating or underestimating the patient's respiratory needs. However, studying respiratory mechanics in a sedated, non-intubated sedated patient is very complicated. Several methods have been reported for adults, although the majority of these are rather complex—above all, in the critical patient. These measurements are even more difficult to obtain in pediatric patients.

In clinical practice

1. If a respiratory pattern is selected (e.g. normal, obstructive, restrictive or mixed), then the percent assistance is programmed. Some authors

have reported starting at 20% and then gradually increasing every 35 min (to 40, 60, 80, 90 and 95%), until reaching maximum assistance, or until respiratory assistance has improved (i.e. dyspnea and respiratory frequency have both decreased), or until the patient shows signs of intolerance. Others start directly with 80 to 100% assistance.

2. If programmed ventilation is chosen, then the parameters are set as follows:
 - Flow assistance (FA): a starting value of 1 cm H₂O/L/sec is used, and then the value is increased in increments of 1 cm H₂O/L/sec.
 - Volume assistance (VA): a starting value of 2 cm H₂O/L is used, and then the value is increased in increments of 2 cm H₂O/L until excessive pressure is reached (i.e. patient discomfort, leakage and highly extended inspiratory time), at which point the value is decreased until well tolerated by the patient.
 - Some authors have reported use of the following fixed values (which are later adjusted according to the patient's needs): FA of 2 cm H₂O/L/sec and VA of 5 cm H₂O/L.
 - Percent assistance: a starting value of 20 to 30% is used, and then the value is gradually increased as described above.

Adjustments to ventilation assistance

The parameters for ventilation assistance should be adjusted for the clinical scenarios listed below.

- Hypoventilation: the ventilator values for elasticity and resistance should be increased.
- Hyperventilation: the ventilator values for elasticity and resistance should be decreased.
- Hypoxemia: the FiO₂ and/or PEEP should be increased

Indications and efficacy

- PAV has proven utile in both invasive ventilation and NIV for adult ARF and CRF patients.
- The indications of PAV in NIV are the same as PSV: RF due to a disease of the airway or to lung parenchyma. Patients must maintain a normal respiratory frequency and minimum breathing work.
- Owing to the scarce amount of clinical experience with PAV in pediatric patients, no clear pediatric indications have yet been

established. Currently, PAV can be used in cooperative older children for whom elasticity and resistance can be measured and/or in whom the response to changes in FA and VA can be well evaluated.

Comparison with other ventilation modes

Only a few studies comparing the efficacy and side effects of PAV to those of other NIV modes have been published. The majority of these did not find any differences in patient mortality, length of mechanical ventilation, frequency of intubation, or secondary effects. Some authors have reported that for invasive ventilators, PAV requires lower pressure and provides a quicker drop in respiratory frequency than does PSV. Moreover, the flow adjusts better to the patient, providing better tolerance and requiring fewer modifications. Nonetheless, more studies comparing PAV to other NIV modes are needed.

Advantages

- In PAV, the ventilator instantly adapts to the patient's respiratory effort, providing ventilation close to spontaneous breathing, which in turn enables better patient adaptation and comfort.
- PAV can reduce the patient's breathing work using less pressure than do other ventilation modes.

Disadvantages and side effects

- PAV is hard to program at the beginning of ventilation due to the difficulty in measuring elasticity and resistance, especially in critical patients, and above all, in children (the younger the patient, the more difficult the measurement).
- Asynchrony: the phenomenon of escape—whereby the respirator continues delivering airflow even after the patient has completed their inspiration—has been reported in adult patients when an FA of 80% and a VA of 45% were used, despite the fact that these values were lower than the patients' measured resistance and elasticity, respectively. Studies using models have revealed that this problem is due to a lack of expiratory sensitivity (i.e. the ventilator can not detect when the patient has begun expiration). This problem can lead to asynchrony, discomfort and hyperinflation.

- Risk of hypoventilation: PAV generates greater variability of the controlled volume than does PSV. If the patient reduces their respiratory effort by taking shallow breaths, then the ventilator only provides minimal assistance.
- Currently there is almost no clinical experience with pediatric PAV.
- PAV is only available in some invasive ventilators and some NIV ventilators.

INDICATION OF NON-INVASIVE VENTILATION MODES ACCORDING TO PATHOLOGY

Among NIV modes, double pressure modes with continuous flow seem to be the best tolerated by patients. However, there have been very few comparative studies on the efficacy and tolerance of NIV modes, none of which have dealt with pediatric patients.

Chronic respiratory failure

- For adult CRF patients, including those with a heightened condition, assisted/controlled, PSV, S/T and PAV modes have all been shown to improve minute ventilation, respiratory frequency and arterial gas levels. In some cases volume-controlled and pressure-controlled methods have been reported to be better at decreasing respiratory effort than PSV.
- For pediatric CRF patients the NIV mode or method used varies according to the pathology: for cystic fibrosis is most often treated with PSV; restrictive pulmonary disease and central hypoventilation, with volume-controlled methods; and OSA, with CPAP or bi-level pressure ventilation.

Cardiogenic acute pulmonary edema

The most widely used modes for cardiogenic acute pulmonary edema are CPAP and S/T, as they decrease the respiratory frequency, correct respiratory acidosis and improve hemodynamics.

Acute respiratory failure

For adult and pediatric ARF patients, bi-level pressure (S and S/T), assisted/controlled, PSV, and PAV (only studied in adults) have all been shown to improve minute ventilation, reduce respiratory frequency and breathing work and improve blood

gas levels, thereby lowering intubation rates. No study has shown any of these modes to be superior.

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Non-invasive ventilation methodology for acute pediatric pathologies

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This chapter is intended as a guide to non-invasive ventilation (NIV) for acute patients in intensive care. Since the available data on pediatric patients is not strong enough to use as the basis for any clinical guidelines, the authors of this chapter provide certain recommendations drawn from the relevant literature and from their own experience. It should be underscored that NIV for acute patients must always be performed in the ICU by well trained and judicious personnel using the best possible materials.

Careful selection of patients by hospital staff can prevent certain inevitable failures that could lead to higher patient mortality, and consequently, a loss of confidence in NIV. As the indications and contraindications of NIV are described in detail in Chapter 3, herein are presented only those pathologies or clinical scenarios for which NIV has been widely used and has afforded good results.

In the first section of this chapter, therapeutic strategies are outlined according to the latest classification of acute respiratory failure (ARF). Ideally, special cases would have been treated here in detail; however, due to the limited pool of clinical evidence on pediatric patients, this was not possible.

TYPE I ACUTE RESPIRATORY FAILURE

Type I acute respiratory failure (RF) is characterized by V/Q mismatch without alveolar hypoventilation. In pediatric patients it tends to arise

with pneumonia, acute pulmonary edema (APE), chest wall trauma, neonatal respiratory distress syndrome (NRDS) and acute respiratory distress syndrome (ARDS) (Fig. 1).

Indication

Since NIV provides slow physiological improvement, it has limited use for hypoxemic ARF patients; nonetheless, it can prove somewhat effective, especially in cooperative children. NIV is further limited for this pathology because it requires rapid adaptation. However, with sufficiently experienced personnel and the right equipment, NIV can be employed to treat hypoxemic ARF patients, thereby avoiding intubation. In some publications, NIV is not recommended for patients with $\text{PaO}_2/\text{FiO}_2 < 150$.

The authors of this chapter believe that NIV should not be started based on the same arterial blood gas criteria as that used to start conventional mechanical ventilation (CMV) (i.e. $\text{PaO}_2 < 60$ mm Hg and $\text{FiO}_2 0.5$). Indeed, the decision to initiate NIV must be made with more prudence, as this treatment will be preventative, rather than substitutive. The hemoglobin saturation index ($[\text{Sat O}_2]/\text{FiO}_2$) could prove interesting as an alternative basis on which to select patients for whom NIV is indicated; however, it has yet to be validated as a marker in pediatrics.

Early initiation of treatment strategies that optimize oxygenation is especially important for

those pathologies in which oxygen therapy alone does not compensate for the ARF (see Chapter 10; and Chapter 23, Figure 5).

Choosing an interface

For younger pediatric patients, the preferred interface is an oral-nasal mask that adapts well to the patient's face. For adolescent patients, the interface of choice is a full face mask, although good results have been reported for cooperative adolescent patients treated with nasal masks. For infants, medium-sized nasal interfaces (e.g. oral-nasal) can be used (see Chapter 5, Fig. 2). Despite a lack of controlled studies, and based solely on periodic experiences, a helmet interface used with a conventional or specially designed ventilator can be a valid option for pediatric patients. Nasal interfaces can be tried for infants or for cooperative patients over 10 years, as well as for those patients for whom an oral-nasal interface generates too much leakage and/or causes discomfort. Lastly, it should be remembered that for adolescent patients with Type I RF, full face masks can be employed if oral-nasal masks fail.

Choosing a ventilator

The ideal ventilator would be an NIV-specific ventilator equipped with an oxygen blender. If this is not available, then the next choice would be a conventional ventilator with NIV software. Some home ventilators feature an oxygen valve that enables enrichment of the airflow with up to 60 to 80% oxygen, depending on the recommended values for pressure and respiratory frequency (see Chapter 6). In NIV-specific ventilators lacking a blender, oxygen (for patients requiring less than 50%) can be delivered via a T-piece at the patient-end of the tubing. In certain unpublished cases of infants younger than 6 months suffering from bronchiolitis, good results have been obtained with nasal masks and special neonatal ventilators. Conventional ventilators without an NIV option should never be used for Type I ARF patients, as the chances of success are minimal. The only exception to this rule is that in treatment of ARDS, conventional ventilators used with a helmet can deliver a positive end-expiratory pressure (PEEP) of 10 to 12 cm H₂O. This technique has been employed by certain pediatrics groups in Italy.

Table I. Acute respiratory failure

Type I
<ul style="list-style-type: none"> • Pneumonia • Acute pulmonary edema • Chest wall trauma • Acute respiratory distress syndrome • Neonatal respiratory distress syndrome • Bronchiolitis
Type II
<ul style="list-style-type: none"> • Bronchiolitis • Asthmatic status • Obstructive apneas • Central apneas • Neuromuscular diseases <ul style="list-style-type: none"> – Duchenne's disease – Infantile spinal atrophy – Guillain-Barré syndrome – Myasthenia gravis

Programming

NIV-specific ventilators

Start with a continuous positive airway pressure (CPAP) of 4 to 8 cm H₂O, with FiO₂ of 0.5 to 1. If no rapid improvement is observed, then increase the CPAP up to 10 cm H₂O. If this proves insufficient, then spontaneous/timed (S/T) mode should be initiated with the following starting values: inspiratory positive airway pressure (IPAP) of 8 to 10 cm H₂O and expiratory positive airway pressure (EPAP) of 5 to 6 cm H₂O. The IPAP should then be increased in increments of 2 cm H₂O; effective IPAP ranges from 10 to 22 cm H₂O, with the best tolerated values between 10 and 14 cm H₂O. The recommended EPAP is 6 to 8 cm H₂O.

Due to the lack of published pediatric clinical experience with pressure assist ventilation (PAV), this mode is only explained from a theoretical perspective (see Chapter 7, "Non-invasive ventilation modes and methods for children").

Conventional ventilators featuring an NIV option

- CPAP:
 - Recommendations: Use a PEEP of 4 cm H₂O, and then gradually increase up to a maximum of 10 to 12 cm H₂O. Use respiratory frequency

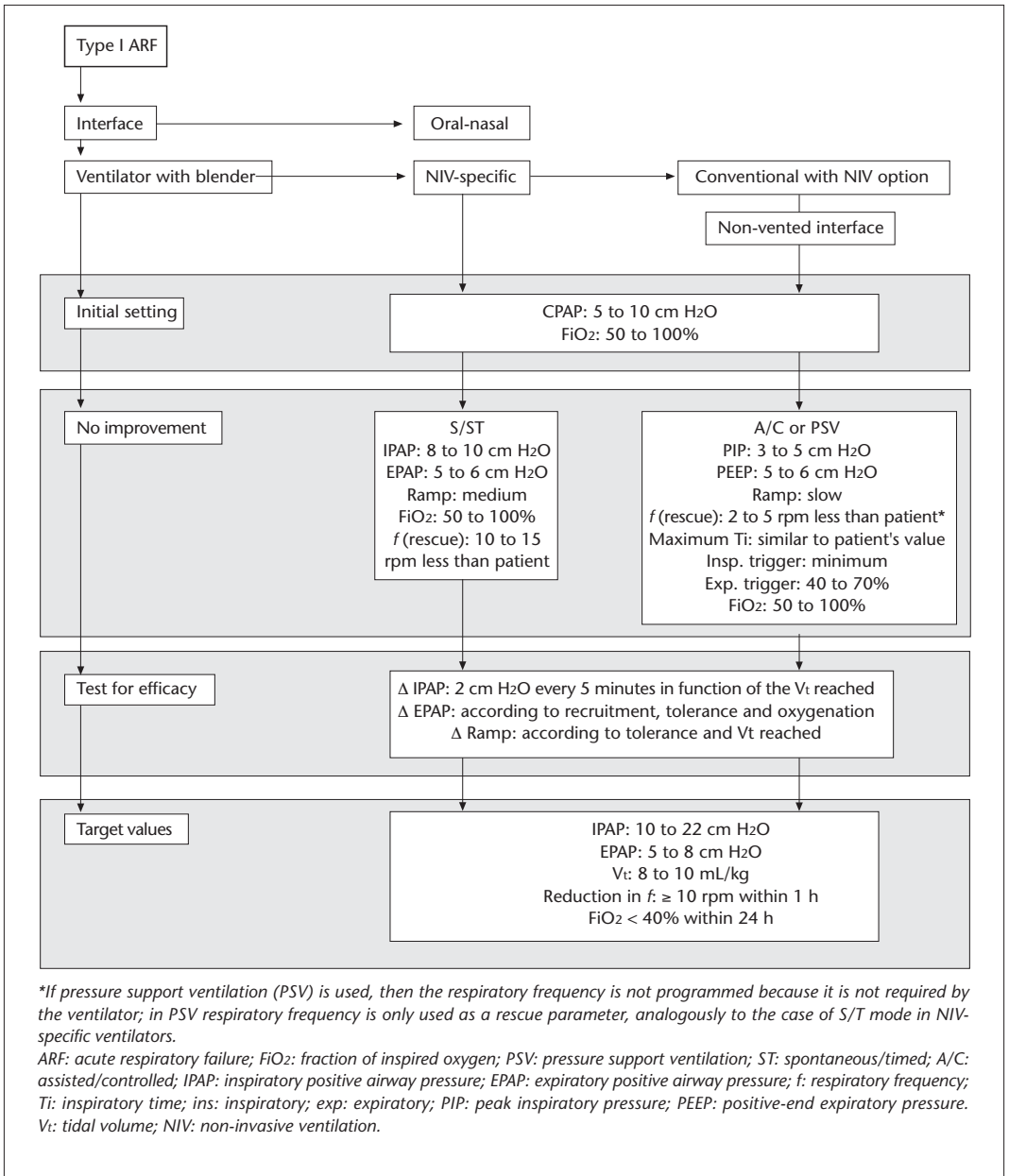


Figure 1. Algorithm for Type I acute respiratory failure (ARF).

- as rescue parameter with an inspiratory time (T_i) < 0.5 sec.
- PSV:
 - Recommendations: Use a PEEP of 4 cm H₂O and a pressure support of 4 cm H₂O (above the PEEP). Set the end of the inspiratory cycle, or the expiratory trigger, to 40 to 70% of the peak flow reached. Use respiratory frequency as rescue parameter for an inspiratory time (T_i) < 0.5 sec.
- Pressure-assisted/controlled ventilation (PACV): If expiratory synchronization can not be achieved, then PACV mode should be used instead, with the respiratory frequency and T_i

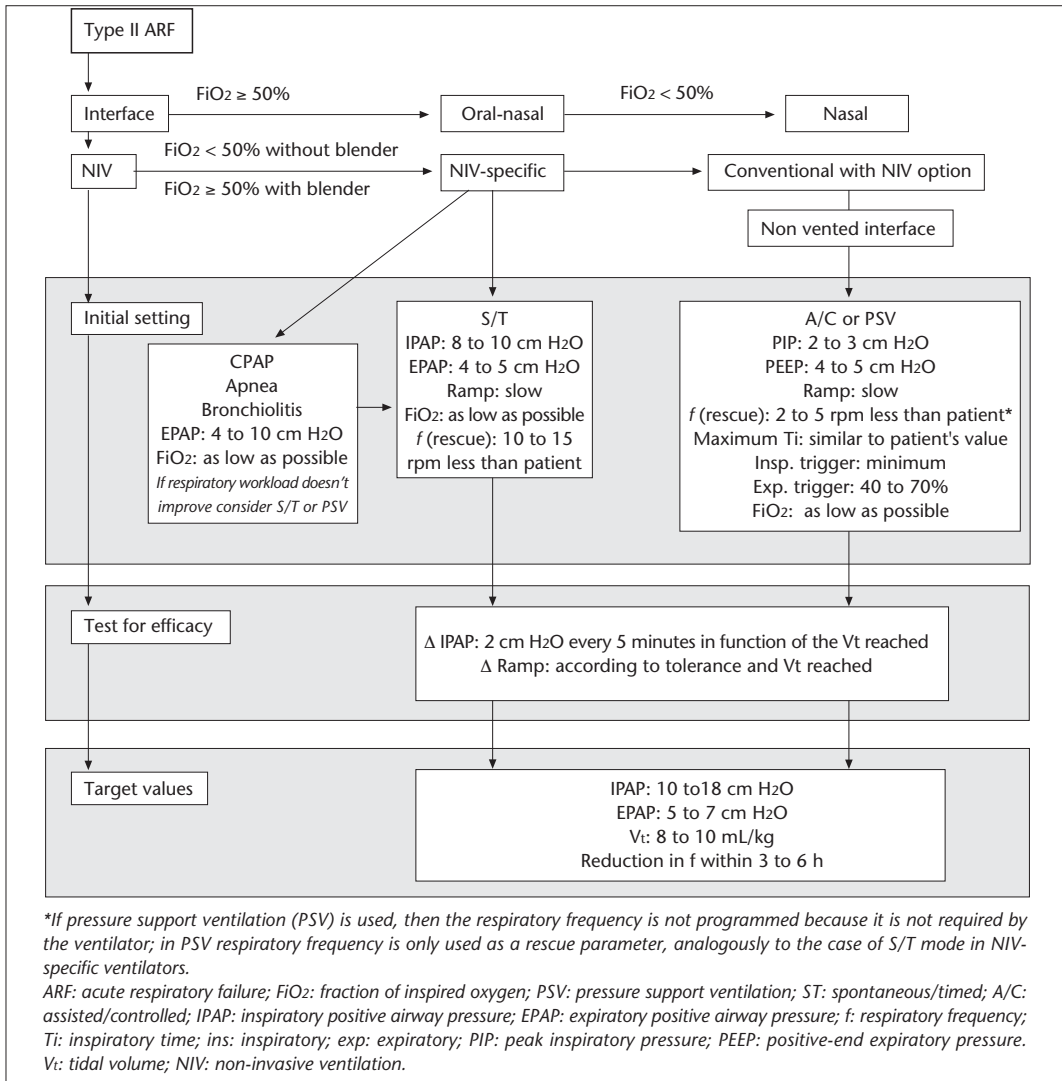


Figure 2. Algorithm for Type II acute respiratory failure (ARF).

adjusted to the values reached spontaneously by the patient. Starting parameters: use a PEEP of 4 cm H₂O, a peak inspiratory pressure (PIP) of 4 cm H₂O, and respiratory frequency and T_i similar to those of the patient.

TYPE II ACUTE RESPIRATORY FAILURE

Type II ARF is characterized by alveolar hypoventilation. It tends to be associated with conditions that affect the respiratory impulse, as well as airway obstruction, neuromuscular weakness,

chest wall abnormalities, and morbid obesity. Oxygen therapy alone is not sufficient to treat Type II ARF; the conditions causing alveolar hypoventilation must be remedied (Fig. 2).

Choosing an interface

Nasal masks are well tolerated but must be adapted to, as the patient has to keep their mouth closed in order to avoid leaks in the circuit. Said adaptation tends to be slow, though it can range from just a few minutes to several days. For patients who are hypoxemic, younger than 6 years, or unable

to fully cooperate, ventilation should be initiated with an oral-nasal interface, preferably one with an expiratory port to minimize dead space.

Choosing a ventilator

The preferred ventilator would be an NIV-specific device that delivers two levels of pressure (IPAP and EPAP) in synch with the patient's breathing.

Programming

Non-invasive-specific ventilators

S/T mode. Due to hypoventilation, ventilation should be started with two levels of pressure, except for in patients with apnea or signs of bronchiolitis.

Starting parameters: Use an IPAP of 8 cm H₂O and an EPAP of 4 cm H₂O; Once the patient tolerates the interface well, raise the IPAP gradually in increments of 2 cm H₂O until reaching 14 to 20 cm H₂O. In patients with atelectasis, the EPAP should be raised to 5 to 7 cm H₂O. FiO₂ is delivered at levels sufficient for maintaining hemoglobin saturation between 92 and 95%. The clearest sign that proper alveolar ventilation has been achieved is a reduction in oxygen demand, since in these patients, hypoxemia is secondary to hypoventilation.

CPAP. Obstructive sleep apnea (OSA) is a Type II ARF etiology which tends to be treated with CPAP, since, once the airway obstruction has been cleared, hypoventilation disappears. Recently, it has been also demonstrated for patients with bronchiolitis.

Starting parameters: Begin with a CPAP of 4 cm H₂O, and then gradually increase the value up to 10 cm H₂O; if this is not sufficient for opening the airway, then switching to an S/T mode or PSV, A/C would probably afford better results.

Conventional ventilators featuring a non-invasive ventilation option

PSV. Recommendations: Use a PEEP of 4 cm H₂O and a pressure support of 4 cm H₂O (above the PEEP). Set the end of the inspiratory cycle, or the expiratory trigger, to 40 to 70% of the peak flow reached. Use respiratory frequency as rescue parameter for an inspiratory time (T_i) < 0.5 sec.

Pressure-assisted/controlled ventilation (PACV). If expiratory synchronization can not be achieved, then (PACV) mode should be used instead, with the respiratory frequency and T_i adjusted to the values

reached spontaneously by the patient. Starting parameters: use a PEEP of 4 cm H₂O, a peak inspiratory pressure (PIP) of 4 cm H₂O, and respiratory frequency and T_i similar to those of the patient.

Conventional ventilators

Conventional ventilators can be programmed in any mode, although PACV with flow trigger is recommended, despite the fact that it does not provide optimal synchronization or compensate for leakage. In this mode, the respiratory frequency is set to 2 to 5 respirations/min (rpm) less than the patient breathes spontaneously. In PSV mode, in which the T_i does not finish until the programmed pressure is reached, leakage extends the T_i, leading to asynchrony and, consequently, failure (see Chapter 7). Conventional ventilators should always be used with interfaces that are non-vented (i.e. that lack an expiratory port) and that do not have an anti-asphyxia valve, since leaks in CMV are not controlled through the tubing or interface (see Chapter 5, Fig. 6).

Regardless, the authors of this chapter believe that CMV should only be used as a last resort, and only in the least severe Type II ARF patients (i.e. oxygen requirement < 50%).

Starting values for parameters:

- Set sensitivity to the minimum; if possible, use flow trigger if it does not lead to autocycling.
- Set the respiratory frequency close to the patient's value and then synchronize.
- Use the same values as those used in conventional ventilators with an NIV option.
- In the event of high leakage, an oxygen flow can be added to the expiratory loop to "trick" the alarms for low minute volume and for apnea (see Chapter 11, Fig. 5).
- The patient may need to be sedated.
- Puede requerirse sedación.

STOPPING NON-INVASIVE VENTILATION

Stopping NIV has not been studied systematically. The majority of publications on NIV recommend maintaining treatment as long as possible in the first 24 hours, and then adding rest periods (e.g. for eating, receiving physical therapy or medication, or bathing) according to clinical

criteria. Some physicians have recommended the following criteria for NIV patients to be given a rest period: respiratory frequency < 24 respirations/min, heart rate < 110 beats/min, hemoglobin saturation > 90% with FiO_2 < 4 L/min, and pH > 7.35.

CRITERIA FOR FAILURE OF NON-INVASIVE VENTILATION

The criteria for failure of NIV must be established before treatment is started. Hospital staff must understand the limits of NIV in their ward according to their own experience and the available materials. The following factors should be considered as signs of NIV failure, especially within the first 4 to 6 hours of treatment:

- No improvement in symptoms (e.g. respiratory frequency).
- Patient-ventilator desynchronization.
- Appearance of contra-indications (e.g. a decrease in consciousness, hemodynamic instability, arrhythmias).
- General deterioration of the patient's condition.
- No improvement in blood gas levels.
- Appearance of complications that are incompatible with NIV (e.g. abundant secretions or severe hypoxemia).
- Decision by the patient's parents to end treatment; The option of intubation should be specifically evaluated for each patient. For patients in whom NIV proves ineffective and for whom intubation was ruled out early on, alternative therapies should be sought.

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Caring for non-invasive ventilation patients

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INTRODUCTION

Thanks to its efficacy, rapid application, ease of use, flexibility, and comfort for patients, non-invasive ventilation (NIV) is being increasingly used in the pediatric intensive care unit (PICU). Consequently, hospital staff must have expertise in this technique and be able to resolve any complications that may arise during its use. This chapter provides an overview of patient care in NIV, encompassing ventilation equipment set-up, patient preparation, and troubleshooting.

PREPARATION

Before administering NIV to a patient, hospital personnel must first prepare all of the components of the ventilation system and ready themselves for any complications that could arise during treatment. It is crucial that patients are very closely monitored in the first few hours of NIV to determine its efficacy; hence, hospital staff must anticipate any distractions that would force them to leave the patient unattended.

Hospital staff must anticipate and avoid any circumstance which could interfere with NIV treatment once it has begun. The following points should be considered:

Setting up the equipment

The NIV system must be adapted to the specific ventilator chosen, including its power needs, and all of its components, to which it must be coupled correctly. A basic NIV system comprises the ventilator

body, an anti-bacterial filter, a humidifier, a water trap, tubing, an expiratory valve, and interface with its harness (or other fastening system). The authors of this chapter propose the following set-up sequence:

1. Place the equipment close to the patient, ensuring that the tubing does not limit the patient's mobility or autonomy. Choose a safe, stable location, protected from sunlight or other sources of heat (e.g. heaters, lamps and unfiltered windows) that could heat the ventilator or its components to temperatures above 55 °C.
2. Connect the ventilator to the electrical outlet (or other power source): its Power/On indicators should light up.
3. Attach the (non-hydrophobic) anti-bacterial filter between the ventilator's air outlet and the tubing, ensuring that it can withstand the programmed airflow (the manufacturers of these filters generally specify the minimum and maximum intended flows).
Be sl as rere units PICU)4. Connect the filter to the humidifier; this normally requires a small piece of tubing. Fill the humidifier with distilled water to the level indicated by the manufacturer.
5. Connect the far (ventilator) end of the tubing to the humidifier, and connect the near (patient) end of the tubing to the expiratory valve or interface, according to the models used. If the interface contains an expiratory valve, ensure that the outlet capacity is not blocked by the patient's clothes or the bed. The

outlet must not be directed at the patient, as the airflow would cause local irritation or discomfort at the site where it was positioned. If a conventional ventilator with NIV option is used, then do not attach an expiratory valve or use ventilated interfaces: these ventilators already contain expiratory tubing or branches that divert expired air, and any leaks from a leak control outlet on an expiratory valve or interface would interfere with ventilator function. If specific tubing is to be used for humidification (i.e. heated tubing which contains an internal filament for insulating heated air to avoid water condensation), then check the connections between the humidifier's temperature sensors and the tubing, as faulty connections could give false readings, delivering air at excessively high or low temperatures that could cause nasal passage burns, and consequently, patient discomfort.

6. If the ventilator has an independent near-end pressure segment, then connect this segment to the specific outlet on the ventilator at one end, and to the pressure intake on the interface or expiratory valve (depending on the models used) at the other end.
7. If the ventilator does not have a specific oxygen intake, then the system can be outfitted with an oxygen T-piece, which enables variable delivery of oxygen into the airflow delivered to the patient. The T-piece should be positioned according to the following factors:
 - If it is placed at the ventilator end, then a more homogeneous airflow will be obtained at the interface, but the FiO_2 will be highly variable, as the oxygen will be diluted by the air inside the tubing.
 - If it is placed at the patient (interface) end, then the FiO_2 will be more stable, but there will major turbulence in the airflow that the patient draws in, which will cause the patient some discomfort.
8. Choose the interface according to the patient's age (size) and pathology and choose the harness according to the shape of the patient's face and the ventilation mode selected (see Chapters 5 and 6). Use of more than one interface for each patient is recommended: by alternating between various interfaces that are supported on different

areas of the patient's body, the risk of pressure sores can be reduced.

9. Wash the interface with a liquid soap that is free of conditioners—if unavailable, use a detergent which is free of ammonia and chlorine. Rinse the interface thoroughly in warm water, and then dry it carefully. Interfaces can normally be used directly without a prior washing step. They must be used exclusively for one patient only, and washed after each use and if the patient vomits or has abundant secretions, in which case the anti-asphyxia and security valves must be checked for correct functioning (e.g. ensure that exhaust ports are open and have the correct diameter).

Once all of the materials have been prepared, the following conditions must be met before starting NIV:

- Ensure that all ventilation equipment works correctly, (e.g. aspirators, oxygen source, humidifier and pulse oximeter). Running the equipment briefly before initiating treatment is recommended.
- Have the following ready for immediate use: an aspiration system (vacuum flow meter, tubing, and container for secretions); a sufficient quantity of sterile, disposable aspiration probes (of the appropriate caliber) for removing vomit or secretions; and a container of water for cleaning the aspiration system after each use.
- Have the following ready and close to the patient: a self-inflating resuscitation bag with its corresponding interface (adjusted to the patient's size and tidal volume) connected to an oxygen source capable of delivering a minimum flow of 10 L/min.
- Ensure that appropriate resuscitation materials and medication are available for each patient.

Preparing the patient

Conditioning the patient (Fig. 1)

The protocol for conditioning the patient before beginning NIV treatment should include the following steps:

1. Check that the prescribed treatment corresponds to the patient.
2. Confirm that the patient does not have any contra-indications to NIV.

3. Check the permeability of the patient's airways, aspirating their secretions and removing any objects (e.g. nasal prongs) that could potentially compromise permeability. Pacifiers should not be used in small children who are treated via face mask, since in the event of vomiting, these could become an additional obstacle to removing the vomit. Furthermore, as patients with the most severe forms of acute respiratory failure (ARF) breathe primarily through their mouth, a pacifier could markedly limit their capacity for ventilation. Contrariwise, pacifiers can be extremely useful for controlling pressure in patients treated with nasal interfaces, which leave the mouth free. Specifically, pacifiers tend to improve the basal tone of the muscles that both keep the mouth closed at rest and ensure that it does not easily open upon application of positive pressure to the airway.
4. Check the patient for gastric distention, which is a common side effect in NIV among neuromuscular disease (NMD) patients for whom an IPAP above 15 cm H₂O can overcome the closing pressure of the cardia (approximately 25 cm H₂O in healthy individuals). If there is any doubt as to the patient's ability to control gastric distension secondary to NIV, then treat the patient with an open nasogastric tube.
5. Prevent pressure sores by protecting the zones of the patient's body that will be subject to continuous pressure from the interface or harness straps. The most sensitive areas are listed below according to the source of irritation.
 - Irritation caused by the interface: nasal root, forehead, cheeks (in patients with prominent cheeks), and edges of the cheekbones (in patients with little adipose tissue)
 - Irritation caused by the harness: cheeks, ear pavilions, occipital margin, upper back neck, the chin (in harnesses with a chin strap), plus areas that come into contact with rough surfaces (e.g. seams, Velcro and rigid edges)
 - Irritation caused by tubing rubbing on the patient's body: chest and abdomen.
 - Irritation caused by other materials: special care should be taken with areas that come into contact with nasal-gastric probes or with some other device (e.g. catheter or drain)



Figure 1. Equipment positioned between the patient and the harness can increase the risk of pressure sores.

inserted between the patient's skin and the interface or harness (see Fig. 1).

For use in preventing pressure sores, some manufacturers provide padding (e.g. Microfoam®) with their interfaces. If this is not available, then soft-adhering hydrocolloid strips can be used (Fig. 2). Hospital staff should apply these bandages to cover vulnerable areas of the patient's body at the very onset of ventilation; they should not wait until having observed the initial signs of pressure sores (reddened skin) to act.

The patients should also be given brief pauses from treatment (1 minute per hour) to alleviate pressure, especially on the nasal bridge area. During these breaks, the most sensitive areas should be moisturized and massaged. As previously mentioned, switching between two or more well-adjusted interfaces with different support areas can help minimize localized pressure. Children's faces should be periodically treated with an appropriate moisturizing lotion as well as with hyper-oxygenated oils (e.g. Corpitol and Mepentol, in Spain), which favor vascularization in areas submitted to pressure and can prevent or heal pressure sores up to grade 1. Use of barrier creams is recommended for scratched or damp areas. Lastly, hospital personnel should prevent the tubing from scratching or cutting the child's skin.

6. Ensure that the proper analgesic is administered in each case; this is especially important for patients experiencing chest pain, since they tend to hypoventilate this area. The patient's pain—



Figure 2. Application of hydrocolloid dressings before initiation of non-invasive ventilation.

and subsequently, the efficacy of the analgesic—should be characterized and registered using analog and/or visual scales.

7. Plan occasional rest periods from ventilation during which the patient can be cared for (e.g. fed, bathed, medicated, or attended to for secretions), their sensitive skin areas can be treated, interfaces can be alternated, and ventilator equipment can be repositioned, cleaned or otherwise maintained. These pauses are designed to not interfere with ventilation therapy. Various criteria have been proposed for these periods: some authors have recommended 20 to 30 minutes every 4 to 6 hours, some have recommended 5 to 15 minutes every 3 to 6 hours, and some have recommended adjusting the pauses to each patient's tolerance.
8. For NIV administered in the PICU or similar ward, patients often must be mildly sedated via continuous infusion during the initial phases of treatment.

Accommodating the patient

Once the patient has been conditioned, they must be properly accommodated: the recommended position, when possible, is for the patient to be seated at a 45° angle, with their legs bent and their popliteal space supported. This enables relaxation of the abdominal muscles and allows broader diaphragmatic movements using less force (see Fig. 3). This initial posture can be supplemented with auxiliary positions such as:

- Both axillae supported to relieve the chest wall and spinal column of their support load and enable broader costal movement



Figure 3. The patient's posture must be corrected to favor respiratory movements.

- Both sides of the face cushioned to secure the head in a neutral position
- Cervical region of the spinal column supported by cushions or a pillow to prevent the neck from bending over the chest wall (since excessive spinal extension can compromise the opening and permeability of the airway, especially in small children).
- Lumbar region of the spinal column supported to favor lordosis and prevent the chest wall from sagging over the abdomen, thereby enabling broader diaphragmatic movements

The aforementioned positions provide the patient with the greatest comfort and respiratory efficacy possible in the context of their pathology. A comfortable patient will always be more willing to cooperate with hospital staff. Patients with respiratory sleep disorders suffer from more apneas in the supine position; hence, it is recommended that they adopt the lateral semi-supine position. In this case, for small children or those who tend to adopt other positions, an object (free of sharp edges) can be placed behind the patient's back, such that the supine position becomes uncomfortable, and consequently, they gravitate towards the semi-supine position. When positioning the patient, especially very young children, hospital staff should anticipate the possibility of the patient falling by using safety rails or similar equipment.

Educating the patient and their caretakers

The patient and their caretakers should be familiarized with the maneuvers required to prevent complications inherent to NIV and acquire good habits to this end. These include:

- Optimizing breathing work: Due to the elasticity of their chest wall, infants and small children

tend to take abdominal or diaphragmatic breaths, which are the most effective. As patients age, they gradually shift to costal respiration, which is less effective and consumes more energy. Since NIV patients remain conscious during treatment, they should be taught how to make proper respiratory movements through diaphragmatic breathing and forced expiration exercises in which they must optimize respiratory efficacy. However, it is difficult for critical patients to be receptive to breathing instructions; hence, hospital staff must wait until these patients are in the proper physical and physiological state to modify their respiratory behavior.

- **Effective cough:** One of the advantages of NIV is that it enables children to maintain their reflex and ability to cough. However, patients often use short, weak coughs (which are not very effective). Hence, hospital staff should teach these patients how to cough correctly, using exercises for forced inspiration, laryngeal occlusion, and contraction of the diaphragm in synch with glottal relaxation. Neuromuscular disease (NMD) patients require assisted cough (either manual or automatic).
- **Preventing and relieving gastric distension and its consequences:** Application of positive pressure to the airway can cause gastric distension, which in turn can lead to vomiting and regurgitation. Discontinuous NIV treatment should not start until at least 1 hour after the patient's last meal. There is less risk of compromising the airway with vomit when nasal interfaces or tubes are used, as the mouth is not blocked. Children who require uninterrupted NIV can be taught to detect their own gastric distension and to control it through burping. The patient and their caregivers must be advised of the possibility of vomiting and how to respond if it occurs (they should have towels or swabs on hand, plus a container for the vomit). Patients treated with oral-nasal interfaces must be taught how to quickly and correctly remove these; this will provide them with a greater sense of control over the situation and reduce their fear.
- **Maintaining the seal on the interface:** The patient and their caregivers must understand the importance of maintaining a proper seal between the mask and the skin to avoid leakage. For the

patient to collaborate, they must be taught how to properly adjust the straps on the interface and how to avoid dragging the mask or tubing. The patient may need to use a safety strap to affix the tubing to their clothes in order to minimize any problems with the interface.

- **Valsalva's maneuvers:** these are designed to keep the Eustachian tubes and sinus drainage areas permeable in order to prevent otitis and sinusitis. With these movements, the Eustachian tubes retain their ability to balance pressure between the middle ear and the oropharynx. There are two main exercises:
 1. Keeping their mouth closed and nose pinched, the patient expels air towards the nostrils, increasing the pressure from the oropharynx until feeling that the Eustachian tubes have opened (the patient will feel their ears click), thereby allowing air to enter into the middle ear.
 2. Keeping their mouth closed and nose pinched, the patient swallows saliva; upon traveling towards the esophagus, the bolus will produce a negative pressure in the oropharynx, which in turn will cause the tubes to reopen (and compensate for the difference in pressure).

Getting the patient involved in their own treatment

This is achieved by honing the structural, technical and human elements that surround the patient. By ensuring that the child does not perceive the therapy as dangerous or strange, hospital staff will make the child feel comfortable and gain their cooperation. This can be accomplished by addressing the following points:

- **Minimizing sources of stress around the child:** Both hospital and home NIV require surroundings in which the patient feels calm and comfortable. This enables objective evaluation of the efficacy of the treatment. The most frequent complication in NIV—and one of the main causes of treatment failure—is a lack of patient adaptation due to agitation or disordered, ineffective breathing. These problems can be drastically reduced by creating the right environment—namely, by minimizing the volume and number of alarms or of any

unnecessary sounds; moderating the volume and content of conversations held around the patient; lighting the area in function of the child's activity level (i.e. intense light for activities, soft light for resting, and near or total darkness for sleeping); carefully decorating the room; respecting and facilitating the patient's intimacy and modesty; and providing the child with age-appropriate activities such as games (see Fig. 4).

- Fostering confidence in the efficacy of NIV: Patients, especially those who suffer from chronic conditions with episodes of ARF, and their caregivers are skeptical of any treatment that they are not familiar with. Educating patients and their caregivers on NIV can reduce their anxiety and foment success of the treatment.
- Gaining the trust of the patient: Upon meeting the patient for the first time, hospital staff should be amiable, not make any sudden movements, look directly at the patient when speaking, focusing on an imaginary point just above their eyes, try to bring themselves to the patient's height, and use a moderate tone of voice, avoiding major fluctuations. Doctors and nurses should introduce themselves by name, state their treatment objectives, ask the patient their name, and refer to the patient by their name. Once an initial feeling of trust has been established, hospital staff should have greater physical contact with the patient.
- Encourage patient cooperation by using rewards and supportive behavior and phrases.

Clinical evaluation before treatment

It is imperative that the patient is clinically evaluated before being treated with NIV, in order to assess the specific consequences of the treatment for them. Said evaluation encompasses two main areas:

1. Monitoring and recording of vital signs: heart rate, respiratory frequency, oxygen saturation, blood pressure, and venous or arterial blood gas levels.
2. Evaluation and recording, for subsequent follow-up, of:
 - Pain (location, and intensity according to scales).
 - Permeability of airways (based on the presence, quantity, consistency and appearance of nasal, oral and tracheal secretions).



Figure 4. Making the patient as comfortable as possible, and minimizing their causes of stress, will make them more cooperative.

- Respiratory state (cyanosis, dyspnea, or signs of increased work of breathing, such as paradoxical breathing, use of accessory abdominal muscles, sagging of the xyphoid process and flaring of the nostrils), including existence and efficacy of cough.
- Mental state (agitation, anxiety, depression, confusion, and ability to cooperate).
- Diameter of the abdomen and occurrence of vomiting.
- Dermatological state (existence, location and grade of skin sores, and level of topical and systemic hydration); Scales such as the Bramen scale are useful for gauging the susceptibility of the patient's skin to scores. These are based on a broad range of factors, including the patient's level of mobility, activity, perception, local and general skin hydration, and nutrition.
- Signs of conjunctivitis and of otitis.

INITIATING NIV

When starting NIV, the following steps should be followed:

1. Attach the cap or harness evenly, such that once interface is connected, it will remain well-positioned on the patient's face or head and will not shift to one side. Care should be taken to avoid that the labels and other sharp parts of the straps do not come into direct contact with the patient. In the smallest children (neonates and infants) a crown-type harness should be used to avoid excessive pressure on the occipital zone and the upper neck in order to prevent vascular complications.

2. Start the ventilator, and if required, connect it to an oxygen source and start the humidifier.
 3. Connect the chosen interface to the tubing and begin ventilation. Air should begin to flow through the interface, causing a noise that could frighten the patient; assure them that everything is fine.
 4. Attach the interface to the patient's face. Whenever possible, the patient should attach the interface themselves, using the pressure required to obtain a good seal, allowing a certain level of air leakage if needed. This way, the patient will gradually become accustomed to the interface and its effects, overcome any fear or anxiety, and better adapt to the system. Alternatively, NIV treatment can be begun by first attaching the interface to the patient's face, and then starting the ventilator. However, this second method is more difficult for patients with major dyspnea, anxiety or agitation, since, depending on the expertise of personal attending them, they may desaturate. This can be prevented by introducing a flow of oxygen at the point where the interface connects to the tubing. This method is advantageous, as it provides for better attachment of the interface, obviating subsequent repositioning and resealing. Moreover, during adaptation patients do not have to experience the bothersome leak compensation that occurs in the first method, which can annoy them to the point that they initially reject NIV. When warned, interfaces that have silicone gel seal strips afford better adaptation to the patient's face and better sealing. Warming can be accomplished by running the interface under hot water; this liquefies the gel, making it more malleable. Once the interface reaches a suitable temperature, it can then be delicately positioned on the patient's face.
 5. Once the interface has been optimally adapted to the patient's face, attach it to the patient using the straps on the harness or cap. Care should be taken to ensure that the support areas on the interface remain positioned on the patient's protected areas (i.e. against skin sores). Interfaces should not be attached too tightly: there should be enough room for two fingers to fit between the straps and the patient. The optimal fit will provide the best seal with the least tension. For oral-nasal masks, the best fit is obtained by first adjusting the lower part of the mask to the patient's chin, and then adjusting the upper (nostril area) part using the frontal straps; in the reverse order, the masks tends to place too much pressure on the nostril area and leak through the chin area. The mask should be adjusted to be well centered on the patient's face, and supported on the aforementioned protected areas, and to reduce leakage in the system. It is crucial that the nostrils, nasal bridge and forehead remain well protected. It should be remembered that when nasal or oral-nasal interfaces are used for infants, there is a tendency to place too much support on the frontal cushion; this gives the interface an exaggerated incline which causes leakage in the lower portion.
 6. Gradually adjust the ventilation parameters until obtaining a suitable reduction in breathing work and improved vital signs. Pennock et al. have reported that effective adaptation can be achieved within 15 to 30 min of patient-interface interaction under strict supervision by hospital staff. The authors of this chapter have learned from experience that this initial period of ventilation is fundamental for deciding whether the patient should continue receiving the treatment or should be switched to conventional mechanical ventilation (CMV). The level of patient care can be somewhat reduced after said period; however, the patient should remain under strict vigilance for the first 12 hours, which is a crucial window of time for adaptation and for monitoring any side effects. This level of vigilance should be extended, and may need to be held permanently, for patients with pathologies that imply an especially high risk of complications such as cardiorespiratory instability or difficulty in sedation (e.g. infants with severe ARF secondary to bronchiolitis).
- Patients are considered to respond well to NIV if they exhibit the following: good adaptation, improved respiratory and mental states, reduction or elimination in breathing work and in dyspnea, and no signs of gastric distension. Blood gas levels take longer to correct, and therefore, should not be used as criteria for determining the success of NIV before at least 1 hour of treatment (see Chapters 13

and 23). Acidosis and hypercapnia may require several hours to correct.

Hospital staff should act according to the following guidelines for providing successful treatment and avoiding any related complications:

1. Ensure that airways are permeable by aspirating and humidifying secretions as often as needed.
2. Protect and monitor areas of the patient's skin that are susceptible to irritation from pressure or scraping (from the interface or tubing) to avoid skin sores or cuts.
3. Protect the patient's eyes from the effects of leakage from the interface; prevent conjunctivitis by using eye drops and ointments if needed.
4. Monitor functioning of the ventilator and its accessories.
5. Help the patient maintain the best posture for their needs.
6. Adjust the interface frequently to avoid or correct excessive leakage (one of the main causes of failure in NIV).
7. Monitor and record vital signs: heart rate, respiratory frequency, oxygen saturation, blood pressure, temperature, etc.
8. Avoid contamination of the system by changing the antibacterial filters and washing the interfaces every 24 hours, eliminating condensed moisture in the tubing, and, when required, refilling the water in the humidifier using all required protocols for sterility.
9. Watch for signs of gastric distension by listening for borborygmus with a stethoscope in the patient's epigastric region and monitoring any increase in abdominal diameter. If needed, insert a nasogastric tube to reduce the patient's gastric tension.
10. Prevent otitis by periodically hydrating the nostrils with an isotonic saline solution and aspirating the secretions, frequently providing the patient with liquids in small quantities, and encouraging the patient to perform Valsalva's maneuvers.
11. Ensure that the patient maintains adequate bodily hygiene by bathing them at least once a day with warm water and mild soap. For young children, use age-specific products.
12. Feed each patient according to their specific needs, including their recommended pauses in NIV. During flare-ups of respiratory failure,

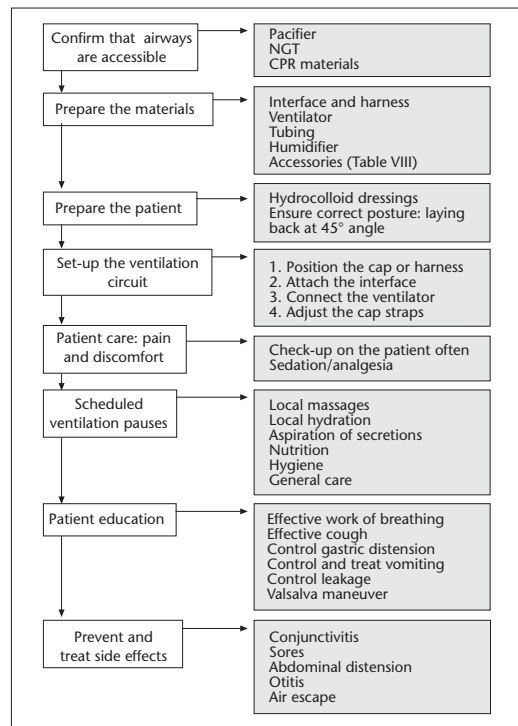


Figure 5. Algorithm for patient care in non-invasive ventilation (NGT: nasogastric tube; CPR: cardiopulmonary resuscitation).

- continuous enteral feeding (if possible, transpyloric) is recommended. More-stable patients can be fed frequently with small quantities of easy to swallow, energy-rich foods.
 13. Ensure that the patient is involved in their care and participates in their treatment.
 14. Make the patient as comfortable as possible.
 15. Ensure that the proper medication and treatment are provided to each patient.
- Patient care in non-invasive ventilation is summarized in the algorithm shown in Figure 5.

HOME CARE

Transferring an NIV patient from the hospital to their home requires the contributions of all members of the multi-disciplinary NIV team. Nurses, technicians and therapists have an especially important role here, both in the hospital as well as in primary care teams at community health clinics. In the hospital, their primary tasks are to teach patients and their caregivers, as well

as other NIV team members, and to develop a treatment plan specific for each child and each ventilation system. Outside of the hospital, nurses have several duties:

1. Evaluate the area where the patient is to be treated and the individualized treatment plan developed for each patient according to the following factors:
 - Accessibility of the patient's home to emergency and support personnel and equipment.
 - Availability of private and public transport (from home to hospital).
 - Proximity of the patient's home to emergency services (i.e. response time).
 - Hygienic conditions in the home: cleanliness, ventilation, light, temperature, and facilities for personal hygiene. Since home NIV treatment aims to help patients reintegrate into society, it is important to avoid creating a hospital-like environment in the patient's house.
 - Quality and power capacity of the electrical installations in the patient's home (e.g. fuse boxes).
 - Availability of public health resources for the patient: medical care at school, social security and social services
 - Level of competence of the patient's caregivers.
2. Oversee an individualized plan for each patient that comprises:
 - Detailed pharmaceutical prescriptions and an outline of the course of treatment, written in clear language for the patient and their family and caregivers
 - Training for the patient's family or caregivers in the treatment protocol, including maintenance of the ventilation equipment used.

CONCLUSIONS

There is no doubt as to the benefits of NIV for the patient, their family, health services and the public. Hospital personnel must accept their role in starting NIV treatment with decisiveness and clarity, basing their clinical practice on technical expertise, experience and constant learning.

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Monitoring of non-invasive ventilation for pediatric patients

M.Á. García Teresa, R. Porto Abal, P. Fernández Deschamps

The aim of non-invasive ventilation (NIV) is to aid the patient's pulmonary function and to improve any symptoms, signs or blood gas alterations resulting from respiratory failure (RF). Monitoring of NIV comprises tracking of various parameters in the patient (e.g. clinical, analytical and functional) and in the ventilator to evaluate the treatment as early as possible to determine if it should be continued, modified or stopped. The techniques and frequency of monitoring differ between acute respiratory failure (ARF) and chronic respiratory failure (CRF) patients and vary with the severity of the pathology, the location of treatment (i.e. hospital or home), and the time which the patient has been receiving NIV.

MONITORING OF NON-INVASIVE VENTILATION IN ACUTE RESPIRATORY FAILURE PATIENTS

In ARF patients, NIV is used to ameliorate respiratory function without resorting to intubation, by improving symptoms, reducing work of breathing, and improving gas exchange.

Clinical monitoring

This type of observation is crucial for determining the efficacy of NIV. Patients should be monitored continuously, especially in the first 4 to 6 hours of treatment (or more, based on their needs). This demands that hospital personnel remain at the patient's bedside to make any adjustments to the parameters, change the interface or switch the patient to intubation.

First and foremost, hospital staff must determine the level of comfort and adaptation of pediatric patients, as these factors can dictate treatment success. They depend on the type of ventilator, ventilation mode, IPAP and EPAP values, patient-ventilator synchrony, the sensitivity of the ventilator trigger, the type of interface, the pressure that the interface places on the patient's face, and the amount of leakage in the ventilation circuit. The patient's age, pathology, level of cooperation, and personality can also be influential. Any sources of discomfort must be recognized and corrected.

Hospital staff should endeavor to minimize crying and speaking in children treated with nasal masks, since these cause a loss in efficacy of ventilation and an increase in discomfort from leakage, which can worsen the RF. Breathing work and polypnea should be closely watched: NIV should reduce both. Dyspnea should improve, and any use of any accessory muscles in breathing should diminish, within 1 to 2 hours of treatment. Lack of patient-ventilator synchrony can lead to failure of NIV. It is important to remember that neuromuscular disease (NMD) patients, and patients with an altered respiratory center, may not present with dyspnea, despite having severe RF. It should also be remembered that normal respiratory frequency depends on age and that children can tolerate greater tachypnea than adults. Hospital staff should also watch for cyanosis, observe the patient's chest wall mobility, and monitor the patient's level of consciousness as a marker of hypercapnia.

Listening to the patient's chest with a stethoscope is important for checking for adequate entry of air, adjusting the IPAP level and tracking their respiratory pathology.

Constant monitoring of the patient's heart rate and respiratory frequency is mandatory: successful NIV should reduce both, although in many published cases, these could not be used to gauge the efficacy of the treatment. Periodic measurement of blood pressure is required.

Daily chest wall and abdominal radiography could be considered for assessing pulmonary pathology and discard complications.

Gas exchange

Measurement of arterial blood gases (arterial oxygen pressure [PaO₂], arterial carbon dioxide pressure [PaCO₂], and arterial pH) is considered to be the gold standard for evaluating pulmonary gas exchange. However, it is rarely used in pediatric patients that do not have already have an arterial catheter placed, which is often the case in pediatric NIV patients. Repeated puncturing of arteries is painful, and therefore, can cause the patient to cry, which leads to false blood gas readings. Furthermore, arterial puncture can be technically difficult in very young children. Nonetheless, it should be strongly considered for Type I ARF patients when ARDS is suspected (see Chapters 13 and 23).

Oxygenation in these patients is monitored continuously and non-invasively using pulse oximetry. It is absolutely crucial during the first 24 hours of NIV and preferably would be maintained throughout the entire course of treatment. This highly simple technique simultaneously measures oxy-hemoglobin, arterial blood pressure wave and heart rate. Saturation values < 80% are less reliable, but are still clinically useful. Values > 98% may indicate that PaO₂ = 100 mm Hg (in which case hyperoxia would go undetected).

For patients with acute lung injury (ALI) or acute respiratory distress syndrome (ARDS), who are included in the most severe cases of Type I ARD, and a transcutaneous SatO₂ < 98%, the hemoglobin saturation index (SatO₂/FiO₂) has proven utile for valuating the PaO₂/FiO₂ index, using the following formula: $\text{PaO}_2/\text{FiO}_2 = [(\text{SatO}_2/\text{FiO}_2) - 64]/0.84$. This index can be employed to determine the degree of

intrapulmonary shunt before and after NIV treatment, and for ARDS patients, can be used for closer blood gas monitoring to avoid prolonging failed NIV or preventing the patient from becoming contra-indicated (PaO₂/FiO₂ < 150).

Transcutaneous PO₂ can also be measured continuously and non-invasively through an electrode attached to the patient's skin. In hemodynamically stable children this value correlates well with PaO₂. However, this method is typically not employed due to technical difficulties: calibration and attachment of the electrode, warming of the skin, long response time, and the need to frequently reposition the electrode to avoid burning the patient. It is primarily indicated in neonatal pathologies, as it can prevent hyperoxia. It is also useful in infants, children and adolescents.

The success of NIV can be assessed by using capillary PCO₂ obtained from a punctured artery after heating the site of extraction (e.g. heel, earlobe or fingers). This value correlates well with PaCO₂, although it can become bothersome for children if repeated several times in a short period. Although it is not common practice, venous PCO₂ (PvCO₂) measurements can be used; these are easy to obtain, since nearly all children tend to already have a venous catheter placed. PvCO₂ is 5 to 6 mm Hg higher than PaCO₂. Generally, absolute readings are not evaluated, but rather changes in readings, which are caused by NIV or by alterations in the patient's state.

There are two non-invasive techniques for monitoring PCO₂: capnography and transcutaneous PCO₂ measurement.

Capnography continuously measures and records the concentration of CO₂ in exhaled air. For NIV and spontaneous ventilation, sidestream capnographs, which measure outside of the respiratory circuit, should be used. For NIV, a thin piece of tubing is connected to the exhalation port on the mask, from which the exhaled air travels to the capnograph. For spontaneous ventilation, the tubing is attached to the nostrils (analogously to oxygen cannulae) or to the mouth (if the child is breathing through their mouth). The ideal location would be the hypopharynx. Exhaled CO₂ (end-tidal CO₂, or ETCO₂) readings and curves in NIV are often erroneous to due to the constant flow in bi-level pressure (BiPAP) systems or to major leakage. If the



Figure 1. Transcutaneous PCO₂ monitor.

ETCO₂ value increases and the baseline does not reach zero, this is a sign of re-inhalation.

Transcutaneous monitoring of CO₂ has the same advantages and disadvantages as transcutaneous monitoring of PO₂. Measured CO₂ values are higher than those for PaCO₂, although in hemodynamically stable patients these two parameters correlate strongly (see Fig. 1).

Monitoring of acid-base equilibrium: In some reports on adult patients, the patient's blood pH at 2 hours of NIV is used as a predictive factor for treatment success.

Pulmonary mechanics and monitoring of the ventilator

For patients treated with invasive ventilation, the curves for flow, volume and pressure, and the values for lung compliance and resistance are monitored using pneumotacographs and pressure sensors whose measurements are analyzed by and displayed on the ventilator. Currently, there are commercially available non-invasive ventilators that provide continuous monitoring of pressure, flow and volume curves (Fig. 2). Both conventional and NIV ventilators used in the hospital monitor the estimated tidal volume and minute volume, the peak pressure, percent of breaths initiated by the patient, and leakage level, and feature alarms for apnea, low minute volume and high or low respiratory frequency. Said alarms should be used in function of the patient's age and the treatment objectives.

Monitoring of side effects

Area in which the interface is supported. These areas—above all, the nasal bridge—must be watched with extreme care. Interfaces tend to be attached too tightly, and children often can not vocalize that the interface is hurting them. Children have more sensitive

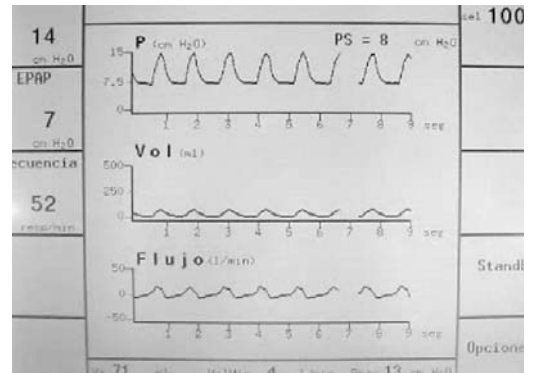


Figure 2. The display of an NIV ventilator showing pressure, flow and volume curves for use in monitoring. This ventilator also measures the estimated expiratory tidal and minute volumes, peak pressure, percentage of breaths initiated by the patient, and leakage.

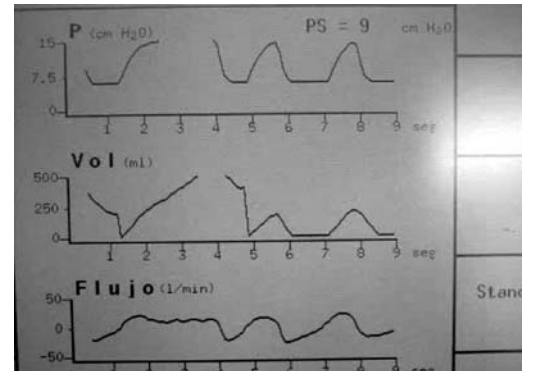


Figure 3. Leakage plotted on an NIV display.

skin than adults: a light rash can develop into a pressure sore within a few days, forcing NIV to be stopped.

Gastric distension. This should be monitored and treated, since it can worsen the patient's respiratory state via restrictive pulmonary compromise. Preventive care using an open nasogastric tube is recommended.

Leakage. Leaks can be observed clinically (i.e. they are felt or heard by the patient or cause the patient's hair to move) or, in certain ventilators, measured (see Fig. 3). A leak rate < 30 L/min is preferable for avoiding pressure sores. The airflow from leaks can cause conjunctivitis by drying out the patient's eyes.

Pneumothorax. This should be monitored in high risk patients (e.g. those with chest wall trauma).

MONITORING OF NON-INVASIVE VENTILATION IN CHRONIC RESPIRATORY FAILURE PATIENTS

In CRF patients, NIV is used to ameliorate symptoms, improve the patient's diurnal and nocturnal blood gas levels, better their quality of life by improving the quality of their sleep, enhance their functional state, reduce the duration of their hospital stay, preserve their pulmonary function and prolong their life.

In some patients, ventilation is begun for flare-ups (usually caused by an infection), whereas for others, it is indicated for gradually worsening CRF.

Monitoring at the beginning of NIV

Clinical observation. As previously explained, the emphasis here is on evaluating the comfort and adaptation of the child. For home NIV patients, this process starts in the hospital and continues at their home. Patient-ventilator synchrony must be observed, as should chest wall movements. The patient's chest wall should be listened to with a stethoscope during entry of air in NIV. As mentioned above, leakage must be closely watched.

Gas exchange. This is measured using continuous pulse oximetry, since for the majority of pediatric CRF patients requiring NIV, hypoxia will be indicative of hypoventilation. ETCO_2 values can also be used, with the same limitations as those explained for PCO_2 : the response time is too slow for detecting temporary periods of hypoventilation; and the transducer signal can be altered by the patient's movements, which requires that the detector be frequently repositioned and recalibrated. Neither arterial nor capillary blood gases are typically measured due to the discomfort that they cause the patient. Alternatively, measurements can be taken from a venous source (treated with anesthetic cream before being punctured): the variations in PCO_2 compared to the baseline throughout the night can be evaluated to determine if the child can tolerate a higher IPAP (if needed).

Blood pH. Respiratory acidosis compensated for by a high level of bicarbonate is indicative of chronic hypoventilation.

Monitoring of NIV side effects. As previously mentioned, the highest priority here is protecting the nasal bridge from pressure sores.

Monitoring of patients at home

Organization

Patients receiving home NIV must also be monitored for adaptation, ventilation efficacy and side effects. Indeed, the home ventilation set-up typically includes pulse oximetry and oxygen therapy. Hence, before the patient is sent home from the hospital, their parents should be taught basic monitoring skills.

Close monitoring of patients is crucial to the success of NIV. Their parents must have 24 hour telephone access to hospital staff to call for assistance. The technician from the home ventilation company should visit the patients at their home several times during the first few weeks of treatment and should advise the patient's physician of any problems that they detect.

Monitoring in the hospital can be done on an outpatient or inpatient (one night) basis, according to the patient's needs. The patient can make their first visit to the hospital 4 to 6 after having been released from the hospital, plus additional visits as needed. Once the patient has been stabilized, they can be examined with less frequency; depending on the pathology, they should visit the hospital two to four times annually. The patient's nocturnal pulse oximetry should be recorded at home, and based on the results they should be evaluated for hospital admission to make adjustments to their ventilation.

Monitoring should be especially vigilant for infants and small children (15 days after having been released from the hospital, and then monthly during their first year of life), as these patients require periodic adjustments to their ventilator and mask.

Pediatric patients often present with complications associated with NIV and consequently, require multidisciplinary care (e.g. cardiology, pulmonology, neurology, rehabilitation, nutrition and traumatology). Hence, their appointments with different specialists should be coordinated.

Methodology

Improving symptoms and signs

The patient should be monitored for improvements in or resolution of symptoms which are signs of successful NIV. Adolescents present with the same symptoms as adults (morning headache, difficulty concentrating, enuresis, severe exhaustion, and

hypersomnolence) and may suffer from dyspnea. Very young children tend to show irritability, psychomotor delay, low academic performance, enuresis, malnutrition, and poor sleep, in which they often wake up from nightmares. They may present with somnolence or show signs of pulmonary hypertension or cor pulmonale (e.g. hepatomegaly or edemas).

Improved or normalized lung pressure, as determined by echocardiography, and gaining of weight are both indicative of NIV success.

Gas exchange

Gas exchange should be measured diurnally and nocturnally to determine the effects of NIV. For adult NMD or kyphoscoliosis patients, effective NIV provides major improvements in diurnal PaO₂ and PaCO₂.

Oxygenation is evaluated using pulse oximetry while the patient is awake as well as when they are asleep. Appearance of desaturation during NIV may be due to persistent hypoventilation, intermittent airway obstruction, excessive leakage (due to mask adjustments), or patient-ventilator asynchrony.

The efficacy of NIV can be gauged by capnography while the patient is not connected to the ventilator. Normalization of diurnal PCO₂ is neither required nor desirable in NIV, as it may imply an increase in the IPAP that the child can not tolerate, or extended use of the ventilator, which the child may not accept. No ideal value of PCO₂ has been established, as it varies with each patient. In some children, the symptoms of cor pulmonale may improve, and the signs may disappear, despite the fact they have a PCO₂ of 50 to 60 mm Hg.

In order to achieve normoventilation in children with central sleep hypoventilation—whether idiopathic (e.g. Ondine's Curse) or secondary (e.g. Arnold Chiari malformation, medullar lesion, etc.)—gas exchange must be measured while the patient is sleeping.

Quality of life of the patient and their family

Hospital staff should assess the quality of life of the patient and their family by asking them specific questions on health (nutrition, infections, and hospital admissions), functionality, autonomy, academic progress, socialization and activities (e.g. playing, or doing sports). The quality of the patient's sleep can be indirectly determined by gauging improvements

in symptoms or via nocturnal pulse oximetry or polygraphy at home. Full polysomnography is not a routine monitoring technique: it is very expensive, only available at a few centers and in high demand. However, some authors have reported using it to adjust ventilation in complicated cases.

Pulmonary function

Patients should be monitored by spirometry as often as needed according to their age, level of cooperation, pathology, and rate of respiratory deterioration. NMD patients with vital capacity < 40% of the theoretical value may begin to retain CO₂; if their condition worsens despite treatment, then they should be ventilated for longer periods.

Side effects and complications

In addition to the side effects and complications described in this and other chapters, long-term ventilation patients should be observed for possible facial bone deformities, and those treated with oral interfaces should be monitored for dental damage.

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Complications and technical difficulties in non-invasive ventilation

M. Pons, M. Balaguer

COMPLICATIONS

Complications in non-invasive ventilation (NIV) are defined here as any adverse effect in the patient which arises after treatment has begun and which can be attributed exclusively to the treatment.

EPIDEMIOLOGY

Reported rates of complications in adult patients range from 10 to 20%. The most frequent complication is skin necrosis where the interface is supported, which accounts for 70% of all complications. Gastric distension, pneumothorax and aspiration each do not occur in more than 3% of NIV patients. The findings of the EPIVENIP epidemiological study, performed in Spanish pediatric intensive care units (PICUs) from 2004 to 2005, correlate well with the aforementioned figures (Fig. 1).

COMPLICATIONS

Complications in NIV can be classified into five groups:

Complications due to the interface

Skin irritation. This occurs in the area where the interface is supported, typically in the nasogenian area. Periodic use of moisturizing creams can help alleviate this irritation.

Skin sores. Until very recently, this was one of the most common problems in patients treated with

continuous NIV. Although the most frequent location is the nasal bridge, skin necrosis can appear at any point in which the interface is supported. The rate of skin necrosis has been markedly reduced through the use of special anti-sore dressings (e.g. Comfeel®). Home NIV patients can be further protected by alternating between different interfaces or by using an Adams-type interface (Fig. 2).

Conjunctivitis. Air leaking out from the sides of masks can cause conjunctivitis and even corneal sores. This can be prevented or treated by adjusting the mask or changing to an interface which better suits the patient's face. Special care should be taken for patients with lagophthalmos (Fig. 3). Some nasal interfaces contain a bubble-like similar to the Comfort Flap™ by Respirationics, which, upon being filled by the inspiratory airflow, molds itself to the patient's face to minimize leakage (Fig. 8, chapter 5).

Airway obstruction. Tracheal tubes used as nasal-pharyngeal interfaces in infants younger than 3 months can obstruct the nostrils if the permeability of the tubes and of the nostrils is not adequately protected; hence, hospital staff should take special care with these patients. Likewise, the inner plastic layer of nasal and oral-nasal interfaces can block the nasal fossa; this can be resolved by trimming the plastic (see Fig. 4).

Maxillar hypoplasia. Home ventilation over several years has been associated with maxillar underdevelopment and secondary malocclusion of the cheekbone.

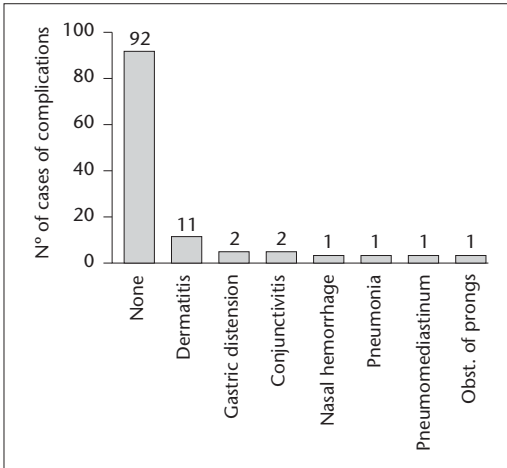


Figure 1. Results of the EPIVENIP study on complications in pediatric non-invasive ventilation.

Hypercapnia. Oral interfaces with large dead space carry a higher risk of hypercapnia, especially for small children with high respiratory frequency. Currently, for small infants, medium sized-nasal interfaces are used as oral-nasal interfaces and provide good results. For the patients described above, or for those with Type II ARF, vented interfaces are preferable to non-vented ones; if these are not available, then a Plateau valve can be used in place of the expiratory valve as a preventative measure.

Complications related to the interface straps, belts or harness

Accidental disconnection. In patients who are highly dependent on ventilatory support, accidental disconnection is as dangerous as accidental extubation: they may suffer from hypoxemia secondary to alveolar derecruitment, plus related problems. Despite not being described in the literature, this is a very real danger.

Axillary vein thrombosis. Helmet interfaces are attached through belts under the armpits, and therefore, imply a risk of thrombosis of the axillary vein. As a preventative measure, some centers attach weights to the belts to minimize the pressure on the axillary zone. Helmets designed for infants feature a special harness that is supported around the diaper area (see Chapter 5, Figure 19).

Basal ischemic lesions. In neonates, interfaces which have been attached too tightly have led to



Figure 2. Adams interface.



Figure 3. Protecting the eyes of a child with lagophthalmos from the effects of air leaks.

ischemic lesions: due to bone plasticity, the excessive pressure from the straps or belts compresses the cerebral basal circulation.

Complications related to pressure in the airway

Inspiratory blockage. This phenomenon is related to a glottal reflex which closes the vocal chords in the event of hypocapnia due to excessive pressure. The increase in resistance in the airway tends to facilitate leakage and patient-ventilator desynchronization. It

is critical to anticipate this complication, which is resolved by lowering the inspiratory peak airway pressure (IPAP).

Gastric distension. This complication tends to arise only when inspiratory pressures > 25 cm H₂O are used; however, in neuromuscular disease (NMD) patients, it can occur with inspiratory pressures < 20 cm H₂O due to the weakness of their diaphragm and lower esophageal sphincter (LES). Gastric distension can be dangerous because it carries a risk of vomiting. In one exceptional case, it was associated to compartmental abdominal syndrome with hemodynamic deterioration; however, the patient was a 65 year old who had refused to accept insertion of a nasogastric tube before beginning NIV.

Food aspiration. There is a risk of vomiting and food aspiration for patients fed orally or via nasogastric tube, especially those treated with a face mask. This risk can be exacerbated by use of sedation to improve patient adaptation; hence, hospital staff should take precautions such as temporarily suspending enteral feeding or intubating the patient with a transpyloric tube.

Pneumothorax. Pneumothorax has been most widely reported in chest wall trauma patients with fractured ribs. However, according to the EPIVENIP study of 2005, it only occurs in less than 1% of all PICU NIV patients (see Fig. 1). Recent studies described a percentage of 3%.

Air embolism. Neurological lesions brought on by air embolism have been described in patients suffering from pneumothorax.

Pulmonary hyperinflation. This can occur in the event of dynamic hyperinflation caused by administering an expiratory positive airway pressure (EPAP) higher than the patient's intrinsic positive-end expiratory pressure (PEEP).

Hemodynamic deterioration. This is rare, but a drop in preload and hypotension, can be detrimental for hemodynamics, especially in hypovolemic patients.

Complications related to humidification

Due to lack of humidification. Humidification of the airflow leads to alteration of the nasal mucosa with blockage of ventilation, leading to a loss of treatment efficacy.

In home-NIV patients with oral leakage, a lack of humidification has been shown to increase nasal

resistance, diminish the tidal volume and cause the patient discomfort.

Lack of humidification can also lead to formation of mucous layers that can facilitate airway obstruction and NIV failure and complicate intubation.

Due to excess humidification. Patients exhibit poor tolerance to conventional mechanical ventilation (CMV) humidifiers when the target temperature is set to 39 °C.

Complications related to NIV indications

The most severe complications in NIV are the result of trying to treat contra-indicated patients; fortunately, this rarely occurs.

In adult ARF patients, a higher mortality rate has been observed for those that first undergo a trial period of NIV before being intubated than for those that start with CMV. In adult patients with acute pulmonary edema (APE) of cardiac origin, a higher rate of heart attacks has been observed for those who are treated with NIV than for those who are only treated with continuous positive airway pressure (CPAP).

In NIV patients who have had recent esophageal or gastric surgery, dehiscence is a potential complication. Nonetheless, some authors recommend use of NIV for morbidly obese patients that have had gastropasty, since these patients have an elevated risk of respiratory complications in the postoperative period.

Esophageal-pleural fistula has been described in an NMD patient that had suffered a spontaneous esophageal rupture secondary to Boerhaave's syndrome three years before beginning home NIV treatment.

Orbital herniation has been described in a few patients with ethmoidal fractures. It should be reiterated that facial fractures are a contra-indication to NIV.

TECHNICAL PROBLEMS

Non-invasive ventilation using a conventional ventilator

This is rarely used today. Technical problems with this method are due to the fact these ventilators are not designed to handle strong leakage (which is intrinsic to NIV).



Figure 4. Profile Lite interface modified for use as an oral-nasal interface by trimming its internal membrane.



Figure 5. Connecting an external oxygen flow to the expiratory end of the ventilator.

Expiratory volume alarm

Backflow of expiratory gas in the tubing is minimal; hence, this alarm should either be set to the minimum or turned off. In ventilators in which the alarm can not be shut off, an external airflow or oxygen flow can be added to the expiratory end of the tubing to prevent the alarm from sounding (see Fig. 5).

Autocycling

Non-compensated leaks in the ventilator cause a drop in flow that the ventilator erroneously interprets as inspirations, leading to autocycling. If the leaks can not be improved by adjusting the interface, then the inspiratory trigger should be set to the minimum to prevent it from inadvertently going off.

Opening of the anti-asphyxia valve

Oral-nasal interfaces from certain manufacturers (e.g. Respironics and Hans Rudolph) feature an anti-asphyxia valve which serves as a security mechanism when the ventilation system loses pressure. One of the consequences of non-compensated leaks is that the PEEP can not be maintained, which then causes the anti-asphyxia valve to open. Albeit this problem can be minimized by increasing the PEEP, the best solution is to avoid using these interfaces with conventional ventilators.

Desynchronization

Many conventional ventilators lack an adjustable expiratory trigger, which implies that active work is

needed to start expiration: the patient must fight against the ventilator, causing them greater exhaustion instead of relaxation. For these ventilators, synchrony can be improved by shortening the inspiratory time.

Desynchronization can also occur if the ventilator fails to detect the patient's inspiratory efforts, as is often the case with small infants or with ventilators that lack a flow trigger. In these scenarios, the best mode to use is pressure assisted/controlled ventilation (PACV), using a respiratory frequency similar to the patient's spontaneous respiratory frequency.

Lastly, desynchronization can also arise if the patient's airway is blocked with secretions that they can not expel; hence, they must be checked for this possibility.

In conventional ventilators that feature an NIV option, adjustment of the expiratory trigger often enables optimum synchronization; in those that lack this option, the best strategy is to use modes equivalent to PACV.

Non-invasive ventilation using a non-invasive-specific ventilator

Despite providing better support for leakage than conventional ventilators, NIV-specific ventilators still have their drawbacks.

Oxygen therapy

For models that lack an oxygen blender or an oxygen input valve (e.g. VPAP II, BiPAP S/T and BiPAP Harmony), the airflow delivered to the patient must

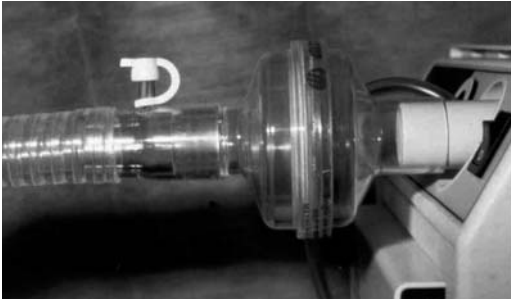


Figure 6. Oxygen T-piece for enriching the ventilator airflow with oxygen.

be enriched with oxygen either through the tubing or through one of the inlets available on the interface. The maximum FiO_2 possible with this method is 0.5. Some newer models (BiPAP Synchrony, VPAP III, VsUltra, and Legendair) feature an oxygen input valve. For these models, the maximum FiO_2 possible is 0.8; the FiO_2 can be calculated based on data tables provided by the manufacturers.

Positioning an oxygen T-piece close to the ventilator-end of the tubing minimizes turbulence but provides a lower concentration of oxygen. Contrariwise, positioning the T-piece at the interface-end will provide a greater FiO_2 but greater turbulence. If the patient's hypoxemia can not be compensated for by this type of oxygen input, then either a ventilator equipped with an oxygen blender or a conventional ventilator should be used.

Hypercapnia

Using a single arm circuit facilitates re-inhalation of CO_2 , above all in patients with tachypnea. Using an EPAP of at least 4 cm H_2O allows exhaled air to be forced out of the leak-control area. If this proves insufficient, then the EPAP can be increased to up to 8 cm H_2O ; or the fragment of tubing in which the expiratory valve is located can be cut, and then replaced with a Plateau valve (see Chapter 13, Figs. 2 and 3). Some authors have recommended adding an oxygen flow of 4 to 6 L/min into the interface or near the expiratory valve to diminish re-inhalation of CO_2 . Alternatively, hospital staff can switch to an interface which has less dead space or which features exhalation ports, provided that the patient adapts to it. All of the aforementioned methods should be considered, keeping in mind that the tidal volume

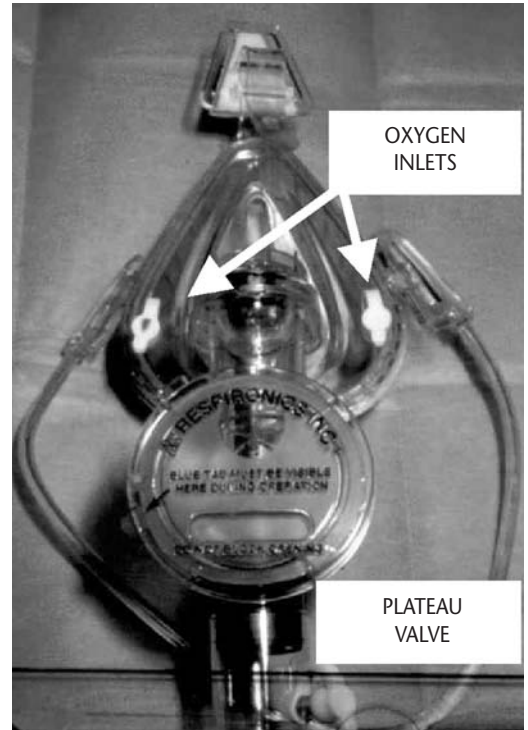


Figure 7. Plateau valve.

administered to the patient has been optimized at a particular IPAP.

Desynchronization

The most frequent cause of desynchronization with NIV-specific ventilators is excessive flow used to compensate for leakage from a poorly adjusted or sized interface. As explained above for conventional ventilators, desynchronization can occur if the ventilator fails to recognize the patient's inspiratory efforts. This is especially true for infants younger than 6 months and for ventilators with impedance-based triggers. The best option for these scenarios is to use controlled modes (S/T or T), adjusting the respiratory frequency according to the patient's spontaneous respiratory frequency. Another cause of desynchronization is inadequate inspiratory ramp time: in infants, if the time is too short (0.05 seconds), then it will lead to patient discomfort from elevated initial flow; in adolescents, if the time is too long (0.4 seconds), then it will make patient feel that they can not draw in air, or it will slow the response of the

inspiratory trigger. Sedation should always be a last resort for achieving good patient-ventilator synchronization.

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Sedation in non-invasive ventilation

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INTRODUCTION

Compared to conventional mechanical ventilation (CMV), non-invasive ventilation (NIV) offers less complications (e.g. volutrauma, barotrauma, pneumonia, and laryngo-tracheal sores) and lower requirements for sedation in critical pediatric patients. Using less sedation helps conserve the patient's airway defense mechanisms, their capacity to speak and swallow, and their cough reflex, which enables them to spontaneously eliminate secretions. In certain cases, it also helps the patient maintain their ability to be fed orally. Nonetheless, NIV often demands that the patient be sedated. However, literature on sedation in NIV, such as pharmacological guidelines on the use of sedatives, is scarce.

A recent study performed at Hospital Universitario Central de Asturias (HUCA) revealed that 63% of pediatric NIV patients required some type of sedation. Among sedated patients, 84% had to be sedated by continuous infusion, and 16%, by periodic bolus.

Sedatives must be used with extreme caution in NIV, as they can diminish the patient's respiratory efforts, thereby reducing their state of consciousness (a contra-indication to NIV), and consequently, causing the treatment to fail.

PRINCIPLES

Firstly, a clear distinction between sedatives and analgesics must be made, as the majority of sedatives do not have analgesic effects. Relieving the NIV patient of their pain will help improve their relationship with hospital staff and help them to

better tolerate the interface and treatment. Hospital staff should likewise care for patients by treating any fever, alleviating hunger or thirst, and ensuring that they do not feel too hot or cold, all of which are sensations which can cause discomfort and stress, especially in very young children.

Since NIV is intended to alleviate any anxiety or agitation felt by the patient from respiratory pathologies, it is crucial that other factors influencing comfort be separately evaluated and treated (e.g. neurological or metabolic problems, pain). Table I lists measures for minimizing the need for sedation in pediatric NIV patients suffering from anxiety or agitation. The expertise and attention of hospital staff are fundamental for successful treatment (see Chapter 9).

Pharmacological sedation comprises two levels:

1. Conscious sedation, or anxiolysis, in which the patient's level of consciousness is minimally affected, their airway remains open, their reflexes are conserved, and they are able to maintain adequate physical and verbal response; This is the preferred level for NIV.
2. Deep sedation or hypnosis, in which the patient's level of consciousness is markedly reduced and controlled by drugs, and they can not be easily awoken and may lose their protective reflexes and their ability to respond to physical or verbal stimulation. This level should only be used periodically for NIV and with close observation of the patient.

For any pharmacological sedation strategy, hospital staff must ensure that the patient will be adequately monitored. Hence, acute patients are

normally started on NIV treatment in the pediatric intensive care unit (PICU) (see Chapter 4). Monitoring of NIV patients is covered in Chapters 3 and 10. If the patient is to be sedated deeply, then hospital staff may consider monitoring the sedation by employing the Bispectral® (BIS®) index, which is widely used in anesthesia.

BIS® is most valuable in pediatrics for monitoring sedation in short, painful procedures, and is being increasingly used for monitoring chronic patients. Not all sedatives induce an electroencephalographic response which can be translated into a drop in BIS® index value. Those which do generate this type of response include benzodiazepines (e.g. midazolam) and propofol. It has been clearly demonstrated that a BIS® value between 60 and 80 enables sedation with amnesia, with the possibility of maintaining airway reflexes and, in the absence of analgesia, the ability to respond to physical or pain stimuli. To avoid any undesired side effects of sedation, the BIS® value of sedated NIV patients should be monitored so that it does not drop below said range.

The expertise of hospital staff is fundamental when choosing and administering a sedative. Each hospital ward will most likely have in-house pediatric sedation protocols that can be adapted to NIV, especially to the start of treatment. The patient's age is another decisive factor in the choice of sedative.

Lastly, pharmacological sedation is not indicated for chronic NIV, especially in the home, unless it forms part of a palliative course of treatment.

INDICATIONS OF SEDATION IN NON-INVASIVE VENTILATION FOR ACUTE RESPIRATORY FAILURE PATIENTS

No clear indications on the use of sedatives in pediatric NIV patients have been established from any clinical studies. Pharmacological sedation is typically required at the onset of NIV, as support for non-pharmacological methods and to ensure that treatment begins correctly.

The authors of this chapter, based on the limited published evidence and on their own experience, have compiled a list of scenarios in which pharmacological sedation can help in the administration of NIV:

- *Adapting the patient to the interface:* Positioning the interface on the child can cause them

Table I. Non-pharmacological sedation methods for pediatric non-invasive ventilation.

-
- Whenever possible, allow a parent to accompany the child. Encourage physical and verbal contact with the patient while projecting a sense of calm
 - Provide the patient with access to familiar objects (e.g. dolls, pets, pacifiers and books) and music
 - Respect the patient's sleep-wake cycles
 - Maximize the patient's comfort level (e.g. temperature, clothing, light, noise, etc.)
 - Ensure that hospital personnel present themselves in the least aggressive manner possible, instilling the patient with a sense of security rather than of fear. Avoid negative speech
 - Minimize the aggressiveness of treatment methods such as extractions and examinations
 - Emphasize non-invasive monitoring techniques
-

discomfort. In some cases, an initial bolus is sufficient: upon tranquilization, the patient will feel that their breathing has improved, and consequently, better adapt to treatment.

- *Improving patient-ventilator synchronization:* Sedation can help alleviate synchronization problems related to ventilator triggers, especially for very young children. Hence, infants are the patient group which most requires sedation for initiating NIV. Data on the patients of the authors of this chapter reveal that 68% of infants under 24 months require sedation, as compared only 53% of those over 24 months.
- *Controlling hypoxic agitation:* Hypoxemia can agitate respiratory failure (RF) patients. Hence, administration of a sedation bolus at the onset of NIV can help these patients adapt to treatment. Contrariwise, hypercapnia may induce light somnolence in RF patients, which can actually be valuable for initiating NIV.
- *Protecting the lungs by reducing air trapping:* The agitation inherent to the onset of NIV treatment or due to alterations of the interface (e.g. repositioning, or aspiration of secretions) can facilitate or even lead to a higher level of tachypnea, greater air trapping or stronger oscillations in pressure. Depending on the patient, their pathology, and the ventilation mode used, these effects can have severe consequences. Periodic or continuous sedation of these patients may reduce this risk.

DRUGS

NIV patients are typically sedated with drugs commonly used in the ICU. The dose used should be the minimum quantity required to enable adaptation of the patient to NIV without causing any interference in their respiratory efforts. Sedatives are administered intravenously via periodic bolus or continuous infusion. Sometimes, a single injection at the onset of treatment is sufficient for coupling the patient to the ventilator. However, for cases in which adaptation to NIV is more laborious (e.g. treatment of small infants), continuous infusion may be required.

The most common sedatives for pediatric NIV are described below and summarized in Table II.

1. *Midazolam*. Midazolam is the most widely used benzodiazepine for sedation of children and adults, owing to its short half-life (45 to 60 min) and its minor side effects. Typical doses range from 0.05 to 0.2 mg/kg for direct bolus and from 0.05 to 0.3 mg/kg for continuous infusion. For patients that can not be treated intravenously, midazolam can be administered either intranasally or orally, as it functions relatively quickly by these routes. However, if it is administered sublingually or intranasally, the dose should be doubled, and if it is administered orally or rectally, the dose should be tripled.
2. *Fentanyl*. Fentanyl is a synthetic opioid which is 100 times more potent than morphine and has fewer side effects. It has a relatively short half-life (30 to 60 minutes). Typical doses range from 1 to 3 µg/kg for direct bolus and from 0.5 to 4 µg/kg for continuous infusion.
3. *Ketamine*. Ketamine is a potent hypnotic agent and analgesic with a dissociative effect. It has minimal effects on respiratory function but does produce a bronchodilator effect by relaxing smooth bronchial muscles. However, it increases production of secretions, which can compromise NIV in patients that have difficulty eliminating secretions (atropine [0.01 mg/kg] can be co-administered with Ketamine to prevent sialorrhea and bronchorrhea). The most important side effects of Ketamine are hallucinations and delirium; these can generally be prevented by co-administering the drug with low doses of benzodiazepines (e.g. midazolam [0.05 to 0.1 mg/kg]). Ketamine has a short half-life: when administered by IV, it takes effect in less than one minute and remains active for 15 to 20 minutes. The typical IV dose of Ketamine is 0.5 to 1 mg/kg delivered in 2 to 3 minutes (repeatable), and eventually, 0.25 to 2 mg/kg/h. Ketamine is contraindicated for NIV in patients with poorly controlled hypertension, hepatic failure,

Table II. Most widely used sedatives in pediatric non-invasive ventilation

Drug	IV Dose (mg/kg)	Indications & Comments
Midazolam	0.1 to 0.2	Sedative, anxiolytic, amnesiac and non-analgesic Minimal effects on hemodynamics Rapid administration leads to respiratory arrest Effects are reversible with flumazenil
Fentanyl	0.002	Very strong analgesic; sedative Minimal effects on hemodynamics High dose or rapid administration leads to chest wall rigidity Effects are reversible with naloxone
Ketamine	0.5 to 2	Strong analgesic; amnesiac and hallucinogen Bronchodilator (indicated for asthmatics), induces sialorrhea and bronchorrhea (preventable with atropine), hallucinations (preventable with benzodiazepines) and laryngospasm (highly problematic in NIV)
Propofol	1-2	Potent hypnotic Minimal effects on hemodynamics or respiratory efforts at this dose Not recommended for children under 3 years
Remifentanyl	Remifentanyl	Bolus delivery not recommended. Takes effect within 1 minute; effect wanes 3 to 5 minutes after stopping IV

- aneurysms, and pulmonary hypertension. It should be used with extra caution in patients that have airway infections or laryngotracheomalacia, due to the risk of laryngospasm. Ketamine can be also administered intramuscularly, in which case the dose should be doubled; or orally, rectally, nasally or sublingually, in which case the dose should be tripled or quadrupled and whereby the absorption is slower and less predictable.
4. *Propofol*. Propofol is a fast-acting sedative used for short periods of deep sedation. Typical doses are 1 to 2 mg/kg for an initial bolus and 0.5 to 4 mg/kg/h for continuous infusion. The manufacturer of propofol does not recommend using the drug for more than 48 hours in small children or in doses greater than 4 mg/kg/h, due to a risk of lactic acidosis with myocardial failure, which is potentially fatal. Despite the large body of clinical experience with the drug in young children, including infants, the manufacturer does not recommend its use in children under 3 years old.
 5. *Remifentanyl*. Remifentanyl is an extremely fast-acting (1 minute) synthetic opioid whose effects do not last as long as those of Fentanyl. Administration of remifentanyl by continuous infusion is recommended over bolus injection due to a high risk of apneas in the latter. After infusion is stopped, the drug's effects wane quickly (3 to 5 minutes), and it does not accumulate in tissue. The typical dose for

continuous infusion is 0.05 to 0.5 µg/kg/min with or without an initial bolus of 1 µg/kg.

6. *Chloral hydrate*. Chloral hydrate is widely used for painless pediatric procedures. It can be administered orally or rectally. Its main advantage is its long latency (30 to 60 minutes); its half-life is 10 hours. Typical doses range from 25 to 50 mg/kg, without exceeding 1 g/dose and 2 g/day.
7. *Anti-psychotics (neuroleptics)*. Mild anti-psychotics (e.g. levomepromazine) can also be used as sedatives. The typical dose is 1 mg/kg, which carries a risk of causing extrapyramidal symptoms.

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Failure analysis and predictive factors in non-invasive ventilation

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INTRODUCTION

Introducing non-invasive ventilation NIV into the ICU without proper training of personnel can lead to a high rate of treatment failure with dangerous consequences, especially in the first hour of ventilation. Unprepared hospital staff may then develop an aversion to the technique, thereby limiting its future use. Furthermore, even after an ICU has surpassed the learning curve of adopting NIV, it still must face myriad other factors that can lead to treatment failure (Table I). This chapter has been written as a practical checklist for preventing or correcting failure of NIV. It includes descriptions of clinical situations in which the patient's state either worsens or remains stagnant during treatment.

PROBLEMS ANALYSIS

Desynchronization

Desynchronization can occur because of problems with either the interface or the ventilator:

Inadequate interface

For acute patients, especially those who are hypoxemic, nasal interfaces lead to a higher rate of treatment failure. These patients frequently breathe through their mouths, generating leakage which is then compensated for by the ventilator, ultimately causing patient discomfort and leading to patient-ventilator desynchronization. This can be remedied by:

- Using a pacifier to minimize leakage through the

mouth; a sweetener may be added to it to make it more desirable to the child.

- Excessive controlled leakage. Sometimes vented interface can produce autocycling and desynchronization.
- Changing the type of nasal interface or switching to an oral-nasal interface.

Non-invasive-specific ventilators

The most common causes of desynchronization are use of excessive flow to compensate for leakage and use of a poorly adjusted or incorrectly sized interface.

Another cause is failure of the ventilator to detect the patient's respiratory efforts, which often occurs with patients younger than 6 months or when impedance triggers are used.

- In these situations, the best option is to use controlled modes (S/T, T), adjusting the respiratory frequency to the patient's spontaneous respiratory frequency.
- Sedation may be useful for achieving better synchronization and improving the patient's tolerance of the ventilation.

When using a ventilator that features different modes, the preferred mode is the one which will afford the best overall synchronization.

- As a general rule, for patients older than 4 to 6 months, NIV-specific ventilators are superior to conventional ventilators with an NIV option. However, the inspiratory (flow) trigger in conventional ventilators can detect and

Table I. Systematic checklist for possible failure of non-invasive ventilation

<ol style="list-style-type: none"> 1. Desynchronization <ol style="list-style-type: none"> a. Inadequate interface b. NIV-specific ventilator: <ul style="list-style-type: none"> • Leakage in the interface • Inspiratory trigger not activated • Inadequate respiratory circuit • Inadequate ramp c. Conventional ventilator: <ul style="list-style-type: none"> • Insufficient leakage compensation • Correct expiratory trigger 2. Confirm adequate etiological treatment for the cause of RF 3. Facilitate drainage of secretions via physiotherapy 4. Check for any new complications: <ol style="list-style-type: none"> a. Pneumothorax b. Aspiration pneumonia 5. Persistent hypoxemia: <ol style="list-style-type: none"> a. Switch to a ventilator with oxygen blender b. Determine if the EPAP should be increased c. Increase the FiO₂ 	<ol style="list-style-type: none"> 6. Persistent or newly arising hypercapnia: <ol style="list-style-type: none"> a. Check for leakage in the interface b. Confirm that the circuit has leakage control c. Correct any re-inhalation: <ul style="list-style-type: none"> • Increase the EPAP • Change to Plateau valve • Use an interface with less dead space (if possible) d. Prevent desynchronization: <ul style="list-style-type: none"> • Adjust the respiratory frequency and the I/E ratio • Adjust the inspiratory and expiratory triggers (if possible) • Determine if the EPAP should be increased e. Ensure adequate ventilation: <ul style="list-style-type: none"> • Check chest wall expansion • Increase the IPAP or delivered volume • Determine if the mode or ventilator should be changed
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FiO₂: fraction of inspired oxygen; EPAP: expiratory positive airway pressure; IPAP: inspiratory positive airway pressure; I/E: inspiratory to expiratory; RF: respiratory failure

synchronize the respiratory efforts of younger patients.

Another cause of desynchronization is inadequate ramp time: if it is too short (0.05 sec), it will lead to excessive initial flow, causing the patient discomfort; in contrast, if it is too long (0.4 sec), the patient will feel short of breath or will suffer from uncompensated tachypnea due to failure to reach the target inspiratory positive airway pressure (IPAP) or due to discomfort from the slow response of the inspiratory trigger.

- Use of a humidifier in the respiratory circuit can diminish the sensitivity of the inspiratory trigger, especially in the case of infants.

Conventional ventilators with non-invasive option

The problems most frequently encountered with these ventilators are listed below:

- Insufficient leak compensation
 - This can be resolved by increasing the positive-end expiratory pressure (PEEP) to provide greater flow.
- Insufficient expiratory trigger sensitivity. This extends the inspiratory time after the patient has already begun expiration (Fig. 1; and see Chapter

7), and is especially problematic in pressure support mode.

- This can be resolved by adjusting the expiratory trigger and, if possible, limiting the inspiratory time.
- In assisted/controlled (A/C) mode, this can be resolved by adjusting the inspiratory time close to the patient's value.

Inadequate etiological treatment of the cause of respiratory failure

ICU personnel understand that most of the techniques they employ are simply methods for gaining time and ensuring that the efficacy of the etiological treatment, together with the natural course of the illness, enable patients to recuperate. Hence, if the patient does not improve as predicted, the treatment strategy (e.g. antibiotics, diuretics)—and even the initial diagnosis—may need to be reconsidered.

Secretions

For patients that have difficulty eliminating secretions (e.g. neuromuscular disease patients), NIV can easily fail if it is not supplemented with

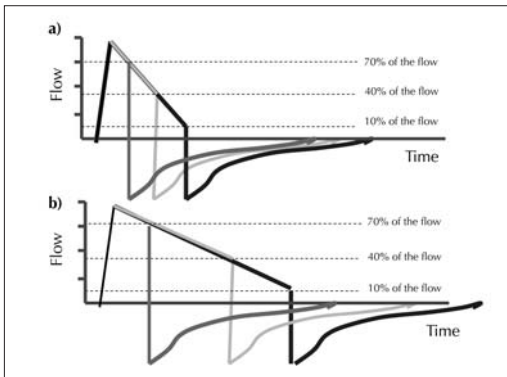


Figure 1. Flow-time plot for pressure support mode: a) without leakage, and b) with leakage; The inspiratory time is lengthened; Increasing the value of the expiratory trigger to higher values of the peak flow reduces the inspiratory time and improves synchronization.

additional respiratory physiotherapy treatment (e.g. manual or mechanical assisted cough) (see Chapter 20).

In patients treated with a nasal interface, NIV may fail if their nasal airway is blocked by secretions. Current NIV systems can not detect this problem, since blockage of nasal flow does not necessarily interfere with functioning or monitoring of the ventilator flow. Hence, this risk must be anticipated and treated clinically.

Another source of blockage—and consequently, of NIV failure—is edema caused by overly aggressive manipulation of the nasal airway.

Assessing new complications that arise during non-invasive ventilation

If a patient stabilized with NIV quickly deteriorates, and leakage is not the cause, then hospital staff must evaluate the patient for complications such as pneumothorax, aspiration pneumonia, and hemodynamic instability. If any newly arisen condition can not be resolved by adjusting the ventilation mode or parameters, then intubation should be seriously considered.

Persistent hypoxemia

Managing hypoxemia tends to be slower in NIV patients, whose oxygen needs often can not be reduced in the first 6 to 8 hours of treatment, especially in the case of Type II patients. Uncontrolled

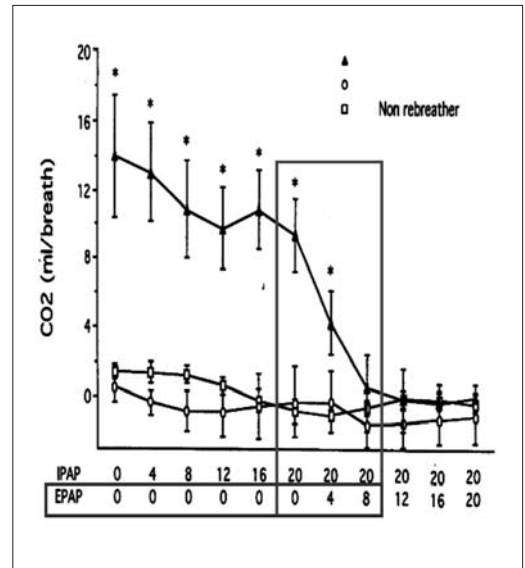


Figure 2. Increasing the EPAP leads to a decrease in re-breathed CO₂. The maximum decrease is observed at an EPAP of 8 cm H₂O (with permission of the author, GT Ferguson, reference 3).

hypoxemia will force the patient to maintain a high level of breathing work, ultimately leading to respiratory failure within hours. Hence, the possible causes of hypoxemia must be analyzed:

Insufficient oxygen in the airflow

For ventilators lacking an oxygen blender or input valve (see Chapter 6, "Non-invasive ventilation devices"), the airflow must be enriched with oxygen either via the tubing or through a port on the interface. The maximum FiO₂ possible with this method is 0.5, although the level will vary in function of leakage, parameter settings and the ventilator used. There are recent models that include an oxygen valve whereby the FiO₂ delivered can be calculated from manufacturer's data tables (maximum FiO₂ = 0.8).

Insufficient alveolar recruitment

If the patient's FiO₂ persistently exceeds toxic levels and can not be reduced, they may be suffering from insufficient alveolar recruitment—whether due to their pathology or because the programmed pressure is too low. The best treatment strategy for this scenario is to increase the expiratory positive airway pressure (EPAP)

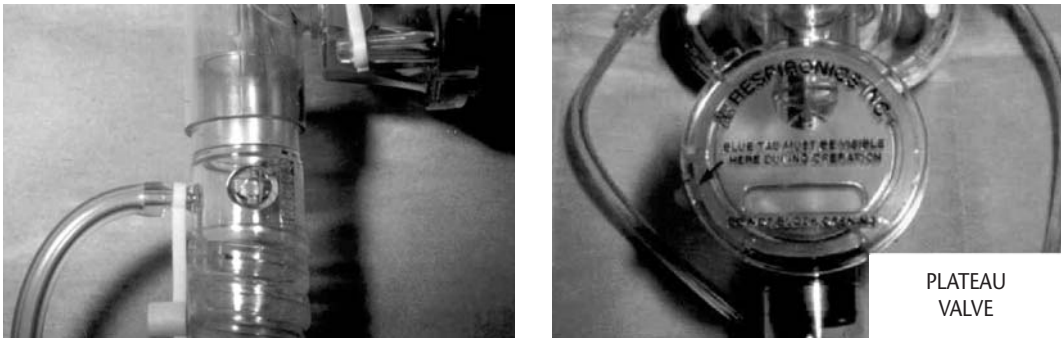


Figure 3. The segment of tubing at the exhalation valve should be cut out, and then replaced with a Plateau valve.

while carefully maintaining a sufficient pressure gradient for ventilating the patient. Hence, in ventilators in which the IPAP is not above the EPAP or PEEP, it should also be increased.

Appearance or persistence of hypercapnia

If hypercapnia is observed at any time during NIV, whether during periodic blood gas, transcutaneous or capnography measurements, then the patient should be evaluated for the following complications:

- a. Obstruction of the airway by secretions.
- b. Re-inhalation. This can easily be identified by capnography from a characteristic pattern on the respiratory graph: the curve never reaches baseline, indicating the presence of CO_2 in the inhaled air. Re-inhalation can be resolved by the following measures:
 - Increasing the EPAP: Using a single arm respiratory circuit facilitates re-inhalation of CO_2 , especially in patients with severe tachypnea. Using an EPAP of at least 4 cm H_2O will force the exhaled air out of the exhalation valve (see Fig. 2); the EPAP can be increased up to 8 cm H_2O . Alternatively, the section of tubing located at the exhalation valve can be removed, and then replaced with a Plateau valve (see Fig. 3).
 - Some authors have recommended adding an external oxygen flow (4 to 6 L/min) to the interface to minimize re-inhalation of CO_2 .
 - Another cause of re-inhalation is use of an interface with large dead space; hence, as long

as the patient adapts well, hospital staff can switch to an interface which has less dead space or which features expiratory ports.

- c. Inadequate ventilation. When taking any of the measures listed below, hospital staff must always ensure that they properly adjust the IPAP to provide the patient with the optimal tidal volume.

- Check chest wall movement.
- Check leakage in the interface: Persistent leaks not only cause desynchronization, they also diminish the tidal volume delivered to the patient. Leaks can sometimes be caused by accidental opening of an interface port; hence, all ports should be checked carefully.
- Check the respiratory circuit: The ICUs to which the authors of this chapter pertain experienced the following problems when first incorporating NIV: on one occasion, hospital staff did not add an exhalation valve in the circuit used with an NIV-specific ventilator; on another, an inexperienced nurse deliberately closed an exhalation valve in the ventilation set-up, thinking that it would be a source of uncontrolled leakage.
- Consider any possible changes in ventilation mode or ventilator: This is especially important in patients with restrictive thoracic diseases, for whom pressure-metric ventilators can not guarantee an adequate tidal volume. Hospital staff should opt for pressure modes that guarantee volume or for volume modes directly.

The term “non-invasive” should never be interpreted as requiring less care; indeed, NIV always demands continuous reevaluation of the patient’s

Table II. Predictive factors for failure of non-invasive ventilation published to date

Authors	Year	Study type	# Patients	Predictive factors
Essouri	2006	Retrospective	114	Multivariate: <ul style="list-style-type: none"> • SDRA • High PELOD score Univariate: <ul style="list-style-type: none"> • PRISM • Decrease in pCO₂ within 2 hours • Decrease in pCO₂ within 2 hours
Bernet	2005	Prospective	42	<ul style="list-style-type: none"> • FiO₂ > 80% after 1 hour
Joshi	2007	Retrospective	45	<ul style="list-style-type: none"> • Diseases of the pulmonary parenchyma • Age: < 6 years • FiO₂ > 60% in first 24 h • pCO₂ ≥ 55 mmHg in first 24 h
Larrar	2006	Prospective Bronchiolitis (nasal CPAP)	53	<ul style="list-style-type: none"> • PRISM • Decrease in pCO₂ within 2 hours
Campion	2006	Prospective (bronchiolitis)	69	<ul style="list-style-type: none"> • Apneas • High pre-NIV pCO₂ • PRISM
Mayordomo	2008	Prospective	116	<ul style="list-style-type: none"> • Type I failure • PRISM • RR decrease at hours 1 and 6

ARDS: acute respiratory distress syndrome; PELOD: pediatric logistic organ dysfunction; PRISM: pediatric risk of mortality; PCO₂: partial pressure of CO₂ in the blood; FiO₂: inspired fraction of oxygen; NIV: non-invasive ventilation; CPAP: continuous positive airway pressure. RR: respiratory rate; ARF: acute respiratory failure.

condition based on strict monitoring, early anticipation of any possible complications, appropriate adjustment of the ventilation mode and parameters, and, when required, careful transition of the patient to CMV.

As reiterated throughout this book, the success of NIV depends on the experience of hospital staff and on the quality of patient care. Hence, a checklist (see below and Table I) to avoid or correct NIV failure, or for use in unequivocally switching to CMV if failed NIV can not be resolved, is an invaluable component of any ward's treatment arsenal.

PREDICTIVE FACTORS OF FAILURE IN NON-INVASIVE VENTILATION

Predictive failure analysis is crucial to improving NIV and defining its indications more clearly. Various studies on adult patients have identified predictive factors of NIV failure within the general population as

well as according to pathology (e.g. pulmonary edema [APE], chronic obstructive pulmonary disease [COPD], and immunosuppression). These factors comprise pH; pCO₂; (PaO₂/FiO₂), both before and 2 hours after initiation of NIV; and a decrease in respiratory frequency. However, there have been very few studies on pediatric patients, and these have either been based on retrospective data or have only analyzed a specific pathology (bronchiolitis) (Table II).

In the most detailed pediatric study published—performed in 2005 on 42 patients (including 6 neonates and 11 post-operative cardiac surgery patients)—the success rate for NIV was 57% and the only predictive factor for NIV failure was an FiO₂ requirement > 0.8 (with a negative predictive value of 71%). However, this study was limited by the heterogeneity of the patient population and of the NIV indications (elective, post-extubation), as well as by the fact that it was based on use of a

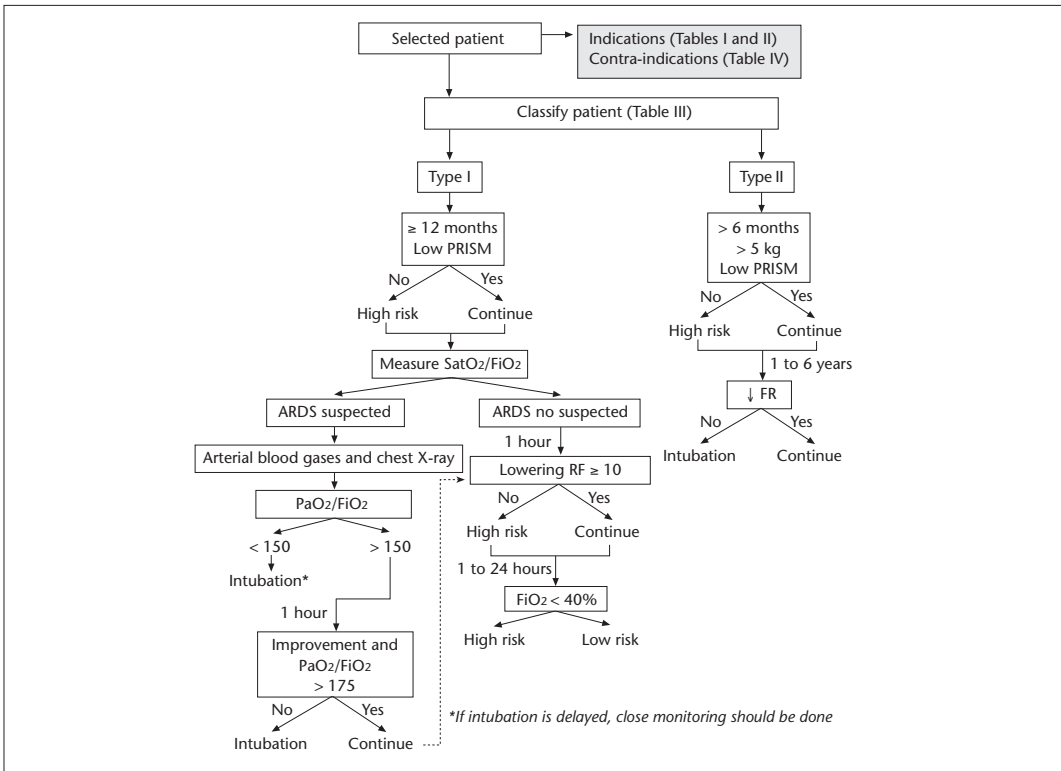


Figure 4. Algorithm for analyzing failure of non-invasive ventilation in Types I and II acute respiratory failure. RF: respiratory frequency; PaO₂: arterial oxygen pressure; FiO₂: fraction of inspired oxygen.

conventional ventilator with NIV option (i.e. these ventilators provide worse synchronization and leakage compensation than NIV-specific ventilators).

A recently published prospective study of 87 adult NIV cases reported an overall success rate of 86%. This study established an algorithm based on the physiopathological classification of each patient's ARF, taking into account that one of the independent factors associated with failure was having Type I ARF.

Patients that respond to NIV tend to improve clinically within the first hour of treatment, experiencing a drop in tachypnea and retractions. Contrariwise, patients that respond poorly to NIV, whether due to poor adaptation or to worsening of their pathology, suffer from increased work of breathing and ultimately require intubation.

The factors which have shown the most sensitivity for determining NIV success comprise a decrease in FiO₂, a decrease in respiratory pH, and an increase in tidal volume, improved blood pH, and

improved PaO₂/FiO₂. Hence, for Type I ARF patients, especially the most severe patients without any contra-indications (i.e. patients with mild acute respiratory distress syndrome [ARDS]), it is critical that arterial blood gases be measured before NIV is started; if the patient's PaO₂/FiO₂ does not improve above > 175 within 1 hour of NIV, then the treatment should be stopped.

To identify patients at the highest risk for NIV failure (and therefore, those that will require intubation), the authors of this chapter have developed an algorithm based on clinical data from the study by Mayordomo et al. and on blood gas data obtained from severe Type I ARF patients (specifically, ARDS patients).

The predictive factors for NIV failure identified in a study of 101 pediatric/adult bronchiolitis patients (success rate: 68%) comprised presence of apneas, initial hypercapnia, and high PRISM. As explained above, these types of predictive factors are invaluable for ascertaining the potential for success (or failure)

of NIV when choosing a course of treatment for critical pediatric patients. The predictive factors for success (or failure) of NIV in pediatric patients that have been published to date are summarized in Table II and Fig. 4.

Patients with post-extubation acute respiratory failure

No study on ARF in patients treated with NIV post-extubation has been published to date. Indeed, these patients are typically grouped together with NIV patients that have not previously received CMV. An exception to this trend is the work of Joshi, who excluded this patient group when analyzing the efficacy of NIV because of the lack of pre-BiPAP values for them. The grouping together of children that have previously received CMV with those that have not can lead to errors in NIV analysis, as an invasive respiratory treatment can have major effects on variables such as heart rate and respiratory frequency as well as on the gas pressures to be administered in NIV.

In adult patients, the most recent works evaluate post-extubation ARF alone. The meta-analysis of Agarwal includes the four fundamentals. In agreement with these studies, use of NIV for post-extubation ARF must be differentiated according to the following two patient groups:

1. Patients that develop ARF post-extubation: This group has been analyzed in two randomized studies (Keenan and Esteban). Adult ICU patients from this group that were treated with NIV did not exhibit lower rates of reintubation or of mortality compared to those given the conventional medical treatment. In fact, the authors even observed a statistically insignificant trend of higher mortality in the NIV patients, and in both studies, there was a higher rate of reintubation in this group.
2. Patients at a high risk of developing post-extubation ARF that are given NIV as preventative treatment (by being phased out of CMV and into NIV): This group has also been analyzed in two randomized studies (Nava and Ferrer). The authors found that ICU patients given NIV in combination with the conventional medical treatment had lower rates of intubation and of mortality than those given the conventional medical treatment alone.

A prospective study on 27 cases of post-extubation ARF, which did not include the distinction made in the studies described above, was performed at the pediatric intensive care unit (PICU) of Hospital Universitario Central de Asturias. In the multivariate analysis, the only variable independently associated with the success or failure of NIV was the FiO_2 , at 1 and 6 hours. Using these data, the authors sought cut-off points: at 1 hour, an $\text{FiO}_2 \geq 50\%$ had a sensitivity of 80%, a specificity of 82.53%, a positive predictive value (PPV) of 72.23%, and a negative predictive value (NPV) of 87.50%; and at 6 hours, an $\text{FiO}_2 \geq 50\%$ had a sensitivity of 80%, a specificity of 94.12%, a positive predictive value (PPV) of 80%, and a negative predictive value (NPV) of 94.12%.

The fact that no significant differences were observed for any of the more specific indicators of a patient's oxygenation state (e.g. $\text{PaO}_2/\text{FiO}_2$) between the successful NIV group and the failed NIV group is most likely due to the small sample size: arterial blood gas measurements were only available for 15 patients. The same explanation probably holds true for pCO_2 .

The aforementioned data reveal that we should closely monitor the oxygenation level of patients treated for post-extubation ARF. Indeed, an increase in oxygen needs is a red flag for possible NIV failure.

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Non-invasive ventilation with heliox*

F. Martín-Torres

Non-invasive ventilation (NIV) is highly effective for respiratory care of pediatric patients. Owing to constant advances in NIV ventilators and interfaces, as well as the increasing familiarity of hospital staff with this technique, clinical use of NIV is increasing both in frequency, scope and efficacy. Patients receiving NIV may simultaneously require supplementary techniques either at the onset of treatment or throughout the progression of their pathology. These techniques may be complementary to NIV and may even enable synergistic effects. Alternatively, NIV may be indicated simply to improve the respiratory state of a given patient before they are treated with a different, complimentary procedure.

Combinations of helium and oxygen, or heliox, have been used in ventilation therapy. The majority of published cases have dealt with treatment of adult patients for flare-ups of chronic obstructive pulmonary disease (COPD). This chapter provides an overview of the theoretical basis, existing clinical evidence, and practical guidelines for use of heliox in pediatric NIV.

PROPERTIES OF HELIOX

Helium was first introduced into the medical arena in the 1930's by Barach, who showed that

when it was combined with oxygen, the resulting mixture (which he dubbed "heliox") improved airflow in patients with obstructive laryngeal, tracheal or lower airway lesions. Since then, studies on pediatric use of heliox have demonstrated its efficacy for treatment of various conditions, including upper airway obstruction caused by diverse pathologies, as well as asthma and acute bronchiolitis.

Helium, a noble gas, is inert, colorless and odorless and has very low density. If the nitrogen in inspired air (composed of 78% N₂ and 22% O₂) is replaced with helium, which is seven times less dense, a mixture (78% He and 22% O₂) is obtained which is three times less dense than normal air. The therapeutic utility of heliox lies in this very difference in density: when a patient breathes heliox instead of instead of air, airway resistance to gas flow is reduced, leading to a reduction in respiratory work. Furthermore, heliox also improves gas exchange, above all in alveolar ventilation: in small airways, where elimination of CO₂ is facilitated by diffusion, it diffuses four to five times faster in heliox than in normal air.

CLINICAL APPLICATIONS OF HELIOX

As an inert mixture, heliox lacks any intrinsic therapeutic effects. However, it can act as a therapeutic buffer, maintaining the patient in improved conditions, delaying onset of muscle fatigue and respiratory failure, and obviating the use

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of more aggressive treatments, until either other therapies can be administered or the patient's condition spontaneously resolves itself.

Heliox is most effective at the highest possible concentrations of helium (typically, 60 to 80%). Its principal clinical applications are based on its physical properties: it tends to be used for predominantly obstructive respiratory diseases in which alveolar ventilation is compromised and airway resistance is elevated, forcing the patient to do greater work of breathing. Table I summarizes the main clinical indications of heliox in pediatric medicine.

According to the literature heliox is typically administered to patients with spontaneous breathing or to intubated patients using modified conventional mechanical ventilation (CMV) devices.

For patients with spontaneous breathing, the preferred method is via mask with reservoir and unidirectional valves at flows of 10 to 15 L/min. If required, supplementary oxygen can be delivered through nasal prongs or cannulae, but at < 2 L/min, since a higher flow could excessively reduce the helium concentration.

Warming and humidification of heliox, which is especially important for very small children, can readily be achieved by modifying standard equipment used for air-oxygen mixtures. Oxygen hoods or tents are not ideally suited to heliox therapy since they lead to greater mixture with air, with the helium (less dense) going to the top, and the air (more dense) going to the bottom, close to the patient's airway. Simple face masks or nasal cannulae may be amenable to heliox therapy; however, they tend to cause dilution of the heliox flow with external air, thereby markedly reducing the chances of successful treatment.

The delivery of invasively administered heliox depends on the ventilator used. The heliox is introduced via the pressurized-air inlet on the ventilator. Hospital staff must first confirm that the ventilator is heliox compatible, consider the various consequences of the physical properties of heliox on the ventilation parameters and performance (e.g. recorded volumes, FiO_2 and flow measurements, and trigger sensitivity), and then take any required corrective measures. The safest way to ventilate a patient with heliox is to use a pressure-controlled ventilation (PCV) mode, following pressure goals. Heliox has also been delivered using high-frequency jet ventilation (HFJV), high-frequency percussive

Table I. Primary clinical applications of heliox in pediatric medicine. Heliox has shown the greatest efficacy in treatment of obstructive diseases of the upper airway; among all its indications, this one is most widely supported by clinical evidence. In contrast, use of heliox to treat conditions in which the lower airway is compromised remains controversial

-
- A. Obstruction of the upper airway:
 - A1. Infectious etiology (e.g. laryngitis, epiglottitis and tracheitis)
 - A2. Inflammatory etiology:
 1. Post-extubation subglottal edema
 2. Post-radiotherapy edema
 3. Angioedema
 4. Edema caused by inhalatory lesions
 5. Spasmodic or recurring croup
 - A3. Mechanical etiology
 1. Foreign bodies
 2. Paralysis of the vocal chords
 3. Subglottal stenosis
 - A4. Laryngotracheomalacia
 - A5. Tumor etiology:
 1. Expansion of the larynx and trachea
 2. Extrinsic compression of the larynx, trachea and bronchi
 - B. Obstruction of the lower airway:
 - B1. Acute asthma attacks
 - B2. Bronchiolitis
 - B3. Bronchial hyper-reactivity
 - B4. Neonatal respiratory distress syndrome
 - B5. Bronchopulmonary dysplasia (BPD)
 - C. Driving gas for drug nebulization
 - D. Fiberoptic bronchoscopy (FOB) and/or instrumental manipulation of the airway
 - E. Other conditions:
 - E1. Hyperammonemia
 - E2. Pneumothorax
-

ventilation (HFJV) and high-frequency oscillatory ventilation (HFOV).

There is major clinical evidence for the efficacy of heliox as driving gas for drug nebulization in both adult and pediatric patients. A 20 to 25% greater flow is used for heliox than for air or oxygen, as the nebulization time for a given volume of solution will be longer if driven with heliox than if driven with air or oxygen. Hospital personnel must ensure that during nebulization, the patient's entire minute volume be filled using heliox. The best results reported for drug nebulization have been obtained by using Y-shaped masks with reservoirs. Alternatively, an ultrasonic nebulizer can be used.

RATIONALE FOR USING HELIOX IN NON-INVASIVE VENTILATION

Work on NIV of adult patients with heliox published by Jolliet et al. in the late 1990's sparked interest in use of this treatment for acute flare-ups in pulmonary lung disease patients. Since then, its efficacy for these patients has been demonstrated. The first successful case of pediatric NIV using heliox instead of air-oxygen mixtures was in the mid-1970's. It was used to wean infants that had undergone post-operative cardiac surgery from mechanical ventilation. However, this practice did not spread (nor did NIV at that time), and no other reports on the use of heliox in pediatric NIV appeared until the authors of this chapter published work on treatment of infants with acute refractory bronchiolitis.

Clinical data on adult mechanical ventilation, and experimental data from simulations, both demonstrate that at a given target pressure, heliox provides greater minute volumes –and therefore, better alveolar ventilation– than do air-oxygen mixtures.

Increasing the expiratory flow reduces air trapping and generation of auto-PEEP, thereby improving lung compliance, restoring the mechanical advantage to inspiration, and decreasing work of breathing. This in turn expands the tidal volume generated per cm H₂O of pressure used. Moreover, NIV with heliox improves the patient's elimination of CO₂ and reduces their sensations of dyspnea.

Heliox has complimentary effects when used with NIV; indeed, the combination of heliox and NIV can even be considered synergistic. As positive pressure, NIV can help reduce the load on respiratory muscles, prevent or correct atelectasis, prevent airway collapse, and promote and facilitate distribution of heliox throughout blocked airways. Heliox can further reduce work of breathing and improve CO₂ elimination. It can also provide higher expiratory flow than air-oxygen mixtures at the same pressure, which in turn can help improve passive expiratory lung mechanics, reducing the risk of barotrauma by gas trapping and thereby limiting any deleterious side effects from continuous positive airway pressure (CPAP) in blocked airways.

Application of continuous positive pressure can lower the patient's FiO₂ requirements, enabling them to be treated with a higher concentration of helium,

and consequently, increasing the likelihood of treatment success.

Hypoxia secondary to development of atelectasis has been described in patients treated with heliox. Neonates and small infants are at especially high risk for this complication. However, this highly serious side effect can easily be prevented through concomitant use of CPAP.

Given that heliox can reduce the pressure gradient required to maintain a given flow, less pressure can be used to obtain the target tidal and minute volumes, which in turn diminishes peak pressures and minimizes the risk of barotrauma or volutrauma.

Lastly, heliox delivered by NIV can delay or even obviate endotracheal intubation of the patient and subsequent invasive mechanical ventilation, each of which carries its respective complications. Although endotracheal intubation is the preferred method for airway isolation, it can produce local inflammation, ischemia of the mucosa, subglottal edema, and/or stenosis. Likewise, invasive positive pressure ventilation can cause lung damage by altering lung mechanics, specifically, barotrauma, volutrauma, atelectrauma and biotrauma.

INDICATIONS OF HELIOX IN PEDIATRIC NON-INVASIVE VENTILATION

The authors of this chapter have compiled a list of indications of heliox used with NIV for pediatric patients, based on the physical properties of heliox as well as on published data from simulations and from clinical studies on adult patients. These comprise:

1. Children with spontaneous breathing that are already receiving heliox therapy and that are not meeting their oxygenation requirements and/or whose FiO₂ requirement is either > 0.40 or increasing.
2. Children already receiving NIV:
 - For whom the ventilation level achieved is inadequate and/or that require higher pressure, or whose pressure requirements are increasing, and/or...
 - That show insufficient improvement in dyspnea or in clinical respiratory score, and/or...
 - Whose pathology requires protective ventilatory strategy (i.e. the lowest possible pressure for ensuring a target CO₂ level).

PROTOCOL FOR USING HELIOX WITH NON-INVASIVE VENTILATION

a. Equipment designed for heliox delivery: currently, there are four commercially available ventilators designed for heliox delivery: Aptaer® Heliox Delivery System (GE Healthcare), Inspiration® (E-Vent Medical Ltd.), Avea® (Vyasis Healthcare) and Helontix Vent® (Linde Gas Therapeutics). The main characteristics of these machines are summarized in Table I. They remain limited in distribution and use; indeed, none of these devices have appeared in any of the few works on pediatric patients published to date. The Aptaer® features inspiratory and expiratory triggers, enabling use of pressure support with heliox. The Inspiration® is a conventional ventilator that includes an option for NIV delivery of heliox. The Avea® offers all the standard modes used for invasive ventilation, plus the option for invasive or non-invasive ventilation with heliox. The Helontix Vent® was specifically developed for heliox therapy. It allows use of pressure support and only comes in a single model for adults and older children.

b. Equipment adapted for heliox delivery: heliox can be safely delivered by modifying standard NIV ventilators according to literature guidelines. However, as with use of any equipment beyond its manufacturer's indications, extreme caution must be applied when using this approach. Hospital staff must have technical expertise in both the ventilator and in heliox therapy to minimize any potential risks in this method.

1. When heliox is used with NIV, the average flow and volume readings are not reliable, unless an external pneumotacograph (which is not influenced by gas density) is used. Hence, ventilation should be programmed and controlled in function of the programmed pressures (which are not affected by heliox) and the resulting blood gas values (arterial O₂ saturation and CO₂ levels).

2. NIV delivery of heliox instead of air-oxygen mixtures generates greater inspiratory and expiratory flows at the same pressure and provides far superior CO₂ diffusion. In terms of protecting the patient's lungs, this implies that the pressure gradient required to reach

a given target CO₂ level will be lower with heliox than with an air-oxygen mixture.

3. If pure helium is used—which is generally not recommended and is prohibited by legislation on therapeutic gases in most European countries—, then the patient must be continuously monitored by oximetry to prevent hypoxic conditions. Nonetheless, the safest and most practical clinical option is to use helium-oxygen mixtures at predetermined concentrations (typically, 80:20 or 70:30), and then add any required supplemental oxygen according to the patient's needs.

There are two ways of adapting standard NIV equipment for delivery of heliox: pre-dilution connection and post-dilution connection.

Pre-dilution connection

In this approach heliox is directly connected to the ventilator through a pressurized-gas inlet or a blender. It can be employed with the BiPAP Vision® (Respironics), and the Infant Flow, Infant Flow Advance and SiPAP® (EME/Viasys) systems. The helium or heliox source is connected to the ventilator's air inlet (probably the best option) or oxygen inlet. In the former case, the FiO₂ is regulated using the ventilator's FiO₂ control; whereas in the latter case, the FiO₂ control is set to 1.0 to ensure that only heliox is being delivered. If supplementary oxygen is required, it can be added through a T-piece attached to the respiratory circuit. Alternatively, an oxygen blender can be attached to the ventilator's air inlet or oxygen inlet, such that helium and oxygen can be added simultaneously before entering the ventilator.

For cases in which the gas flow is directly regulated (e.g. in the Infant Flow® system), the following factors are used to convert flow meter readings from air-oxygen values to heliox values: for 80% He and 20% O₂, multiply by 2.1; for 70% He and 30% O₂, multiply by 1.7; and for 60% He and 40% O₂, multiply by 1.4. These conversions enable determination of the real amount of heliox required to maintain the target pressure. If heliox is introduced through the air inlet, then the automatic limits of the alarm should be adjusted by first temporarily setting the FiO₂ control to the same percentage as the oxygen in the heliox used, and then resetting it to 0.21. This aim of this technique is to avoid false

Table II. Main features of the commercially available ventilators designed for non-invasive delivery of heliox

Model	Aptaer®	Avea®	Event®	Helontix Vent®
Distributor	Datex Ohmeda	Vyasis Healthcare	Event Inspiration LTD	Linde Gas Therapeutics
Adjustable FiO ₂	No	Yes	Yes	Yes
Adjustable PEEP	No	Yes	Yes	Yes
Pressure support	Yes	Yes	Yes	Yes
Pediatric model	No	Yes	Yes	No*
Standard ventilation modes	No	Yes	Yes	No
Heliox consumption	Low	Medium	Medium	Low
Difficulty for portable use	Medium	High	High	Low
Price	Low	High	High	Low**

*Pediatric model currently in development. **Device provided free with gas purchase.

alarms caused by discrepancy between the concentration set on the oxygen blender and the concentration detected by the oximeter (whose minimum value is the percentage of oxygen in the heliox introduced at the air inlet).

NIV delivery of heliox using the BiPAP Vision® ventilator has been validated in an experimental model. However, if this device is used, the initial leakage test of the expiratory valve should not be performed; paradoxically, this will provide better functioning of the ventilator, including greater accuracy of the trigger. Using this method with the FiO₂ set at 1.0 enables safe and accurate administration of helium at concentrations > than 60%.

The NIV ventilators best suited to modification for heliox delivery (i.e. those for which heliox causes the least interference in functioning, including in measurements) comprise, in decreasing order of preference: Servo 300®, Galileo®, Galileo Gold® and Veolar FT®. For volume controlled ventilation (VCV), there are specific correction factors for tidal volume and FiO₂ to be used with the most popular NIV ventilators (see References).

Post-dilution connection

In this method, the heliox is introduced directly into the respiratory circuit tubing, after the ventilator, ideally, as close to the patient (interface) end as possible. In this set-up, the concentration of helium that the patient receives is primarily dictated by the flow of helium used. It requires external

oximetry to guarantee adequate FiO₂ delivery. Furthermore, since the parameter values registered by the ventilator are not reliable, external pneumotacography is also needed. This set-up is an option in some ventilators (e.g. BiPAP Vision®), whereas it is the only option in others, which generate pressure by drawing in ambient air (e.g. BiPAP S/T-D30, Knightstar 335 [Mallinckrodt], Quantum PSV [Respironics] and Sullivan VPAP II ST [ResMed]). Analogously to the case in standard NIV of trying increase the FiO₂ by introducing oxygen in the circuit or interface, this approach is limited by the fact that the operator can not determine exactly how much helium is being introduced into the circuit, and therefore, delivered to the patient), which carries a risk of affecting ventilator function. Nonetheless, it has been validated experimentally. Using any of the aforementioned ventilators with heliox (80% He and 20% O₂) flows of 18 L/min ensures delivery to the patient of helium at concentrations > 60%. Furthermore, at this flow rate, heliox only causes minimal interference (BiPAP S/T?D30 and the Quantum) with ventilator function or does not interfere at all (Knightstar, Sullivan, and BiPAP Vision), nor does it alter the programmed inspiratory or expiratory pressures in any of these models. Logically, with this heliox delivery approach, the final concentration of helium delivered to the patient is influenced by the tidal volume obtained: higher inspiratory pressure and greater tidal volume at a constant heliox flow correlate with a lower concentration of helium administered to the patient.



Figure 1. BiPAP Vision® (Respirronics®) non-invasive ventilator adapted for heliox delivery: the heliox is introduced through the device's pressurized-oxygen inlet.

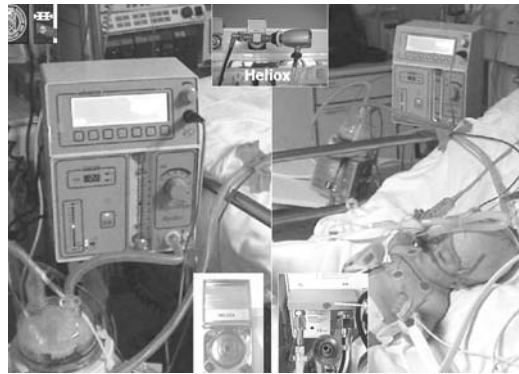


Figure 2. InfantFlow Advance® (EME®) non-invasive ventilator adapted for heliox delivery: the heliox is introduced through the device's pressurized-air inlet.

SIDE EFFECTS AND DRAWBACKS

Side effects

Although heliox is inert (non-toxic), when used with NIV it may lead to certain side effects, namely:

1. *Hypoxemia.* The primary side effect is insufficient oxygenation, since this treatment implies use of the lowest FiO_2 possible to maximize the positive effects of helium. Hence, strongly hypoxemic patients, who are characterized by high oxygen requirements, can not be treated with heliox (at least not at any therapeutically significant concentration of helium). Hypoxemia can also be caused by inadvertent use of a hypoxic mixture ($\text{FiO}_2 < 21\%$) in cases in which the helium and oxygen are mixed manually. This can be avoided by using tanks of pre-mixed heliox at known concentrations, or by employing continuous oximetric monitoring (with an alarm) of the mixture delivered to the patient.
2. *Hypothermia.* One of the most therapeutically important physical properties of heliox is its high thermal conductivity (six to seven times that of air); hence, prolonged heliox treatment at temperatures under 36°C carries a risk of hypothermia. Neonates and small infants are at the highest risk for this side effect, which can be prevented by ensuring proper warming and humidification of the heliox and by carefully monitoring the patient's body temperature.

Drawbacks

1. *Cost.* There have not been any studies on the cost effectiveness of NIV heliox treatment. Compared to other gases, heliox is much more expensive: two to three times as much as air, and eight to ten times as much as oxygen. Using non-NIV-specific devices for delivery of heliox can lead to increased costs due to internal gas consumption, leakage compensation and or excessive internal leaks. However, NIV-specific ventilators also have their respective drawbacks, which vary according to model.
2. *Technical difficulties.* The physical properties of heliox— above all, its low density— can interfere with fundamental ventilator operation, especially recording of FiO_2 volumes, as well as trigger functioning, flow measurements, and the automatic leakage compensation featured on some models. These technical difficulties vary with the ventilator used, and are primarily dictated by the type of valves and pneumotacograph used. In any case, pressure transducers are generally not affected by heliox; hence, treatment should be adjusted according to the programmed pressures.

CONCLUSIONS

Using heliox with NIV is a promising therapeutic option for children with various respiratory pathologies that do not respond to conventional treatment. Heliox is complementary to NIV, and

together, they may even have synergistic effects. Albeit there is only a small body of literature on heliox in pediatric NIV –focusing on treatment of severe acute bronchiolitis patients that can not be treated with standard therapies–, the results have been positive. The ideal ventilators for heliox delivery are devices which are specifically designed for this task; however, their use remains limited. Alternatively, other ventilators can be modified to administer heliox in NIV, although these must be used with extra precautions. Theoretically, NIV with heliox embodies a new strategy for lung treatment and protection. However, this technique must be further evaluated in clinical studies, and its indications and treatment guidelines must be more clearly established.

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Humidification and bronchodilator therapy in non-invasive ventilation

A. Esquinas and M. Pons

HUMIDIFICATION

Introduction

There is a general consensus on the need to condition inspired gases in order to maintain adequate ciliary function, conserve the rheological characteristics of respiratory mucosa, facilitate gas exchange and promote clinical progress. Humidification of inspired gases is essential for patients treated with medicinal gases, oxygen therapy, invasive mechanical ventilation (via oral-tracheal tube or tracheotomy), and non-invasive ventilation (NIV).

Mouth breathing in acute patients leads to the following complications:

- Loss of heat.
- Increased resistance in the nasal cavity.
- Drying out of mucosa.
- Thickening of secretions.

Indications of gas humidification in pediatric respiratory medicine

Any gas administered to a pediatric patient should be humidified. Insufficient humidification, or underhumidification, is especially detrimental to patients presenting with abundant bronchial secretions, chronic respiratory pathology, high inspiratory fraction, deficient pre-treatment hydration state, or hypoxemic acute respiratory failure (ARF); in patients receiving prolonged NIV treatment; and in patients whose ventilation is marked by high ventilator flows and/or major leakage.

The primary indications of gas humidification in pediatric respiratory medicine are summarized in Table I.

Methodology

Humidifiers

Choosing a humidifier, rating its efficacy and evaluating its clinical and morphological effects on respiratory mucosa depend on various factors. Ideally, a humidifier should:

1. Have low resistance in the inspiratory and expiratory phases of the respiratory cycle.
2. Not interfere with monitoring for hypercapnia (in order to avoid generating re-inhalation).
3. Not interfere with the ventilator's triggers.
4. Not cause heat loss in the patient's respiratory circuit

The humidifiers used to condition respiratory gases can be passive or active. Some active humidifiers contain a heated wire circuit.

Passive humidifiers (artificial noses), also called heat and moisture exchangers (HMEs)

Passive humidifiers are currently the most widely used humidification systems for conventional mechanical ventilation (CMV). They contain both hydrophilic and hydrophobic components, delivering heated and humidified air at low inspiratory and expiratory resistance and with low internal volume. However, these systems are ineffective in NIV for the following reasons:

1. Their ability to maintain adequate heat and moisture exchange is limited at high oxygen flows for prolonged periods of time.
2. They are not recommended for use with nasal masks due to the risk of losing gas exhaled through the mouth.

Table I. Indications of humidification in pediatric medicine: clinical situations in which humidification is critical

- Patients with deficient drainage of secretions
 - NMDs
- Patients with thick secretions
 - Cystic fibrosis
 - Dehydration
- Patients with hypoxemic ARF
 - High FiO_2 requirements
 - High ventilator flows
 - High risk of leakage
- Patients with limited cooperation
 - Infants
 - Prolonged NIV (> 72 hours)

ARF: acute respiratory failure; FiO_2 fraction of inspired oxygen; NIV: non-invasive ventilation; NMD: neuromuscular disease.

3. When used with a face mask, the effort required of the patient to set off the ventilator's trigger may cause patient-ventilator desynchronization.
4. They can increase resistance in inspiratory and expiratory flows.

Active humidifiers (with or without a heated wire circuit)

Active humidifiers with servo-control provide relative humidification from 33% (those without a heated wire circuit) to 100% (those with a heated wire circuit). There is a general consensus that these systems prevent drying out of mucosal membranes in NIV, although they are less effective in patients treated with nasal masks. These systems have several drawbacks:

1. They interfere with the ventilator's triggers and delivered volumes. Infants younger than 6 months and very weak patients (whether due to the stage of their respiratory failure or to a neuromuscular disease [NMD]) are especially prone to this complication.
2. In intubated patients, it has been demonstrated that active humidifiers which generate aerosols carry an increased risk of nosocomial pneumonia.
3. They use more water than passive humidifiers and are more difficult to maintain.
4. They are more expensive than passive humidifiers.

There is a wide range of commercially available humidifiers and of tubing, the majority of which has an internal diameter of 22 mm (see Fig. 1). Tubing



Figure 1. Active humidification without a heated wire circuit, using 22 mm tubing (Intersurgical®).



Figure 2. Active humidification with a heated wire circuit, using 25 mm tubing (Fisher-Paykel®).

diameter is important in NIV-specific ventilators: some ventilators have problems adapting to the strong resistance generated by use of high flows.

The authors of this chapter are only aware of one type of tubing available with an internal diameter of 25 mm; this model contains an internal heated wire circuit to reduce condensation in the respiratory circuit (Fig. 2).

Target temperature and humidity

Inspiratory gases are typically conditioned to a temperature of 37 °C and a relative humidity of 100%. However, since the delivered gas in NIV does not directly reach the trachea but instead must first pass through the nasal cavity or cross the face, 37 °C may prove excessive, causing the patient discomfort and leading them to reject treatment. Hence, some humidifiers now feature the option to heat gas to 34 °C (Fig. 3); this temperature can be used during the adaptation phase of NIV if the patient does not tolerate 37 °C well.

The clinical complications related to gas humidification are summarized in Table II.

Table II. Factors that influence complications with humidification in non-invasive ventilation

1. Type of acute respiratory failure (hypoxemic or hypercapnic)
2. Type of interface (e.g. nasal, oral-nasal, face or helmet)
3. Duration of NIV
4. Severity of the pulmonary pathology that is affecting the airways
5. Related pathologies (e.g. cardiopathy or neuromuscular disease [NMD])
6. NIV parameter values: FiO₂, pressures, flows and leakage
7. Patient's hydration level
8. Intercurrent factors (e.g. fever, and loss of liquids)
9. Patient's nutritional state: namely, protein metabolism
10. Metabolism of the respiratory epithelium during mucus production
11. Vasoactive drugs
12. Diminished cough reflex and decreased consciousness

FiO₂ fraction of inspired oxygen; NIV: non-invasive ventilation.

Underhumidification can have minor side effects (e.g. drying out of mucous membranes, and bleeding) or cause major complications (e.g. uncontrollable dyspnea, uncontrollable secretions, and patient intolerance to the interface), and may even result in the patient needing to be urgently intubated. These effects are listed in Table III.

BRONCHODILATOR THERAPY

A common delivery method for bronchodilator is aerosol (inhalatory) therapy, in which the patient inhales a suspension of the drug, which is then delivered directly to the target organ. Compared to other routes, aerosol therapy is advantageous in that it uses much smaller doses (which translates to lower costs), is much faster and leads to lower concentrations of drug in the blood (i.e. it has a better therapeutic index).

Fundamentals of aerosol therapy

An aerosol is a suspension of particles in an air current. The efficacy of drugs administered by aerosol is primarily influenced by the following factors:

**Figure 3.** Button for selecting the temperature.

1. **Particle size.** The size of drug particles (measured in microns) in an aerosol used for respiratory diseases dictates where in the respiratory pathway they will be deposited (see Table IV). The ideal particle size for respiratory drugs is 1 to 8 microns. At this size, particles can reach the walls of the distal airways via sedimentation and diffusion. In contrast, very small drug particles (< 1 micron) have poor transportability and a high probability of being exhaled, whereas very large particles (> 8 microns) tend to agglomerate and quickly deposit in the upper airway (tongue and oropharynx), from where they can be swallowed and absorbed, ultimately causing systemic side effects. It should be noted that nebulizers—the devices which generate drug aerosols—do not afford a uniform particle size; rather, they produce a wide range of particle sizes.
2. **Aerosol flow rate.** The patient's inspiratory flow influences the quantity and type of particles deposited as well as the mechanism of deposition. The preferred aerosol flow rate is 30 to 60 L/min. High inspiratory flows (> 100 L/min) favor deposition by impact and provide a high rate of penetration, whereas low inspiratory flows (< 30 L/min) favor sedimentation but carry a risk that the patient will only inhale a small quantity of the drug. Deposition of particles in children's lower airways is hindered by the combination of high flow speeds and the decreasing (from top to bottom) diameter of their airways.
3. **Hydrophilicity:** The affinity of particles for water determines the extent to which they can change size.

Table III. Signs of inadequate heating or humidification of inspired gases**Signs of deficient heating or humidification**

1. Nasal or pharyngeal irritation or discomfort
2. Nasal dryness
3. Nosebleed
4. Nasal blockage
5. Rhinorrhea
6. Coughing
7. Sneezing
8. Bleeding in the airway
9. Viscous respiratory secretions
10. Atelectasis
11. Decreased lung compliance
12. Patient fails to follow treatment

Signs of excessive heating or humidification

1. Irritation or pain of the airway due to burns
2. Diffuse micro-atelectasis
3. Over-hydration or water poisoning
4. Excessive condensation in the respiratory circuit tubing.

4. *Airway geometry.* The numerous bifurcations and narrowness of the respiratory airways amplify turbulence in the gas flow and increase the probability that the drug particles will impact in the most proximal areas.
5. *Type of nebulizer or inhaler used,*

Nebulizers and inhalers

The generation and deposition of aerosols during mechanical ventilation—with or without isolation of the airway—strongly influences the efficacy of the drug, especially in the case of bronchodilators, and can ultimately dictate the success of NIV. There are two ways to generate aerosols: via nebulizers or via inhalers. The choice of device depends on the patient's clinical profile.

The most widely used nebulizers and inhalers amenable to NIV are described below, and their respective advantages and disadvantages are summarized in Table V.

Nebulizers

There are two types of nebulizers: jet and ultrasonic.

1. *Jet nebulizers.* These devices operate by the Bernoulli and Venturi effects. In the former, when pressurized gas (air, oxygen or heliox) is pushed through the open end of a capillary tube whose opposite end is submerged in a liquid at ambient

Table IV. Distribution by size and by location of bronchodilator particles delivered by aerosol therapy

Size (microns)	Location	Percentage
>10	Mouth, nose and trachea	100
5	Between larynx and bronchioles	90-95
3	Between bronchioles and acini	85
1	Acini	60
0,5-0,6	Alveoli	35

pressure, the resulting sub-atmospheric pressure causes the liquid to be aspirated upwards to the gas-end, where, upon contact with the gas, it fragments into an array of different sized particles by diffusion (< 1 micron), gravity (1 to 6 microns) and inertia (> 10 microns).

2. *Ultrasonic nebulizers.* These devices exploit the piezoelectric ability of quartz to vibrate upon exposure to an electric current: the vibrations are transmitted through a plastic membrane that contains the liquid to be nebulized. The vibrating liquid is converted into an aerosol which is temporarily stored in a chamber, from where it is delivered to the patient by a stream of pressurized air generated by a ventilator. Experience with ultrasonic nebulization in NIV is very limited; however, it appears to be the nebulization method which least interferes with NIV (see Fig. 4).

Inhalers

Inhalers produce fixed doses of very small sized particles by subjecting a solution to a pressurized flow; the dose size varies with the device. They are more widely used than nebulizers for stable patients (i.e. those not receiving mechanical ventilation) able to achieve a minimum level of synchronization and cooperation. This indication is based on the work of Fuller; however, other published studies have reported that no differences in clinical outcome were observed between treatment with inhalers and treatment with nebulizers.

Metered dose inhalers (MDIs) (Fig. 5) use a pressurized canister to generate different sized particles (from 2 to 4 microns). MDIs have three main components:

1. A variable capacity canister which contains the active drug and propellants, either as a liquid

solution or gas suspension, at a pressure of 3 to 4 atmospheres.

2. A metering valve which releases a controlled and reproducible dose of the micronized drug each time the patient presses down on the canister.
3. A plastic case which covers the canister; Pressing down on the canister opens the valve, which releases the aerosol through a small opening.

Nebulization and inhalation in non-invasive ventilation

The preferred aerosol therapy option for mechanical ventilation patients depends on the patient's clinical profile (i.e. age, respiratory frequency, level of respiratory difficulty, level of consciousness, and blood gas levels) and on ventilation treatment factors (e.g. adaptation, synchronization, stage of NIV). Just as in patients with spontaneous breathing, in NIV patients there may be a slight preference for the use of inhalers. However, nebulizers are probably the best choice for pediatric patients—especially the youngest ones—with acute pathologies and those in the initial phases of NIV.

Indications of aerosol therapy in pediatric medicine

According to the few existing publications on aerosol therapy in pediatric patients, there are two main pathologies for which this treatment is indicated:

- *Status asthmaticus*. It seems obvious that once these patients have been started on NIV, they should be maintained on continuous bronchodilator therapy to avoid respiratory failure. In less severe patients, inhalers provide better peak expiratory flow than do nebulizers.
- *Cystic fibrosis*. Nebulization used with pressure support NIV of 10 cm H₂O provides 25% better drug deposition than does nebulization alone.

Methodology

The following guidelines should be followed when administering aerosol therapy to NIV patients:

1. *Positioning the inhaler or nebulizer*. Inhalers with spacers should be placed at the far (ventilator) end of the respiratory circuit for two reasons: firstly, this reduces impact of the drug on the mask walls, and secondly, it enables coordination of the start of ventilation with that of drug

delivery. In contrast, nebulizers should be introduced into the respiratory circuit close to the mask (typically a face or oral-nasal mask, to prevent loss of the drug).

2. *NIV parameters*. The inspiratory positive airway pressure, pressure support (where required), and expiratory positive airway pressure should be adjusted to achieve optimal inspiratory flows and tidal volume without compromising patient comfort and tolerance. The lowest level possible of FiO₂ is recommended.
3. *Cardiorespiratory monitoring*. The patient's vital signs should be checked before and during aerosol therapy to evaluate the efficacy of the therapy and identify any side effects.
4. *Drug dose, nebulization time, and nebulizer gas particle size and flow rate*. The drug dose should be calculated according to the patient's weight (see Table VI). The nebulization time must be monitored (it should be at least 20 to 30 min) and the particle size in the nebulizer gas flow should be controlled (the target particle size dictates the position of the nebulizer in the circuit). For jet nebulizers, maximizing particle deposition in the upper airway generally requires an oxygen flow of 4 L/min, whereas focusing delivery on the lower airway generally requires an oxygen flow of 6 to 8 L/min (12 L/min for heliox).
5. *Supplementary devices*. If the respiratory circuit is equipped with a Plateau (Respironics®) valve, then the nebulizer should be positioned in between the valve and the interface to avoid loss of elasticity in the valve's diaphragm. For the double-circuits of conventional ventilators, the nebulizer or inhaler should be positioned in the inspiratory arm. Other devices introduced into the respiratory circuit (e.g. aspirators) can compromise deposition of aerosols in the circuit.
6. *Humidification*. As previously mentioned, nasal masks should not be used with passive humidifiers.
7. *Evaluation of bronchial secretions*. The patient's bronchial secretions should be evaluated to optimize the aerosol therapy. All bronchial secretions should be eliminated before beginning therapy.

Precautions in aerosol therapy

The main complications in aerosol therapy derive from incorrect administration of the drug, including

Table V. Respective advantages and disadvantages of nebulizers and inhalers

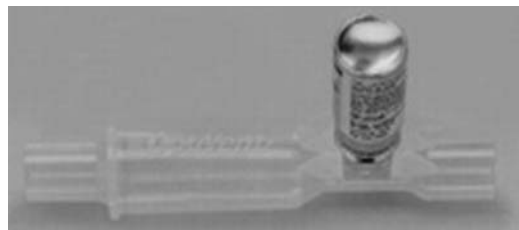
	Nebulizers	Inhalers
<i>Advantages</i>	Require less coordination Allow for high doses (including continuous dosing) Do not release chlorofluorocarbons (CFCs)	Comfortable Cheap
<i>Disadvantages</i>	Expensive Waste drugs Not available for all drugs Require a source of pressurized gas Slower acting Greater risk of infections	Deposit drugs in the larynx Difficult to administer in high doses Not available for all drugs

Table VI. Dosing of the most common aerosol therapy drugs

Drug	Dose	Interval
<i>Salbutamol</i>	• MDI: 2 (4 to 8) puffs • Nebulization: 0.2 mg/kg/dose Minimum: 1 mg; Maximum: 5 mg	4 to 6 hours
	• Continuous nebulization: 0.3 to 0.5 mg/kg/hour Maximum: 30 mg/hour	Continuous
<i>Terbutaline</i>	• MDI: 2 to 3 puff • Nebulization: 1 mL/kg/day	4 to 6 hours 8 hours
	• MDI: 4-8 puff • Nebulization: < 4 years: 250 µg/dose; > 4 years: 500 µg/dose	4 to 6 hours
<i>Iprratropium bromide</i>	• MDI: 4-8 puff • Nebulization: < 4 years: 250 µg/dose; > 4 years: 500 µg/dose	4 to 6 hours
<i>Beclometasone</i>	• MDI: 100-400 mg/day	12 hours
<i>Fluticasone</i>	• MDI: 100-2.000 µg/day	12 hours
<i>Budesonide</i>	• MDI: 100-400 µg/day	12 hours

overdoses. There are two precautionary factors that must be remembered when using nebulizers:

1. Children treated with nebulizers can suffer from over-hydration and excessive moisture in the airways. This leads to increased density of the delivered air, causing greater resistance to the passage of the airflow, and consequently, increased dyspnea in the patient. In extreme cases, patients can face a risk of drowning from liquid which has condensed in the airways.
2. If distilled water is used as the solvent for the drug to be nebulized, it can dilute the surfactant of the alveoli, thereby increasing the patient's dyspnea and worsening their respiratory condition. Moreover, since it is hypotonic, water can irritate the mucous membranes of the

**Figure 4.** Ultrasonic nebulizer.**Figure 5.** Metered dose inhaler (MDI) canister for use with a mechanical ventilator.

airways and may ultimately cause edemas or bronchiospasm. Therefore, the recommended solvent for drug nebulization is an isotonic 0.9% saline solution or, for bronchiolitis patients, a 3.0% hypertonic solution.

Bronchodilator drugs

There is a broad array of bronchodilator drugs that can be used in aerosol therapy. However, the general opinion at the 2000 Consensus Conference of the American Association for Respiratory Care (AARC) was that literature on aerosol therapy in NIV is rather limited and that most clinical experience in

this area has been with delivery of bronchodilators (see Table VI).

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BRONCHODILATOR THERAPY

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Fiberoptic bronchoscopy in non-invasive ventilation

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Fiberoptic bronchoscopy (FOB), or flexible bronchoscopy, is an essential diagnostic tool for various respiratory diseases. Moreover, as FOB can be employed from the patient's bedside, it can be used for critical patients. Nonetheless, this technique has certain limitations which can adversely affect patients.

Fiberoptic bronchoscopy in pediatric patients

The main risks involved in FOB for pediatric patients depend on the patient's age and respiratory pathology. Hence, for each patient, hospital staff should determine the suitability of this technique, the most adequate entry route and any precautions which should be taken during examination.

Pediatric airways and the size of fiberoptic bronchoscopes

There are currently three sizes (based on external diameter) of pediatric flexible bronchoscopes: 2.2, 3.5 and 4.9 mm. Given that children's airways are relatively small and increase with age, then the younger the child, the greater the resistance that a bronchoscope will imply.

Functional residual capacity of the lungs and metabolic oxygen consumption

Children have lower functional residual capacity (FRC) and higher metabolic oxygen consumption than do adults. Moreover, in pediatric patients with

an underlying pathology, the ventilatory reserve may be even more reduced, thereby further complicating FOB and increasing its inherent risk of altering blood gas levels.

Analgesia and sedation

Examining patients by FOB causes temporary alterations in lung mechanics and in gas exchange, which can lead to varying degrees of hypoxemia and hypercapnia. These changes are primarily dictated by the age and underlying pathology of each patient. Moreover, treating the patient before examination with analgesics and/or sedatives that can affect respiratory function may exacerbate these effects.

Entry routes

Bronchoscopy is typically performed transnasally, although it can also be done via face mask, laryngeal mask or endotracheal tube. The choice of route depends on the patient's clinical profile.

Transnasal

The transnasal route is used for the most stable patients. It enables complete examination of the airways. Supplementary oxygen is usually delivered via nasal cannulae.

Laryngeal mask

Entry via laryngeal mask allows for safer oxygenation and ventilation of the patient; hence,

it is used in less stable patients. However, since these masks are supported directly on the glottis, this route does not enable examination of the supraglottic area.

Endotracheal tube

Examination via endotracheal tube is performed for the most critical patients. Hospital staff must choose an appropriately sized bronchoscope which will permit simultaneous exploration and ventilation. Ventilator parameters and oxygen delivery may have to be temporarily increased during the procedure. This route only permits visualization of the bronchial branches and sample collection; it does not allow for examination of the trachea or the laryngeal area. If these areas need to be explored, then the endotracheal tube must be gradually slid upwards to provide access to the bronchoscope. This maneuver requires that all the equipment for possible reintubation be prepared in advance.

Face mask

Bronchoscopy via face mask allows full visualization of the airways as well as delivery of inhaled anesthetics, supplementary oxygen, continuous positive pressure ventilation (i.e. CPAP) or intermittent mechanical ventilation (IMV). These masks can also be adapted to the patient's existing NIV system.

Clinical basics of fiberoptic bronchoscopy during non-invasive ventilation

Several articles have been published in the past few years in which the risk of gasometric interference during bronchoscopy was reduced by introducing the instrument through a mask. Erb et al. used a specially designed mask with a terminal opening equipped with a silicone membrane. To examine adult NIV patients, Antonelli et al. used a face mask featuring a T-piece (Vitalsigns, Inc.) for insertion of the bronchoscope. They recommended this method for hypercapnic and/or hypoxic patients that require bronchoalveolar lavage (BAL) and whose PaO₂ is not greater than 75 mm Hg or whose SatO₂, with supplementary oxygen and spontaneous breathing, is not greater than 90% (based on the guidelines published by the American Thoracic Society in 1990). Da Conceição et al. used a



Figure 1. Face mask with terminal opening and T-piece.

Fibroxy™ (Peters) mask modified with two openings: an upper one, for connection to NIV; and a lower one, covered with a silicone membrane, for introduction of the bronchoscope. Maitre et al. recently reported good results obtained for hypoxic patients using the Vygon® Boussignac CPAP system adapted to a face mask. Their set-up features two connections: a standard oxygen inlet and a funnel-shaped inlet comprising four microchannels which, when connected to a strong flow of oxygen, produces four high-pressure streams that provide CPAP. The CPAP can be measured using a pressure transducer. Since this system is open to the atmosphere, the jet flow or pressure do not have to be changed before the flexible bronchoscope is introduced.

Adaptors for performing fiberoptic bronchoscopy with mechanical ventilation

FOB can be performed in pediatric NIV patients or in unstable patients that require simultaneous positive pressure ventilation by using the following devices:

Face mask and T-piece

The bronchoscope can be introduced through a T-piece connected to the terminal opening of a face mask (see Fig. 1). The instrument should first be inserted into the T-piece and mask, and then entire set-up should be positioned on the patient, and then attached using elastic straps. If the patient is pre-medicated and sedated according to standard FOB procedure, then the NIV system can be



Figure 2. Vygon® Boussignac CPAP system.

connected using the same parameter settings earlier used for their ventilation, and oxygen delivery can be slowly increased according to their needs.

During CPAP ventilation

FOB in unstable non-ventilated patients that, despite receiving large volumes oxygen, have limited oxygen saturation, can be performed using the Vygon® Boussignac CPAP kit (Fig. 2), which is adapted to a face mask.

CONCLUSIONS

FOB and NIV are not only compatible, they can actually be complimentary. Choosing the best entry route and materials for each patient depends

primarily on their age and pathology. There are commercially available adaptors for facilitating simultaneous bronchoscopy and NIV in pediatric patients.

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Neonatal non-invasive ventilation

*Grupo Respiratorio Sociedad Española de Neonatología**

INTRODUCTION

The high incidence of respiratory disease among neonates, combined with advances in respiratory medicine, has led to a wide arsenal of strategies for neonatal respiratory assistance. Since mechanical ventilation of neonates was begun in the 1960's, the mortality rate of newborns with respiratory pathologies has decreased dramatically. In 1971, Gregory first reported the use of continuous airway pressure as an early treatment for respiratory distress syndrome (RDS). In 1973, Agostino reported the treatment of a series of low birth weight neonates using nasal continuous positive airway pressure (n-CPAP). Non-invasive ventilation gradually became widespread, having been applied through myriad devices such as negative pressure chambers, face chambers and face masks; however, none of these methods entered common practice due to their respective secondary effects. Currently, the most widely used NIV devices are nasal interfaces.

DELIVERY METHODS

Nasal continuous positive airway pressure

Nasal CPAP (n-CPAP) is the continuous delivery of a gas to the airway at a fixed pressure via the nostrils.

Nasal intermittent positive pressure ventilation

Nasal intermittent positive pressure ventilation (n-IPPV) is the combination of n-CPAP with periodic cycles of positive pressure whose frequency and parameters are set by the operator. Albeit this method can theoretically be used in synchrony with ventilators that detect the inspiratory efforts of patients (synchronized intermittent positive pressure ventilation [SIPPV]), currently there is only one commercially available system with a sufficiently sensitive flow trigger for neonatal patients, and clinical experience with this device remains very limited. Good results have recently been reported for patients that were removed from mechanical ventilation and in patients with apneas. N-IPPV has been shown to reduce the number of days of oxygen therapy and ventilation in preterm infants.

PHYSIOLOGICAL EFFECTS

The respiratory system of neonates, especially of preterm infants, is characterized by its immaturity: the chest wall is extremely unstable and the airways are extremely compliant, making them highly prone to collapse. Furthermore, neonates have low levels of lung surfactant and a weak central respiratory impulse, further complicating their ability to combat respiratory diseases.

INTERFACES AND PRESSURE-GENERATORS

Standard interfaces

There is a wide array of commercially available interfaces for neonatal NIV. The challenge with using

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Table I. Indications of neonatal non-invasive ventilation

- Diseases in which the FRC is altered (e.g. RDS and TNT) and/or that cause increased work of breathing
- Weaning from CMV
- In premature infants: apneas
- Pulmonary edema
- Paralysis and/or paresis of the diaphragm
- Laryngotracheomalacia
- Restrictive diseases of the upper airway (e.g. BPD)
- To decrease left-right shunt through persistent ductus

BDP: bronchopulmonary dysplasia; CMV: conventional mechanical ventilation; FRC: functional residual capacity; RDS: respiratory distress syndrome; TNT: transient neonatal tachypnea

this equipment is ensuring a proper seal between the interface and the airway. There are two main classes:

1. *Pharyngeal interfaces.* These are primarily used in the nasopharyngeal area. They can be single-sided or double-sided, although the former is used in the majority of cases. These are easy to adjust and have only minor leakage, but they increase resistance in the airway.
2. *Nasal interfaces.* These encompass nasal cannulae, nasal prongs and nasal masks. They are more widely used than pharyngeal interfaces and are more effective for resolving failed extubation in premature infants. However, they are difficult to adjust, can cause facial deformities and trauma, and suffer from frequent leakage. The most common nasal interface is short nasal prongs (see Chapter 5).

Pressure generators

Both continuous- and variable-pressure generators are used for neonatal NIV. In the former case, the pressure is generated during expiration; the typical set-up comprises a ventilator and one of the aforementioned interfaces. In the latter case, the pressure is generated through the flow of the delivered gas, which is regulated by the interface and the ventilator. Together, they maintain stable pressure during the length of the respiratory cycle, generating less resistance during expiration, which

improves the patient's work of breathing. N-IPPV can be used in this type of system with or without synchronization. Currently available devices for synchronizing the patient's breathing efforts operate by detecting changes in movement (abdominal impedance) or in flow (see Chapter 6).

INDICATIONS

Neonatal NIV was initially used to treat pathologies marked by a low FRC, such as hyaline membrane disease and transitory tachypnea. It has also been used to treat patients that have just been removed from conventional mechanical ventilation (CMV) to prevent reintubation and apneas. As a result of the ever increasing clinical experience with neonatal NIV, the range of indications of this technique has expanded to encompass nearly all neonatal respiratory pathologies.

CLINICAL APPLICATIONS

Clinical use of NIV in neonates, especially in extremely premature infants, can be complicated and requires coordinated hospital care. N-CPAP is initially delivered at a minimum pressure of 4 to 5 cm H₂O with the minimum FiO₂ required to maintain adequate transcutaneous oxygen saturation (SatO₂) for the patient's gestational age and lung pathology (see Table II). The inspired gas should be properly heated and humidified. The pressure should be gradually raised in increments of 1 to 2 cm H₂O until an adequate lung volume is reached; in clinical practice, this pressure ranges from 5 to 8 cm H₂O, although it varies according to each patient and their pathology.

Ideally, n-IPPV should be used as SIPPV; however, currently available devices are rather limited in the quality of synchronization that they provide. They enable regulation of inspiratory and expiratory pressures, inspiratory time and respiratory frequency. The expiratory pressure is typically set at 4 to 6 cm H₂O; the inspiratory time, at least 2 cm H₂O above the expiratory pressure; the inspiratory time, from 0.4 to 0.6 seconds; the respiratory frequency varies in function of the patient's size and pathology; and the FiO₂ used is the minimum value that affords the desired SatO₂ (see above, and Table II).

Table II. Providing neonates with adequate oxygenation

• Pre-term neonates:	PaO ₂ : 50 to 60 mmHg SatO ₂ : 88 to 92%
• Full-term neonates:	PaO ₂ : 50 to 70 mm Hg SatO ₂ : 92 to 95%

Source: Sociedad Española de Neonatología, Grupo Respiratorio Neonatal, 2001.

ENSURING SUCCESSFUL NON-INVASIVE VENTILATION

The success of NIV is determined primarily by the technical quality of the treatment and by the quality of patient care, which is especially important for minimizing any side effects caused by the treatment.

Technical factors

It is essential that the proper interface (i.e. model and size) for each patient is chosen and positioned correctly. It must be fastened with just the right amount of pressure to guarantee a good seal and constant gas flow; too little pressure will generate leakage, whereas too much will cause local pressure sores. Proper heating and humidification of the inspired gas is also fundamental, since the high gas flows in NIV can have deleterious effects on the patient's bronchial secretions, which in turn can lead to technical failure of the treatment and/or aggravation of the patient's respiratory pathology. Inspired gases are normally conditioned to 37 °C and 100% relative humidity (44 mg/mL at 37 °C).

Patient care

Proper care of the patient's upper airway—namely, correct positioning of their head and removal of bronchial secretions which can block this airway—will prevent increased airway resistance, and consequently, avoid increased work of breathing.

NIV patients are normally fed via oral-gastric tubes; however, some patients may be able to be fed orally. The technique must be used carefully to ensure the patient's comfort and prevent gastric distension, which can occur if patients with increased work of breathing swallow the delivered gas. Indeed, the patient's comfort level is a good indicator of how well the technique has been applied. Hospital staff must have sufficient expertise to be able to detect

any decline in the patient's wellbeing and to resolve any problems that arise during treatment. Hospital staff should cooperate closely with the child's parents and make them active participants in the child's care.

The neonate should be closely monitored, primarily by standard non-invasive methods such as pulse oximetry, transcutaneous blood gas monitoring, and chest wall impedance measurements. Chest wall impedance results can be used to quickly assess respiratory patterns in premature infants, who are normally difficult to examine directly because of the high level of humidity and the barriers against luminal contamination inherent to neonatal incubators.

Lung X-rays provide information on lung volume (e.g. collapse and over-compliance) which is important for fine-tuning the level of pressure used in NIV.

Lastly, each ward should establish and put into practice its own protocols for neonatal NIV.

FAILURE OF NON-INVASIVE VENTILATION

When faced with negative results in NIV, hospital staff should first check the following factors before concluding that the technique has failed:

- Ensure that the patient's airway is correctly positioned and that their neck is not subject to excessive flexing or rotation (especially in extremely premature infants).
- Confirm that neither the interface nor the airway is blocked by secretions (a frequent cause of failure in NIV).
- Check that the ventilator is operating correctly and that the interface is positioned adequately.
- Ensure that the patient's mouth is closed (leakage through the mouth can lead to pressure losses of 2 to 3 cm H₂O).

Failure in NIV is characterized by the following signs and symptoms:

- The patient can not reach the target PaO₂ or SatO₂, and/or has high FiO₂ requirements (based on their gestational age and pathology).
- The patient requires administration of exogenous lung surfactant.
- In ARF patients: the PaCO₂ rises above 60 mm Hg at a blood pH of < 7.25
- The patient experiences apneas that either require strong resuscitation or occur more than three

Table III. Complications in neonatal non-invasive ventilation

- Gastric distension
- Increased upper airway secretions, leading to obstructive apneas
- An incorrectly positioned interface can cause deformations or necrosis of the nasal septum
- Excessive pressure can diminish minute volume and increase PaCO₂
- Air escape
- Increased vascular resistance in the lungs, complicating venous return and weakening the heart
- Favor left-right shunt through persistent ductus

times per hour, with concomitant desaturation and/or bradycardia.

REMOVING PATIENTS FROM MECHANICAL VENTILATION

Patients should be taken off NIV gradually once they reach the target PaO₂ or SatO₂ with low FiO₂ (0.3 for ARF) or if they have not experienced apneas in the previous 24 hours. The pressure should be decreased in increments of 1 cm H₂O in function of the patient's response, until ultimately reaching 4 cm H₂O. The procedure for removing patients from n-IPPV is similar to that used in invasive mechanical ventilation.

COMPLICATIONS

If hospital personnel are well-trained and experienced in NIV and in the ventilators used in

their ward, they can avoid the most common complications that arise during treatment (summarized in Table III).

INTERPRETATIVE SUMMARY OF COCHRANE COLLABORATION ABSTRACTS

N-CPAP is widely used in the delivery room; however, whether this treatment reduces the need for subsequent administration of lung surfactant or mechanical ventilation is currently unknown. For RDS patients, n-CPAP is often used as an alternative to mechanical ventilation despite a lack of clinical evidence clearly demonstrating its efficacy. Likewise, many moderate RDS patients given n-CPAP are not administered any lung surfactant, despite a lack of evidence that n-CPAP obviates treatment with surfactant. Early treatment with n-CPAP has been shown to reduce the need for mechanical ventilation (RR 0.55; CI 95%: 0.32 to 0.96; NNT 6). Also, n-CPAP reduces the need for reintubation if it is applied after extubation at a pressure of 5 cm H₂O. There are no data supporting the superiority of single or double nasal prongs in n-CPAP. However, double nasal prongs have been shown to be better at reducing the need for reintubation (RR 0.59; CI 95%: 0.41 to 0.85; NNT 5).

RECOMMENDATIONS

Recommendations for neonatal NIV are listed below. The level of each recommendation (indicated by a letter from A to D) and the strength of clinical evidence for each one are summarized in Table IV.

1. N-CPAP should be used early for all patients at risk for developing RDS, above all, premature

Table IV. Grades of recommendation and levels of evidence

Grade of recommendation	Level of evidence
A	A directly applicable, high quality meta-analysis, systematic RCT review, or RCT
B	Another type of RCT meta-analysis, or a systematic review of case control studies, or a lower quality RCT, with a high probability that the relationship is casual
C	Case control or cohort study with a low risk of bias or of confounding factors
D	Evidence derived from series of cases, individual cases, or expert opinion

RCT: randomized clinical trial. Adapted from the "SIGN Guidelines Developer's Handbook" (www.sign.ac.uk/guidelines/fulltext/50).

infants at 30 weeks of age that are not receiving CMV, until their clinical condition can be accurately evaluated (D).

2. N-CPAP and early administration of lung surfactant should be considered for all RDS patients as a means to reduce the need for CMV (A).
3. Double nasal interfaces are preferred over nasal-pharyngeal tubes since, when used at pressures of at least 6 cm H₂O (A), they reduce the need for intubation (C).
4. After extubation, premature infants weighing less than 1.5 kg should be treated with n-CPAP to avoid reintubation (A).

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Indications of non-invasive ventilation in chronic pediatric pathologies

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INTRODUCTION

Medical and technological advances, an increasing survival rate of critical patients, and a better general prognosis for sufferers of chronic respiratory diseases have all led to a rise in the number of pediatric patients and clinical situations treated with long-term mechanical ventilation. Although conventional mechanical ventilation (CMV) via tracheal tube is the most effective form of mechanical ventilation, tracheostomies are problematic and involve various complications, and consequently, are avoided whenever possible. The increasing use of polysomnography (PSG) in the past fifteen years has enabled better characterization of respiratory sleep disorders. When non-invasive ventilation (NIV) was first used, it was primarily indicated for children and adolescents with neuromuscular diseases (NMDs). Since then, its range of indications has expanded to encompass obstructive sleep apnea syndrome (OSAS) and parenchymal lung disease. This broad array of indications comprises two main groups: pathologies that can be clinically improved (e.g. bronchopulmonary dysplasia [BPD] and laryngotracheomalacia) and those which are stable or progressive (e.g. NMDs and congenital central hypo-ventilation syndrome [CCHS]). Home respiratory care has undergone major developments in the past two decades, owing in great part to technological refinements of ventilation equipment.

CRITERIA FOR INITIATING NON-INVASIVE VENTILATION

When healthy individuals are asleep, they have greater upper airway resistance, reduced tidal volume (above all, during REM sleep), lower respiratory frequency, reduced intercostal muscle tone and weaker central ventilatory impulse. Consequently, their PaCO₂ rises by 3 to 7 mm Hg while their PaO₂ drops by 3 to 9 mm Hg. Children are especially susceptible to these changes due to the following anatomical and functional factors:

- A higher percentage of REM sleep (40 to 70%), and more daytime sleep, than adults.
- A respiratory system which is still undergoing growth and development.
- Greater upper airway resistance, especially at the level of the subglottal area and the choanae, than adults.
- Highly compliant chest wall.
- Diaphragm has a lower number of fatigue-resistant muscle fibers than in adults.

Hence, the number of clinical situations in which children can benefit from home NIV is greater than for adults. The respiratory physiology of children, combined with the muscular hypotonia inherent to REM sleep, together facilitate more severe respiratory sleep disorders which can have diurnal consequences.

Given that the first signs of these disorders often appear during sleep, PSG is one of the most widely applicable tools for diagnosing respiratory disorders.

Symptoms of respiratory disease may be accompanied by hypoxemia, with or without concomitant hypercapnia. However, children are sometimes treated with mechanical ventilation despite not having experienced major changes in blood gas levels, as the disorder may manifest itself in polypnea and intensive work of breathing, which in turn take a massive toll on a child's energy reserves and can ultimately affect their ponderal growth.

Altered respiratory function in children has been associated with disturbed sleep, which, in very young children, may manifest itself as daytime irritability, and in older children, may cause problems with learning, behavior or growth.

Respiratory infections are frequent among pediatric patients, and in some cases (depending on the respiratory pathology) are nearly permanent and can even be fatal. The respiratory compromise resulting from these infections can lead to cardiovascular overload, which can translate into pulmonary or arterial hypertension and even cor pulmonale. Hence, pediatric patients with these types of chronic respiratory conditions require NIV. Although NIV probably will not prolong a patient's life—for example, in the case of progressive NMDs—, it can be useful for relieving symptoms (e.g. lack of air, exhaustion, and poor sleep for the child or their family). It also limits the severity of flare-ups. NIV can be extremely useful in prophylactic treatments, enabling expansion of the chest wall and growth of the lungs. Ventilation is primarily provided while the patient is asleep, when respiratory conditions are the most aggravated and the consequences of hypoventilation are markedly worse. Nocturnal NIV can provide a diurnal reserve of respiratory strength.

Correcting blood gas levels and decreasing work of breathing provide the patient with better quality sleep (i.e. more regular sleep with disappearance of apneas, greater relaxation and decreased sweating), and consequently, improvements in their diurnal state (i.e. better mood, greater attention span and fewer headaches). The decrease in energy expenditure resulting from less respiratory effort can facilitate weight gain, and the improvements in ventilatory mechanics reduce the frequency of respiratory infections. Lower morbidity rates translate to fewer hospital admissions, higher quality of life for the patient and their family, including fewer days of lost work, and savings in healthcare costs.



Figure 1. Child with congenital central hypoventilation syndrome that started non-invasive ventilation (NIV) at the age of 11 days.

The objectives of long-term home NIV are summarized below:

- a. Maintain and prolong the patient's life.
- b. Improve the quality of life of the patient and their family.
- c. Maintain adequate (i.e. age-appropriate) growth and development of the patient.
- d. Promote lung growth and expansion and prevent chest wall deformities.
- e. Reduce morbidity.
- f. Facilitate return of the patient into their family circle.
- g. Optimize the cost to benefits ratio of the patient's healthcare

AGE

NIV is being used for younger and younger patients. This is most likely the result of the growing body of clinical experience with the technique as well as of technological advances—namely, the development of ever-smaller masks. Not long ago, children that required ventilation assistance in the first few years of life were initially tracheotomized, and then, gradually transitioned to NIV several years later. However, NIV is now used for very young patients (see Fig. 1).

One of the major complications to consider when starting early NIV is the effects of the pressure from the mask on the child's facial bone structure. Children's facial bones are constantly growing and highly moldable; by age four, only 60% of the facial structure has been formed. The risk of facial deformation in NIV is very high in patients that sleep several hours per day and that can not sleep without ventilation (e.g. CCHS patients).

INITIATING NON-INVASIVE VENTILATION: DELIVERY METHOD AND LOCATION

Acute pediatric patients are typically started on NIV, or transitioned off of CMV, in the ICU. In chronic situations and other select cases treatment is begun in the general ward. There are also reports of NIV being started at home; however, this method can be problematic. Since the initial phases of NIV can ultimately detect the success of treatment, then hospital staff may consider admitting the patient into the hospital for 3 to 5 days, so that they and their families can familiarize themselves with the equipment, and the patient can get accustomed to sleeping with the mask on while the ventilator is running. The patient and their family should also be familiarized with the typical complications and side effects in NIV and how to resolve them.

In infants, NIV treatment is started by attaching the mask to the child after they have fallen asleep. For older patients, hospital personnel first explain each step of the procedure to the patient, endeavoring to slowly gain the patient's confidence, and then eventually start NIV over the course of the day in increasingly longer periods. These patients are then transitioned to night ventilation, after which they usually improve quite rapidly and accept treatment, especially in the case of obstructive sleep apnea syndrome (OSAS). Use of gradually rising pressure (i.e. a pressure ramp) is often required to facilitate adaptation.

The success of the treatment is highly dependent on the extent to which the parents can motivate their child, especially in the case of home ventilation. In order for the patient's parents to fully appreciate the benefits of NIV, they must be made familiar with each step of the treatment. Albeit NIV is safe and tolerated by the majority of pediatric patients, the rates of NIV failure reported in the literature range from 10% to over 40%. The expertise of hospital staff is also critical to successful treatment.

Use of negative pressure ventilators has continued to decline because they are difficult to transport and imply complications such as frequent obstructive sleep apneas. Volumetric ventilators have specific indications, are bulky and difficult to acquire (see Chapter 6, "Non-invasive ventilation devices"). Children generally adapt well to bi-level pressure ventilators; hence, these have become the most widely used type of ventilator. However, even

these devices may occasionally present adaptation problems.

Ventilation should begin at low pressure (3 to 4 cm H₂O) and then the pressure should be increased according to the patient's level of adaptation. If there is an obstructive component, the preferred ventilation mode is continuous positive airway pressure (CPAP). If desaturation persists even after correction of the obstruction, then the mode may have to be switched to bi-level positive airway pressure (BiPAP). Children tolerate BiPAP slightly better than CPAP. Some authors (e.g. Teague) have reported starting with an inspiratory positive airway pressure (IPAP) of 6 to 10 cm H₂O and an expiratory positive airway pressure (EPAP) of 5 cm H₂O. High expiratory pressures may be required for patients with atelectasis, hypoventilation associated with V/Q mismatch, or obstructive apneas. The tidal volume of infants or NMD patients may be too small to activate the ventilator's trigger (especially during REM sleep); hence, respiratory frequency should always be used as a rescue parameter for these patients (via spontaneous/timed [S/T] mode).

With few exceptions, nasal interfaces are the most widely used type of interface for starting NIV. However, their use in small children may be complicated by the limited number of commercially available age-appropriate models. These patients may need a custom molded interface; however, this is not always an option.

Oral interfaces have been used in some pediatric patient groups, but these require a high degree of patient cooperation and are not always amenable to nocturnal ventilation. Indeed, prolonged nocturnal ventilation using oral interfaces can cause dental problems in small children.

Oral-nasal interfaces may be an alternative for patients with mouth breathing, nasal obstruction or significant mouth leakage. Oral leaks often occur in NMD patients due to their muscular weakness or due to repositioning of their lower jawbone. Oral-nasal interfaces can also be used in acute cases. However, their range of indications remains somewhat limited due to their inherent risk of facilitating aspiration of vomit.

There is no such thing as a perfect interface. For patients that require several hours of ventilation per day, rotating among different interfaces can prevent or at least reduce the risk of pressure sores by shifting

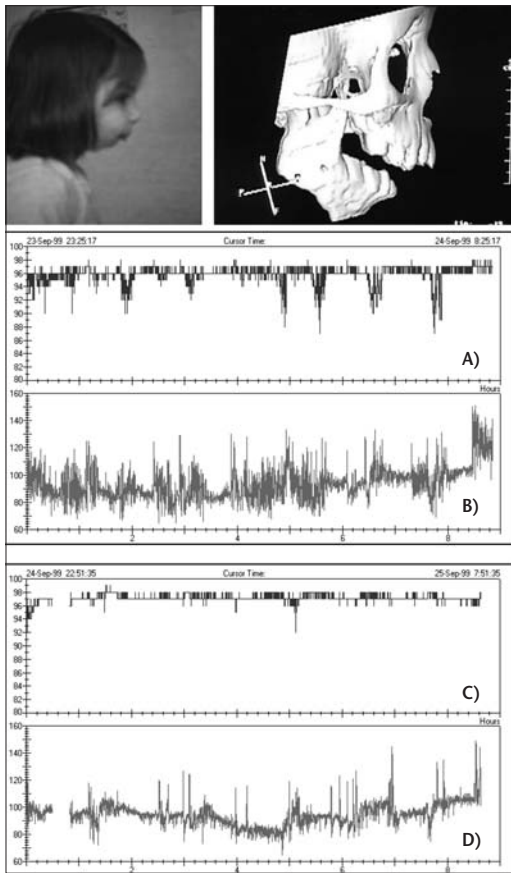


Figure 2. Two year old girl with severe microretrognathia. She presented with severe obstructive sleep apnea syndrome. Nocturnal pulse oximetry before (A, B) and after (C, D) continuous positive airway pressure (CPAP).

the pressure from the interface to different areas of the patient's face, and consequently, varying the local point of maximum pressure and friction.

Once the interface has been positioned and ventilation has begun, the patient must be monitored for respiratory parameters (including SatO_2 and SatCO_2 at the end of each expiration, if possible), recruitment of accessory muscles in breathing, and sweating, which is especially important in the patient's head (sweating improves as the patient becomes better ventilated).

Once the patient's hemoglobin level has increased, reflecting lowered respiratory distress and reduced sweating, hospital staff should explain the benefits of maintaining the patient on regular home



Figure 3. Infant being monitored by polysomnography to adjust ventilation parameters.

ventilation to the patient's parents. In some patients desaturation is small, but as long as they are well ventilated, then their heart rate will decrease. Ventilation parameters can be adjusted according to the results of either nocturnal pulse oximetry (Fig. 2) or PSG (Figs. 3 and 4).

Costal movement ensures lengthwise growth of the ribs—and, therefore, an increase in chest wall parameter—as well as growth of the lungs. Any paralysis of the respiratory musculature, including the inter-costal muscles, leads to stunted growth of the ribs by 10 cm and ultimately causes paradoxical movement of the ribs. Children that experience this shortening early in life will be unable to perform any adequate costal movements. Hence, proper movement achieved through early application of NIV can favor growth of the rib cage.

INDICATIONS OF NON-INVASIVE VENTILATION IN CHRONIC PEDIATRIC PATHOLOGIES

NIV has an ever expanding range of indications in chronic pediatric pathologies (see Table I). These indications are classified and summarized below. Several peculiar cases are also described.

Pathologies of the respiratory system

Compromised airways

1. Craniofacial malformations:

- Retrognathia.
- Micrognathia (e.g. Treacher-Collins and Pierre-Robin syndromes).
- Hypoplasia of the mid-face (e.g. Pfeiffer, Crouzon and Apert syndromes).
- Macroglossia (gigantism syndrome).

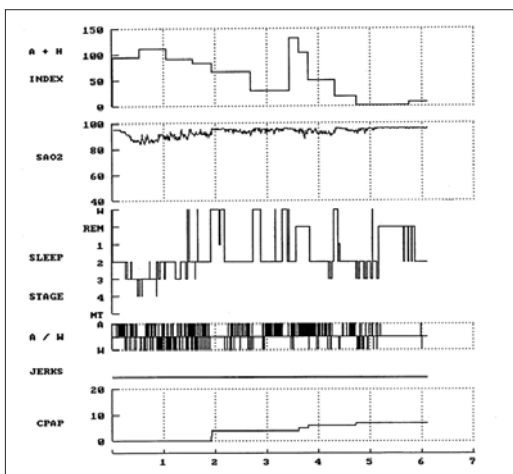


Figure 4. Child with achondroplasia and severe obstructive sleep apnea syndrome being monitored by polysomnography to adjust ventilation parameters. As the continuous positive airway pressure increases, the total number of apneas and hypopneas per hour (A + H index), and the number of micro-arousals (A/W), decrease, and the level of SatO₂ increases as REM sleep begins.

2. Major hypertrophy of the adenoids and of the tonsils and/or soft palate:
 - In patients who are temporarily or permanently contra-indicated to surgery.
 - In diseases characterized by abnormal growth of lymph tissue (e.g. sickle cell disease).
3. Malacia of a segment of the respiratory tract:
 - Isolated.
 - Associated with polymalformative syndrome.
 - Resulting from repeated infections.

Upper-airway obstruction facilitated by atony of the airways may occur in sleeping children with anatomical alterations or malformations (e.g. hypertrophy of the tongue or of the tonsils and palate) or with conditions marked by increased upper airway resistance (e.g. under-development or repositioning of the jaws, narrow palate, large soft palate, or abnormal airway curvature at the base of the skull). Although some of these patients may be treated with surgery (e.g. glossopepy, lower jawbone osteotomy, facial repositioning surgery, or tonsillectomy), they can also benefit from temporary NIV. For some patients, ageing and growth of the face and airways may lead to spontaneous improvements in symptoms. Contrariwise, in children with craniofacial anomalies, hypoxemia or

Table I. Chronic pathologies for which non-invasive ventilation (NIV) is indicated.

1. Pathologies of the respiratory system
 - A. Airways
 - B. Lungs
2. Neurological diseases
 - A. Central
 - B. Peripheral
3. Neuromuscular diseases and chest wall diseases
4. Mixed pathologies
5. Other pathologies

hypercarbia secondary to airway obstruction may have deleterious effects on their neurological development. Indeed, many of these patients suffer from hyperactivity or major delays in growth and development.

Laryngotracheomalacia is a frequent cause of stridor in infants and is the most common cause of partial obstruction of the upper airway. This condition can cause severe complications such as airway obstruction, leading to sudden death, pulmonary hypertension, cor pulmonale, stunted growth, and delayed intellectual development; however, most children overcome this condition by age two. Surgery (e.g. epiglottoplasty) may not be sufficient for some patients. However, before hospital personnel consider treating these patients by tracheotomy, which is associated with a high degree of morbidity, they should consider NIV, which reduces work of breathing. EPAP frees blocked airways and keeps the upper airway open, and increases the FRC, which in turn dilates the pharynx. NIV is similarly advantageous for lower airway malacia disorders.

Lung diseases

1. Cystic fibrosis.
2. Bronchiectasis.
3. Bronchopulmonary dysplasia (BPD).
4. Diffuse interstitial pulmonary diseases.

Children with healthy lungs do not suffer from respiratory alterations that occur during sleep or in response to circadian rhythms. However, in patients with a lung disease involving limited pulmonary reserve, the normal effects of sleep on respiration can lead to clinically significant ventilatory and gas exchange anomalies.

Cystic fibrosis, bronchiectasis, BPD, and diffuse interstitial pulmonary diseases are all exacerbated during sleep, especially due to hypoxemia during REM sleep. Therefore, patients suffering from these diseases can benefit from NIV (see above).

The first use of NIV for cystic fibrosis patients was only as temporary support during lung transplants. However, its indications for this disease have since expanded to encompass treatment of symptoms including acute hypercapnia and respiratory muscle fatigue and to assist in kinesitherapy for improving diminished oxygen saturation. Late-stage cystic fibrosis patients develop hypoxemia and hypercapnia, especially during sleep. Gozal demonstrated that NIV markedly improves alveolar ventilation during sleep, as opposed to oxygen therapy alone, which improves oxygenation without improving sleep patterns or arousals. The same author also demonstrated that NIV improves subjective feelings of dyspnea, facilitates performance of everyday tasks and increases tolerance of respiratory kinesitherapy.

BPD, which is a chronic pulmonary disease that strikes premature infants with respiratory difficulty, causes respiratory failure of varying degrees which can become aggravated during sleep, but which gradually improves. BPD patients are typically treated with oxygen therapy, and in some cases (e.g. to correct hypoxemia) by ventilation via nasal interface. Long-term hypoxemia during growth stages can cause pulmonary hypertension and ultimately, cor pulmonale, and can lead to poor weight gain.

Neurological diseases

- Central:
 1. Congenital:
 - Primary: central hypo-ventilation syndrome (CCHS).
 - Secondary:
 - Type II Arnold-Chiari malformation.
 - Leigh syndrome.
 - Moebius syndrome.
 - Pyruvate kinase deficiency.
 - Carnitine deficiency.
 2. Acquired:
 - Asphyxia.
 - Infections.
 - Trauma.
 - Tumors.
 - Heart attacks.

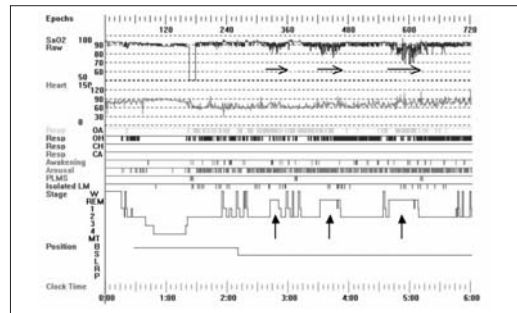


Figure 5. Polysomnograph of a child with a neuromuscular disease. These diseases are characterized by the relationship between desaturations (→) and REM sleep (↑), and often include obstructive apneas (OA), obstructive hypopneas (OH) and arousals.

- Peripheral.

Alveolar hypoventilation is typically only observed in patients with neuromuscular or lung diseases and is classified as congenital or acquired. In the former case, it can be secondary to brain malformations (e.g. Type II Arnold-Chiari malformation) or functional anomalies (e.g. pyruvate kinase or carnitine deficiencies). In the latter case, it may be result from various factors (e.g. vascular, inflammatory, or infectious).

CCHS—which in 2003 was associated with heterozygous mutations of the PHOX2B gene by Debra Weese-Mayer and Jeanne Amiel—is characterized by reduced involuntary control of respiratory function; however, it affects voluntary control to a much lesser extent. Given that NREM is the sleep phase in which automatic respiratory function dominates, it is also the state during which ventilation is most compromised in CCHS. However, the consequences range in severity from minor perturbations of NREM sleep to alterations of both REM sleep and diurnal behavior. The symptoms of CCHS generally appear by age one, and normally affect patients on a daily basis; however, in the past few years, cases have been identified in which symptoms did not arise until late infancy or even adulthood. CCHS does not disappear with age.

Children with CCHS normally require ventilatory assistance during sleep, and the most severe cases may also require it during the day. In the past, all pediatric patients were initially tracheotomized, and those patients treated with primarily nocturnal

hypoventilation were then transitioned to NIV. NIV is now used increasingly more often and in ever younger patients (see Fig. 1).

Children with severe CCHS may require a diaphragmatic pacemaker during the day, to improve their mobility, and NIV during sleep. Whatever ventilation mode is used, the primary objective is to prevent episodes of hypoxia and their consequences on cardiopulmonary (e.g. hypertension) and cerebral (e.g. convulsions and mental retardation) function. Indeed, the prognosis for these patients can be improved if hypoxia can be avoided.

One of the complications that affect young children treated with ventilation is hypoplasia of the mid-face caused by prolonged use of masks. However, it is quite rare: only a few hundred cases have been reported worldwide.

Type II Arnold-Chiari malformation is a complex deformation that affects the CNS, bones and soft tissue. It consists of a downward shift of the medulla and the cerebellum via the foramen magnum. It is often associated with myelomeningocele. Type II is the Arnold-Chiari malformation which is most related to respiratory sleep disorders. Compression of the spinal cord can cause central apneas due to reduced response to hypercapnia or by affecting the peripheral response to hypoxia via compression of the ninth cranial nerve. Obstructive sleep apnea may result from vocal cord abductor paralysis (VCAP) or from compromised function of the pharyngeal dilator muscle caused by lesions in the ninth or tenth cranial nerve.

Decompression of the posterior fossa is the first treatment strategy employed for Arnold Chiari syndrome. However, this may not be sufficient, especially in patients with obstructive sleep apneas; NIV would then be required.

Patients with high spinal cord lesions, which are often caused by trauma, need immediate ventilation assistance if the lesion is above C4; if the lesion is below C4, they will have some respiratory autonomy, but if they suffer any complication, then they will rapidly deteriorate.

NEUROMUSCULAR AND CHEST WALL DISEASES

Respiratory failure is often a major cause of morbidity and mortality in acute and chronic NMD

patients, although this varies highly according to the pathology (see Table II). Hence, respiratory failure in NMD patients with normal lungs may cause hypoxemia and hypercapnia comparable to that found in severe lung diseases. NMD patients have difficulty breathing primarily because they can not expand their chest wall (i.e. lungs, rib cage and diaphragm).

Respiratory complications caused by NMD have been known for quite some time; however, they are often underestimated and occur more frequently than assumed. The role of sleep in these complications was only recently discovered. The CNS controls respiratory musculature differently during sleep than during waking hours, which has major consequences on the body's ability to capture O₂ or release CO₂.

The limitations that NMDs place on respiratory musculature start during sleep and continue during waking hours. The first respiratory anomaly to occur is disturbance of REM sleep by micro-arousals, which can be considered as both a type of adaptive response that shortens REM sleep time as well as a consequence of desaturation. This leads to REM sleep deprivation (see Fig. 5), which has serious cerebral and respiratory consequences: loss of function of the frontal lobe, and consequently, diminished concentration and alertness; mood swings, which in children translates to irritability; decreased response to hypoxia and to hypercapnia; and compromised function of the respiratory musculature. Furthermore, stabilization of the airways by dilatory muscles is diminished, obstructive apneas arise during sleep, and muscle activity in the chest wall decreases, which leads to hypoventilation. Respiration depends on proper functioning of the diaphragm.

Specific problems occur in REM sleep when the NMD implies affectation of the diaphragm. For example, the tidal volume decreases markedly as accessory muscles become paralyzed and respiration becomes dependent exclusively on the diaphragm. Infants with this type of NMD are especially vulnerable because their chest wall is highly compliant and is characterized by very low tidal volumes, and because they sleep a lot and have a high proportion of REM sleep. In healthy infants, diaphragmatic work may correspond to 10% of the baseline metabolic rate, whereas infants with a

Table II. Effects of the most common neuromuscular diseases on respiratory function (adapted from Givan, DC)

Lesion	Disease	Muscular/respiratory affection
Motor neuron	Spinal muscular atrophy	G
	Distal spinal muscular atrophy	Distal muscles of the limbs
Peripheral nerve	Charcot-Marie-Tooth syndrome	UA; D
	Riley-Day syndrome	UA
	Phrenic nerve lesions	D
	Leukodystrophies	G
Neuromuscular junctions	Congenital myasthenia	G
	Myasthenia gravis	G
Muscular (types)	Duchenne and Becker syndromes	G; M
Dystrophinopathies	Emery-Dreifuss syndrome	G; M; D
Non-dystrophinopathies	Muscular dystrophy (MD) of the waist	D; I; A
	Facioscapulohumeral (FSH) MD, oculopharyngeal MD (OPMD)	UA; neck ± D
	Merosine-deficient	G
	Merosine-positive	UA
Myotonic dystrophy	Congenital and non-congenital	UA; M; D; decreased central drive; apnea
Congenital myopathy	Nemaline; central core; minicore; multicore; centronuclear; myotubular; fiber disproportion	G; D; UA
Metabolic myopathies	Acid maltase deficiency (Pompe's disease)	UAS D
Mitochondrial myopathy	Dehydrogenase deficiency	Apnea; G
	Type I respiratory complex deficiency	G; M
	Type IV respiratory complex deficiency	G

D: diaphragm; G: general; I: intercostal; M: myocardial; UA: upper airway.

compromised diaphragm have a very low metabolic reserve.

All NMDs may imply secondary conditions such as scoliosis or pulmonary hypoplasia, which in turn contribute to the development of atelectasis, respiratory infections and respiratory failure (and consequently, all of the aforementioned problems). Hence, these NMD patients ultimately require NIV during sleep.

Medical and technological advances in NIV have fomented use of HMV, which in turn has led to new approaches to many NMDs that were previously considered fatal without exception. Home NIV has increased the life expectancy of pediatric NMD patients and improved their quality of life.

Spinal muscular atrophy (SMA) is a congenital autosomal recessive disorder of the cells of the anterior horn of the spinal cord and frequently affects the motor nuclei of the fifth and sixth cranial nerves. It involves mutations in the 5q 11-13 region of chromosome 5. SMA is characterized by muscle weakness in the extremities of the limbs and

progressive affection of the chest wall muscles. SMA does not affect the motor neurons of the phrenic nerve and only affects the diaphragm in its latter stages. One in 25,000 newborns suffers from SMA.

SMA is typically classified into three types according to the age of onset of the symptoms and to the maximum level of motor function: Type I (Acute SMA, or Werdnig-Hoffman disease), which occurs in infants; Type II (Intermediate SMA or Oppenheim disease), in older infants; and Type III (Mild SMA, Kugelberg-Welander disease or Juvenile SMA), in older children.

SMA is one of the most deleterious NMDs in terms of respiratory consequences. In children with Type I, reduced movement is detected shortly after birth. Their prognosis is rather grim: respiratory failure occurs early on, generally as part of a respiratory infection, and rapidly worsens in the absence of ventilatory assistance. There is a general consensus that NIV is beneficial for all SMA patients except those with Type I. Early NIV



Figure 6. Four year old boy with spinal muscular atrophy that started non-invasive ventilation (NIV) at the age of 18 months. He does not have any chest wall deformation or symptoms.

treatment has been proposed for stimulating development of the chest wall and growth of the lungs. Prophylactic use of NIV (i.e. before symptoms of hypoventilation appear) favors chest wall development and may even reduce symptoms, especially in children with Type II (see Fig. 6). However, the prognosis for each child should be determined on an individual basis, and not according to their type of SMA.

Children with Type II may be able to sit down without help. Muscle function in these patients is only partially compromised, and may go unnoticed before onset of a respiratory infection that ultimately leads to respiratory failure.

Distinguishing between Type I and Type II may be difficult when diagnosing patients that exhibit marked muscular hypotonia before the age of 6 months. Dubowitz developed a grading scale for each type whereby the condition is ranked from 1 to 9: for example, an infant with Type I.9 is closer to Type II than to more severe levels of Type I (I.1 or I.2).

Children with Type III may have total freedom of movement. Respiratory failure in Type III typically occurs in late adolescence or early adulthood.

Duchenne myopathy is the most common form of muscular dystrophy (MD) among infants, affecting one in 3,500 newborns. It is an X-linked recessive genetic disease. The severity of Duchenne MD is reflected in the extent to which the patient is deficient in the protein dystrophin. The least severe form is known as Becker MD.

Pulmonary function in MD patients is characterized by three phases: in the first, up to age

ten, the patient has normal lung growth and development; in the second, pulmonary function begins to plateau and the patient begins to lose muscle strength; and in the third, the patient suffers a gradual loss of forced vital capacity.

The first signs of diminished respiratory function in MD patients appear during sleep: obstructive sleep apneas, in younger children, and then hypoventilation, later on. These complications typically arise during REM sleep, when vital capacity is below 30% of the theoretical value, and increase as the patient ages. Patients with mild to medium nocturnal hypoxia are often asymptomatic; they do not begin to display symptoms until respiratory perturbations affect their REM sleep. This is one of the greatest sources of controversy regarding the benefits of NIV. In one study, NIV treatment led to significant improvements in nocturnal blood gas exchange but did not affect sleep patterns, strength of respiratory musculature, number of hospitalizations, or rate of invasive ventilation. Contrariwise, another study reported a lower number of hospitalizations among patients treated with NIV compared to those treated by tracheostomy. Long-term NIV does not appear to be beneficial.

In myopathies and congenital MDs the level of muscle weakness, and its limitations on respiratory function, are related to the myopathic or dystrophic process. In some cases, NIV may prove insufficient, and the patient must be switched to CMV by tracheostomy.

Isolated scoliosis, unless it is very severe, rarely causes respiratory failure that requires CMV. Patients that do require invasive ventilation typically show signs of muscle weakness, rigid spine syndrome or parenchymal lung disease (see Fig. 7).

MIXED PATHOLOGIES

Respiratory difficulties may be caused by complex mixed etiologies.

The clearest examples of these pathologies are the genetic syndromes listed below, as well as obesity-hypoventilation syndrome:

- Down's syndrome.
- Mucopolysaccharidosis (MPS).
- Prader-Willi syndrome.
- Achondroplasia.



Figure 7. Non-invasive ventilation of a child with a severe chest wall deformity.

Down's syndrome is one of the most widespread genetic disorders, affecting 1.5 in every 1,000 newborns. The particular facial characteristics of children with Down's syndrome are partially due to their abnormal cranial structure. This malformation, combined with the fact that Down's syndrome patients have narrow upper airways, suffer from glossoptosis or macroglossia and are predisposed to other conditions (e.g. obesity, hypothyroidism and generalized hypotonia), leads to a 30 to 50% higher rate of obstructive sleep apnea syndrome (OSAS) in children with Down's syndrome as compared to healthy children. Pulmonary hypertension induced by airway obstruction occurs more quickly in children with Down's syndrome, as it is facilitated by other factors such as pulmonary hypoplasia, congenital cardiopathy (in 30 to 40% of patients), and recurrent respiratory infections. OSAS often goes unnoticed by hospital staff and patient's families: many of its sequelae (e.g. growth, alterations in behavior or sleep, and pulmonary hypertension) are often confused with effects of the syndrome itself.

Airway obstruction in Down's syndrome patients is usually caused by hypertrophy of the tonsils and adenoids; therefore, it is often treated by surgical resection of the affected tissue. However, patients that do not suffer this hypertrophy or for whom surgery does not provide the desired results must be treated with NPPV. Good results have been reported for home NPPV via nasal mask. Other treatments for respiratory sleep disorders in Down's syndrome patients include uvulopalatopharyngoplasty (UPPP), tongue reduction, midface advancement, and tracheostomy.

Patients with mucopolysaccharidosis (MPS) often suffer from compromised respiratory function: their

tongue, nasal mucous membranes, oropharynx, epiglottis, tracheal wall and bronchi become enlarged, ultimately leading to total obstruction of the airways. This progressive process is associated with the characteristic cranial shape of MPS patients, which favors recurrent respiratory infections as well as airway obstruction, which can be severe and cause OSAS.

MPS patients also suffer from bone malformations (e.g. scoliosis, hyperkyphosis, thoracolumbar gibbosity and/or lumbar hyperlordosis) that can affect respiratory function. The extent of respiratory compromise depends on the type of MPS: the most severe consequences occur in Type I (Hurler syndrome) and Type II (Hunter syndrome). These patients are particularly difficult to intubate; furthermore, due to their spinal column abnormalities, they must be intubated with extreme caution. The multifaceted etiology of these patients complicates their treatment. In the past, sleep apneas in these patients were treated by tonsillectomy and/or adenoidectomy. However, due to the diffuse affection of the airway and to the continuous local deposits of polysaccharides that occur in MPS, these approaches are only temporary solutions. Hence, NPPV has become the preferred method for long-term efficacy.

Prader-Willi syndrome is characterized by infantile hypotonia, obesity, hypogonadism, altered behavior, and mild mental retardation. It affects one in 15,000 newborns. Nearly 70% of Prader-Willi patients carry a deletion in the q11q13 region of the long arm of chromosome 15.

Respiratory problems in Prader-Willi syndrome have a mixed etiology, encompassing peripheral and central mechanisms: muscular hypotonia, reduced lung function, facial dimorphism with arched palate and narrow airways, hyperplasia of the tonsils and adenoids, obesity, and malfunctioning of the hypothalamus and of chemical receptors. NIV is a common treatment for Prader-Willi patients with respiratory sleep disorders; however, it is often difficult to administer due to the behavioral perturbations that frequently accompany the syndrome.

Achondroplasia is an autosomal dominant disorder that is manifested in various phenotypes (see Fig. 8). Achondroplasia patients are predisposed to respiratory sleep disorders (including sudden death) through various mechanisms:



Figure 8. Seven month old girl with achondroplasia. Despite having undergone spinal cord decompression, she still requires non-invasive ventilation (NIV).

1. Obstruction of airways:

A. Mechanical:

- Short cranial base.
- Hypoplasia of the middle third of the face.
- Relative hypertrophy of the tonsils and adenoids.

B. Neurological:

- Respiratory control centers are compromised by compression of the brain stem at the (stenosed) foramen magnum

2. Restriction:

A. Small chest wall.

B. Reduced anterior-posterior diameter.

The relative severity of each respiratory condition may vary with the phenotype of achondroplasia. Respiratory disorders in these patients are best characterized via PSG (Fig. 8).

Patients with severe obstructive sleep apneas that can not be resolved through resection of the tonsils and the adenoids or through another surgical procedure (e.g. decompression of the spinal cord) must be treated with NIV.

NIV has also been used for conditions such as cardiopathies, although to a much lesser extent.

At Hospital Pediátrico de Coimbra, the largest patient group treated with NIV comprises NMD patients (approx. 40%), followed by those with some type of airway obstruction (22%).

The decision to initiate NIV is influenced by several factors:

- The technical limitations found in adult patients are exacerbated in pediatric patients, who often have structural alterations in the upper airway, high respiratory frequencies, and mouth leakage and suffer from patient-ventilator asynchrony.
- Each family's definition of quality of life for their child.
- Obtaining the cooperation of the child and their family to optimize treatment.

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Methodology for pediatric non-invasive ventilation in the home

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INTRODUCTION

Home mechanical ventilation (HMV) was first used in the mid-20th century as a treatment for chronic respiratory failure (CRF) caused by the widespread polio epidemic. Now it is used in response to the increased survival rate of CRF patients that depend on respiratory support and/or oxygen therapy. The improved prognosis for these patients is due to several factors, including medical, diagnostic and therapeutic advances, technological outfitting of pediatric and neonatal intensive care units, and broader ethical and psychological criteria for prolonging patients' lives with mechanical support.

HMV has been made possible due to continuing developments and improvements in ventilation equipment amenable to home care, which in turn have stemmed from financial investment in the field.

Discharging patients from the hospital, and caring for them at home, can be laborious tasks that demand the contributions of various professionals and institutions. To ensure the best treatment for the patient, these efforts should be focused in a specific home care program.

INVASIVE VENTILATION VERSUS NON-INVASIVE VENTILATION

Patients can be ventilated at home by two methods:

- Invasive ventilation (via tracheostomy or by using a diaphragmatic pacemaker)
- Non-invasive ventilation (NIV) using positive pressure (NPPV) or negative pressure (NNPV).

The most widely used techniques are invasive ventilation via tracheostomy and NPPV. Although this chapter is focused on NPPV, details for the other ventilation methods are provided.

The choice of method depends on factors such as the age at which treatment begins, pathology, degree of respiratory autonomy, and the extent to which the child and the parents are willing or able to cooperate. Hence, ventilation via tracheostomy is most frequently used in small children or as vital support therapy in patients lacking respiratory autonomy, whereas NIV is more widely used in older children, adolescents and adults as an elective therapy aimed at preventing flare-ups, preserving pulmonary function and increasing survival rates.

Up to the past decade, ventilation via tracheostomy has been the predominant form pattern of pediatric HMV. Indeed, an overview of nineteen articles published in between 1983 and 1998 reveals that of the 455 total children treated, 71% were treated via tracheostomy, as compared to only 13% for NPPV. However, data from an epidemiological study performed in Spain from June 1998 to June 2003 reflect a major surge in use of non-invasive ventilation: 51% treated via tracheostomy and 44% with NPPV. This change is primarily due to major technical advances in NIV ventilators and interfaces.

Some authors have reported that tracheostomy can be avoided or removed in pediatric neuromuscular disease (NMD) patients regardless of the number of hours of ventilation that they require per day. However, in order to receive NIV these patients must be mentally stable; able to cooperate; have sufficient bulbar muscle function to avoid aspiration of secretions which are produced by desaturation below 95%; have cough peak flow (either spontaneous or manually-assisted cough) above 2.7 L/sec; have sufficient lung compliance to enable non-invasive ventilation at a pressure < 40 cm H₂O; and should not require supplemental oxygen (i.e. SatO₂ > 95% maintained with or without ventilation) or have any physical conditions that could impede use of an NIV interface (e.g. nasal or oral mask).

Non-invasive positive pressure ventilation (NPPV)

Advantages

- Technically simple, and easy to administer and remove
- Patient care in NIV is much simpler than in invasive ventilation, making it much easier to discharge the patient from the hospital to begin home treatment
- Can be used intermittently
- Does not involve any of the complications of invasive ventilation with tracheostomy
- Compared to NNPV, NPPV does not cause obstructive apneas, involves more portable equipment, and enables greater patient mobility

Disadvantages

- Not amenable to all patients, especially young ones
- Very limited selection of interfaces for small children
- Interfaces are very uncomfortable and often cause pressure sores
- High risk of ineffective ventilation due to excessive leakage, patient-ventilator asynchrony, persistent hypoventilation, or intermittent airway obstruction
- When the patient moves, the interface can easily become de-adjusted, and consequently, provoke leaks
- More limited access to patient's secretions

- Chronic use is difficult for patients that require more than 20 hours per day of mechanical ventilation or for patients that have difficulty coughing or swallowing

Other home ventilation methods

Non-invasive negative pressure ventilation

In NNPV, a negative pressure ventilator creates a negative pressure around the chest wall and/or abdomen, causing the lungs to inflate during inspiration; return of the lungs to ambient pressure generates expiration. This method is less effective than NPPV. Its efficacy depends on the surface area of the body submitted to negative pressure and on the leakage in the system. NNPV has been used in children and adults with NMDs, kyphoscoliosis, tuberculosis sequelae, and, more recently, has been applied to chronic obstructive pulmonary disease (COPD) patients; however, it is generally ineffective for children that require continuous mechanical ventilation. It is now rarely used, having been replaced by NPPV.

Equipment that has been used for NNPV is listed below:

- Iron lung* (tank): a metal cylinder into which the patient's body is introduced (their head remains outside). Once inside, the patient is inaccessible and he can not move. Iron lungs were frequently used during the polio epidemic.
- Cuirasses*. A ventilator attached to the front of the chest wall and abdomen.
- Ponchos*. A plastic device that covers the upper body, leaving the neck and limbs free.
- Pneumobelt*. A device that covers the abdomen.

Advantages

- Does not involve any of the complications of invasive ventilation with tracheostomy.
- Easy to learn and use.
- If it is only used at night, then the patient is completely free of apparatuses during the day.
- Cheaper than invasive ventilation with tracheostomy.
- The patient's face remains uncovered.

Disadvantages

- Less effective ventilation.

Table I. Indications of pediatric home non-invasive ventilation**1. Alterations of the CNS**

- Congenital and acquired disorders of the respiratory control center (e.g. central hypoventilation, whether idiopathic or secondary to a tumor, trauma or infection)
- Myelomeningocele and Type II Arnold-Chiari syndrome
- Spinal cord injury

2. Neuromuscular diseases

- Infantile spinal muscular atrophy
- Congenital hypotonia
- Myasthenia gravis
- Paralysis of the phrenic nerve or diaphragm
- Myopathies
- Duchenne muscular dystrophy
- Guillain-Barré syndrome
- Botulism

3. Skeletal disorders

- Kyphoscoliosis
- Chest wall deformities

4. Respiratory diseases

- Obstruction of the upper airway:
 - Craniofacial deformation syndromes (e.g. Pierre Robin, and Treacher-Collins)
 - Laryngotracheomalacia
 - Obstructive sleep apnea syndrome (OSAS)
- Bronchopulmonary alterations:
 - Cystic fibrosis
 - Sequelae of acute respiratory distress syndrome (ARDS)
 - Pulmonary fibrosis

5. Metabolic diseases

- Requires the patient to be immobile, hence it is impractical for patients that require several hours of mechanical ventilation per day.
- The patient remains inaccessible and poorly visible to hospital staff, which complicates their medical evaluation and care.
- Some devices cause back and shoulder pain due to use of the supine position.
- Negative pressure can cause upper airway obstruction, especially in children and adolescents, ultimately leading to obstructive apnea. These patients then require ventilation via tracheostomy.

- NNPV patients that have bulbar dysfunction and problems with swallowing can develop bronchoaspiration.
- In patients that do not have a tracheostomy, access to the airway is not guaranteed in the case of emergency.

Ventilation with diaphragmatic pacemaker

Diaphragmatic pacemakers are small devices implanted in the chest wall—either surgically, or, more recently, via laparoscopy—that stimulate the phrenic nerve to induce contraction of the diaphragm. They are used for patients with congenital or secondary central hypoventilation syndrome and spinal cord injury. Currently, there is one Spanish hospital experienced with this technique: Hospital de Paraplégicos de Toledo.

Advantages

- Enables patient mobility, affording them a greater sense of independence with associated psychological benefits.
- Provides more natural (physiological) respiration.

Disadvantages

- The pacemaker must be implanted and controlled by experienced hospital staff.
- Children and adolescents generally require tracheostomy in order to avoid obstruction of the upper airway.
- The pacemakers are not equipped with alarms, and therefore, can go undetected if they fail to operate.

OBJECTIVES OF HOME MECHANICAL VENTILATION

According to the American College of Chest Physicians, the objectives of HMV comprise:

1. Prolong the patient's life and improve their quality of life
2. Provide an environment that stimulates the potential of each individual
3. Reduce morbidity
4. Improve the patient's physical and psychological wellbeing
5. Reduce the patient's healthcare costs
6. Facilitate the patient's physical growth and

psychosocial development and improve the ability of children to perform activities. And the specific objectives of NIV comprise:

Primary objectives

1. Alleviate the symptoms and signs of the respiratory pathology.
2. Improve the patient's diurnal and nocturnal gas exchange.

Secondary objectives

1. Improve the patient's quality of sleep, functional state and pulmonary function.
2. Extend the patient's life.
3. Reduce healthcare costs.

INDICATIONS

CRF patients that require mechanical ventilation are candidates for HMV. The pathologies that cause CRF are listed in Table I.

Clinical criteria. Before being discharged from the hospital, patients that have received NIV for flare-ups must be medically stable, and their infection must be controlled.

Some pediatric CRF patients are admitted to the hospital for NIV as elective therapy. However, since no specific clinical criteria have been established for treating pediatric patients, the criteria for adult patients have been included here (Table II).

Family criteria. Before assuming the responsibility of HMV, the child's parents—and the child, if they are mature enough— should be fully informed of the diagnosis and prognosis, as well as of the advantages, disadvantages and risks of the planned treatment. Sufficiently old patients should be cooperative and motivated and should be familiarized with the treatment objectives.

ADVANTAGES

- Favors the physical, psychological, intellectual and social development of the child.
- Facilitates family life.
- Avoids the secondary effects associated with prolonged hospitalization (e.g. nosocomial infections; iatrogenic complications; lack of affection, family contact or positive stimuli; altered sleep patterns; feeling of being in a hostile

Table II. Clinical criteria for using home ventilation as elective therapy

Stable or slowly progressing chronic respiratory failure (CRF)

1. Symptoms of hypoventilation or altered sleep (e.g. morning headaches, restless sleep, nightmares, diurnal hypersomnolence, hyperactivity, cognitive or behavioral problems, malnutrition, recurrent respiratory infections, enuresis, or late-developing cor pulmonale)
2. Changes in blood gas levels:
 - PaCO₂ >45 to 50 mm Hg during waking hours
 - Nocturnal hypoventilation (SatO₂ < 88% for longer than 5 minutes uninterrupted)
3. Severe alterations in pulmonary function: forced vital capacity (FVC) < 20% of theoretical value (or < 50% in rapidly progressing pathologies)
4. Repeated hospitalization for respiratory flare-ups
5. The patient does not have any contra-indications for non-invasive ventilation (NIV) (e.g. major difficulty expelling secretions or swallowing, severe difficulty coughing accompanied by chronic aspiration, patient is non-cooperative)
6. The patient suffers from hypoxia and hypercapnia despite receiving adequate physical therapy, bronchodilator treatment (in the case of a lung disease), antibiotics and diet

environment; no or inadequate academic studies).

- Increases the number of available beds in the PICU (the number of beds occupied by chronic patients is often high) and reduces healthcare costs.

DISADVANTAGES

For the family:

- Stress and fear related to the responsibility of caring for the child; this is especially heightened in the first few weeks following discharge of the child from the hospital, but gradually decreases as the caregivers become more comfortable with the treatment.
- Change of habits and adaptation to a new situation at home.
- May imply additional costs.
- Prolonged home care may cause the patient's family to feel exhausted, or to reject or feel resentment towards the situation.



Figure 1. Ventilator adapted to a wheelchair.

RISKS

The greatest danger in HMV is ventilator failure (e.g. due to a power outage) while the child is sleeping. For patients treated with NIV as vital support, inadvertent disconnection of the ventilator could cause fatal severe hypoxemia, or ischemic-hypoxic encephalopathy. Complications can be detected early on by monitoring the patient via pulse oximetry.

EQUIPMENT

Ventilators

Ventilators for NIV are described in detail in Chapter 6. For home care, they should be simple, light and equipped with alarms; if possible, they should include an internal battery to prevent disconnection during a power outage as well as to enable ventilation of the patient during transport to the hospital for treatment of a flare-up. For patients that require several hours of mechanical



Figure 2. Pulse oximeter.



Figure 3. Portable aspirator for secretions.

ventilation per day, internal batteries are indispensable, as is the option to connect the ventilator to an external battery and adapt it to a wheelchair (see Fig. 1).

Pulse oximeters

Pulse oximeters for HMV should be simple, dependable, equipped with sonic alarms, battery-powered and highly portable. Pulse oximetry can be used as substitute for or complement to cardiorespiratory monitoring (see Fig. 2).



Figure 4. Assisted-cough device (CoughAssist™ from JH Emerson Co.)

Aspirator for removing secretions

Aspirators can be powered either electrically (AC or DC) or mechanically (by pedal). They should be easy to use and have adjustable aspiration pressure. Aspiration can also be performed using manual devices such as syringes, suction bulbs or manual aspirators. This may be required for NMD patients treated with NIV (see Fig. 3).

Assisted-cough devices

Devices that help patients expel secretions are extremely valuable for NMD patients (see Fig. 4). These are indicated in NMD patients with poor control of secretions for whom manual assisted cough provides ineffective (< 160 L/min) cough peak flow.

Interfaces

NIV interfaces are detailed in Chapter 5. The most common interfaces for HMV are nasal masks. Pressure sores are a serious enough problem that they can lead to temporary suspension of NIV. Hence, interfaces which do not place pressure on the nasal bridge are recommended for patients suffering from sores: these include Adams circuits, the Simplicity (Respironics®) nasal mask and the Breeze (Puritan Bennett®) nasal pillows (see corresponding figures in Chapter 5). NMD patients



Figure 5. Oral interface for daytime support of non-invasive ventilation delivered by nasal interface.



Figure 6. Liquid oxygen vessel.

that require diurnal ventilation can be treated with a combination of nasal and oral interfaces (Fig. 5).

Humidifiers

1. Compressed oxygen: Oxygen gas is stored in a traditional gas tank or cylinder. However, even the smaller of the two available sizes is heavy, and therefore, difficult to move.
2. Liquid oxygen: Liquid oxygen is stored in a tank cooled to -183 °C, from where it is readily transferred to a small and light (i.e. highly portable) refillable vessel. This is the most widely used method in pediatric home oxygen therapy, as it enables a high level of patient autonomy and mobility (see Fig. 6). It should be noted that these vessels vent, even when not in use, emptying within 8 hours.
3. Oxygen concentrators: These devices extract oxygen from ambient air; hence, unlike the

containers above, there is no need for refilling. They deliver a maximum flow of 4 L/min and are either AC or DC powered, the latter of which implies an additional cost. Oxygen concentrators are used for patients with low oxygen needs that do not require mobility during sleep or are immobile, as well as for home care patients.

PREPARING THE PATIENT FOR DISCHARGE FROM THE HOSPITAL

The difficulty involved in discharging the patient from the hospital to begin home care depends on each case: it may range from extremely difficult to extremely easy (in the case of children who had been admitted to begin NIV).

The patient's discharge plan should be coordinated by a healthcare team comprised of specialized doctors and nurses. This team can form part of a larger home care group that handles other pathologies and therapies (e.g. enteral and parenteral feeding, and IV treatments). This multidisciplinary group should include medical specialists (e.g. for intensive care, pulmonary medicine, rehabilitation, nutrition, trauma, cardiology, neurology and neurosurgery), nurses, social workers, physical therapists, and counselors.

The location where treatment is started will vary according to each center, and may include PICUs, intermediate care units, hospitals for chronic patients, and pulmonary medicine or rehabilitation wards.

Guidelines for discharging patients from the hospital to start home ventilation

1. Ensure that HMV treatment is indicated and that the parents accept the responsibility. Hospital staff should foster parent-child relationships to help the parents accept the situation. Moreover, the patient and their family should be placed in touch with other patients who have already been discharged and their families.
2. Train at least two parents or other caregivers. They should spend as much time as possible with the child—if possible, in a private room. The child and their caregivers should gradually be transitioned out of the ward where the child was admitted, until the caregivers become independent and acquire the skills to resolve difficult situations. Hospital staff should employ

Table III. Equipment required for beginning home ventilation

1. For non-invasive ventilation (NIV):

- Ventilator (pressure-controlled or volumetric)
- Interface (e.g. nasal mask)
- Complete respiratory circuits for the ventilator
- Phonendoscope
- Pulse oximeter

2. For oxygen therapy:

- Oxygen source
 - Concentrated oxygen gas (in small or large tanks or cylinders)
 - Liquid oxygen (tank plus refillable vessel)
 - Oxygen concentrator
- Oxygen tubing, nasal cannulae and masks

3. Patient specific materials:

- Feeding pump, silicone nasogastric tube, and gastrostomy connection
- 10 and 50 mL syringes
- Apnea monitoring device
- Wheelchair with external battery
- Nebulizer
- Portable aspirator for secretions, and probes
- Assisted-cough device

training material such as pamphlets, videos and dummies.

The caregivers should be taught how to:

- Position and attach the interface.
- Check for leaks and pressure sores related to the interface.
- Operate all equipment (e.g. ventilator, pumps, humidifier, aspirator for secretions, monitoring devices, oxygen sources, and assisted-cough devices).
- Interpret alarms and adjust all ventilation parameters (if the patient's doctor deems it suitable).
- Administer aerosol therapy and oxygen therapy.
- Evaluate signs and symptoms of any changes in the patient's respiratory condition (e.g. difficulty breathing, changes in coloration or secretions).
- Perform physical, speech, and occupational therapies as well as respiratory rehabilitation therapy (including use of assisted-cough devices).

- Respond to emergency situations; this includes learning CPR.
- Feed the child; this includes becoming familiar with special diets and feeding techniques and, if required, gastrostomy care or how to change a nasogastric tube.
- Care for (e.g. bathing and dressing) and play with the child.

Family is critical to the success of HMV. They should be provided with the maximum support possible to perform home treatment. The time required for training depends on the pathology, whether the child is ventilated via tracheostomy or NIV, and the caregivers' motivation, among other factors. Children who are admitted to the hospital for elective NIV therapy typically stay for one or two days, as patient-ventilator adaptation is normally achieved at home.

3. Provide the caregivers with all necessary equipment and materials for HMV (summarized in Table III). Presently, the Spanish public health system provides rapid and easy access to home care material (e.g. ventilators, humidifiers, aspirators, pulse oximeters, and assisted-cough devices) through leasing plans with oxygen therapy companies. The amount and type of paper work involved depends on regional health services; the oxygen therapy companies can provide information on these requirements. Monthly use of disposable materials must be managed in conjunction with the patient's community health clinic (CAP) or the corresponding hospital.
4. Other aspects for the healthcare team to consider before discharging the patient:
 - The patient's home and family environment should be evaluated. The home should have sufficient space, adequate electricity, water and heating, and a telephone line. The family's work and economic situation should be determined, and other family members should be encouraged to help with the child's care.
 - The team should contact the pediatrician from the patient's community health clinic (CAP) to provide them with clinical information and to discuss any possible home visits and with the corresponding hospital.
 - The team should contact extra-hospital emergency services (in Spain: 112) to provide

them with information on the patient for use in the event of any emergencies.

The parents should:

- Advise their electric company of their child's treatment, underscoring that the ventilation equipment requires dependable electricity.
- Make a list of emergency phone numbers (112, plus the phone numbers for the hospital and the oxygen therapy [ventilation equipment] company).

FOLLOWING UP ON THE PATIENT AFTER HOSPITAL DISCHARGE

Hospital visits. The child should be given periodic check-ups. These should be planned according to the amount of time since the child was discharged, their pathology and any secondary conditions, and the distance between their home and the hospital. Check-ups by different specialists should be coordinated on the same day to save the family trips. In some cases the patient may have to be admitted to the hospital for one or two days.

Home visits. These should be periodic and serve to monitor the patient's progress. The number of visits depends on the distance between their home and the hospital, as well as on the hospital personnel and time available. The companies that lease the ventilation equipment are responsible for its maintenance and for replacing disposable materials.

Trouble shooting. The parents should have 24 hour telephone access to the hospital staff to resolve any problems that may arise; in some cases, they may have to go to the hospital. Internet monitoring is now common practice: high speed (DSL/cable) connections enable bidirectional communication in real time between the patient's home and the hospital with high quality audio and video.

Monitoring of HMV patients: This is detailed in Chapter 10, "Monitoring of non-invasive ventilation for pediatric patients".

Unplanned hospital visits: Respiratory infections and other common diseases that strike infants frequently lead to unplanned medical check-ups. Any blood tests given to the patient should include monitoring of blood gas exchange, which will reveal important information on their respiratory status. Hospital staff should avoid admitting the child to the hospital if possible. Children treated with

ventilators are sometimes admitted to the ER out of fear or uncertainty regarding their condition, rather than because of a medical requirement—this is especially common among pediatric tracheostomy patients. The parents of children treated with HMV are typically highly informed, know their child well, and are capable of evaluating the situation and resolving any problems that arise. Home care patients who are admitted to the hospital will probably be subjected to an exhaustive array of analytical tests and highly aggressive treatments, and may have to remain away from home for a prolonged period of time. This is especially true if the child is new to the hospital.

HOME ASSISTANCE

HMV is not simply a treatment: it is a way of life for the child and their family, who tend to suffer from other medical, psychological and social problems that must be addressed in an integrated fashion. As children treated with HMV are chronically ill and require continuous, specialized care, their families are key to treatment success. However, parents may become overwhelmed with responsibility; hence, they require constant support and resources from medical professionals and institutions.

In the United States, nurses or expert caregivers typically attend to homecare children for 16 to 24 hours daily in order to facilitate treatment and enable the child's parents to go to work. Paying for these healthcare professionals accounts for 60 to 75% of the costs of HMV.

The Spanish public health system still does not have personnel or funds earmarked for pediatric HMV care, although this may become a reality with the passing of a new patient assistance law (*Ley de Dependencia*). Currently, certain professional associations raise funds for children with special medical needs. Moreover, patients who have suffered spinal cord injuries in traffic accidents receive payments from insurance companies to cover the expenses of professional caregivers.

In most cases the family is in charge of care. They should seek assistance from friends and relatives, and should take full advantage of the available human and material resources, including those of the healthcare services of the autonomous

community where they reside (e.g. their community health clinic, city and regional health services, the Ministry of Education, and charity organizations).

SCHOOLING

The parents should be encouraged and supported in their efforts to ensure proper schooling for their child, which often entails surpassing several obstacles stemming from the family itself, the child's pathology, academic professionals or the public school system. Spanish public education institutions employ health professionals that can attend to the child during school hours.

ASSOCIATED PROBLEMS

Nutrition

Pediatric CRF patients often present with malnutrition or, in the case of NMD patients, obesity. Their diet must be optimized for physical growth, pulmonary development and nutrition, since malnutrition diminishes the strength of respiratory muscles. Some patients may have to be fed via gastrostomy or nasogastric tube.

Psychomotor development

Many pediatric CRF patients have compromised motor skills (fine and gross) and psychological development and present with cognitive disabilities. These are due factors including the underlying pathology and any intercurrent conditions. Hence, the contributions of physical, occupational and speech therapists, to the treatment of these children are invaluable. Respiratory physical therapy—especially coughing exercises—is crucial for avoiding respiratory infections and preserving respiratory function. For patients that require a wheelchair for physical therapy, the ventilator must be connected to a battery and then attached to the wheelchair.

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Respiratory physiotherapy in non-invasive ventilation

M.R. Gonçalves

INTRODUCTION

Neonatal respiratory failure requiring respiratory support is most common in neuromuscular diseases (NMDs) such as spinal muscular atrophy (SMA) Type 1, but also occurs in certain congenital malformations such as Pierre Robin syndrome, congenital central hypoventilation, and bronchopulmonary dysplasia. It may result from subglottic stenosis due to damage from intubation or tracheostomy.

Surveys in the United States, Western Europe, and Japan indicate that pediatric use of home mechanical ventilation (HMV) is rapidly increasing. A Swedish survey noted that 80% of 541 HMV users had neuromuscular respiratory impairment and that the great majority used non-invasive ventilation (NIV). A survey of pediatric HMV patients in the United Kingdom reported that 141 children required long term respiratory assistance, of which 33 used intermittent positive pressure ventilation (IPPV) with tracheostomy, 103 used nocturnal nasal IPPV (n-IPPV), and nine used negative pressure body ventilators. Furthermore, 96 of these patients had primary respiratory impairment, and the remainder had other conditions. Some children were treated with more than one non-invasive ventilation method. However, the majority of children that appeared to require more than nocturnal ventilator use, and the majority of those who had difficulty with weaning after intubation during chest infections, required tracheostomy. When the tubes had not been removed after the acute episode, the children usually

remained dependent on full time ventilation. Interestingly, most of the children in studied in this survey attended mainstream schools, but only one-half of the tracheostomy IPPV users resided in the community.

Despite major advances in managing respiratory failure in the pediatric intensive care unit (PICU), most pediatric patients still require conventional mechanical ventilation (CMV), which entails intubation, mechanical ventilation, and then weaning. This chapter reviews respiratory physiotherapy and intervention strategies in this area, describing the most important techniques for ensuring successful NIV in children. Respiratory physiotherapy should be evaluated according to different factors, including measurement of bronchial mucus transport and of expectorated mucus, pulmonary function, use of medication, frequency of acute exacerbations and quality of life.

GOALS OF INTERVENTION

As with adult patients, the goals of intervention in children are to maintain constant lung compliance and normal alveolar ventilation and to maximize cough flows for adequate clearance of bronchopulmonary secretions. Techniques for augmenting normal mucociliary clearance and cough efficacy have been used for many years in patients with respiratory disorders of various etiologies. Recent

advances have enabled more effective and more comfortable treatment for the majority of patients. In most countries, postural drainage with manual chest percussion and shaking has been replaced by more independent and efficacious techniques such as the active cycle of breathing; autogenic drainage; high frequency chest wall oscillation; intrapulmonary percussive ventilation; mechanical insufflation-exsufflation (MI-E); and use of equipment such as positive expiratory pressure (PEP) masks, the R-C Cornet®, and the Flutter® mucus clearance device. However, the evidence supporting use of these methods is varied, and the literature on the clinical indications for each one is confusing and sometimes conflicting. This may be related to differences in the intensity, duration and frequency of the treatments used by physiotherapists in different areas of the world.

Elimination of airway mucus and other debris is critical to effective mechanical ventilation (invasive or non-invasive) of chronic and acute patients with respiratory or oxygenation impairment. In patients with primarily respiratory impairment, 90% of episodes of respiratory failure result from an inability to clear airway mucus during intercurrent chest colds. Moreover, because of difficulties with cooperation in very young patients, acute episodes of respiratory failure must be properly managed, so that the child can reach the age at which cooperation is no longer a problem and morbidity and mortality can be avoided without hospitalization. Older children are capable of following directions and imitating a therapist's demonstration of deep breathing, coughing and active exercise.

Chest physiotherapy in children is focused on improving ventilation and the efficacy of breathing, increasing general strength and endurance (especially of respiratory muscles), improving posture, and addressing relaxation, breathing control, and pacing. Hospital staff should involve the patient's family in their treatment whenever possible. In some cases the parent may perform most of the techniques and repeat instructions to their child under the direct guidance of the therapist. This reinforces parent and family education for later use in home therapy.

Lung Mobilization

Infants with NMDs are unable to take deep breaths. Consequently, their lungs and chest walls



Figure 1. A 2 year old girl with SMA Type 1 undergoing high-span nasal BiPAP (n-BiPAP) after having been successfully extubated in the ICU.

do not grow normally, which leads to severely restricted pulmonary volumes, low pulmonary compliance, and undergrowth of the thoracic cage.

Range-of-motion therapy in pediatric patients maintains compliance, promotes more normal lung growth and prevents chest deformity. Because infants cannot air stack (see below) or cooperate to receive maximal insufflations, those with spinal muscular atrophy (SMA) or other NMDs who have paradoxical chest wall motion require nocturnal high-span bi-level positive pressure ventilation (BiPAP) to rest their inspiratory muscles, prevent pectus excavatum, and promote growth of their lungs. Use of high-span BiPAP during sleep—even without maximal insufflation therapy—prevents rib cage deformities in children with SMA Type 1, and possibly, in other infants with paradoxical breathing.

For patients older than 9 months inspiration-timed deep insufflations can be delivered via an oral-nasal interface in tandem with abdominal compression, to prevent abdominal expansion while air is directed into the upper thorax. Children can cooperate with deep insufflation therapy by 11 to 30 months of age. This therapy is usually performed two or three times daily with delivery of ten to fifteen maximal insufflations via manual resuscitator or by mechanical insufflation-exsufflation (MI-E), using a CoughAssist™ device (J.H. Emerson Co., Cambridge, MA, USA) at a pressure of 40 cm H₂O and timed to inspiration. Periodic maximal insufflations may complement nocturnal BiPAP in preventing pectus excavatum and promoting lung growth; however, there are currently no published data to support this approach.

Once accustomed to positive pressure insufflations, some infants as young as 11 months can use MI-E via oronasal interface. Another technique that promotes lung expansion and increases cough efficacy is air stacking. This technique, which is only efficient in cooperative patients (children older than 2 years), consists of the following: the subject takes a deep breath, then holds their breath, and is then an extra air volume of air (delivered from a resuscitation bag or volume ventilator through an oral or nasal interface). Said volume produces lung distension, enabling the patient to cough with greater volume, and therefore, more effectively.

Another factor to consider is inspiratory apnea, which is assured by functioning of the glottis. Deep inspiration stretches the airways and increases the contraction force of the expiratory muscles and the retraction force of the lung parenchyma. Inspiratory apnea (with glottic closure) facilitates airway distribution to the most peripheral areas of the lung and increases intrathoracic pressure.

Extrinsic pulmonary development is clearly interrelated with musculoskeletal and motor development of the trunk. Therefore, it is crucial that doctors assess patients' functional range of motion through the trunk. This requires elongation of the pectoral, sternocleidomastoid, upper trapezius, and rectus abdominis muscles. Manual lowering of the rib cage is also needed for maximizing chest mobility. Helping the patient achieve proprioceptive input of the scapulae on the posterior thorax helps reinforce active thoracic extension and anterior chest expansion.

Maintenance of alveolar ventilation

During the past decade use of non-invasive ventilation (NIV) to provide mechanical ventilation or respiratory support to various groups of pediatric patients has grown. As part of a multidisciplinary team that provides NIV to children, respiratory physiotherapists play an important role by actively participating in each stage of treatment, especially in ensuring that patients maintain adequate alveolar ventilation. For many NMD patients, respiratory support is indicated for unloading retained carbon dioxide from the muscles and for substituting the failing respiratory pump, particularly during sleep. NIV is based on the cyclical application of a positive

pressure (or volume) to the airways. Previous studies have used volume-targeted ventilators, but most recent pediatric studies have employed positive-pressure-targeted units.

Choosing an appropriate ventilator for children depends on age; vital capacity; lung and chest wall compliance; the extent of gas exchange impairment; and the patient's size, mobility, and level of cooperation. Patient triggering is not always possible for very small and/or weak patients, for whom rate adjustment is highly important. This is typically the case for infants extubated to nasal BiPAP (n-BiPAP). To facilitate patient ventilator synchrony for patients unable to trigger the machine, the respiratory physiotherapist must set the spontaneous timed mode of pressure-cycled machines to be used with a back-up rate slightly higher than that of the spontaneous breathing rate of the patient. In general, back-up rates of 25 to 30 respirations per minute (rpm) are required for infants, 15 to 20 rpm for small children, and 10 to 12 rpm for adolescents.

Low-span nasal BiPAP is generally used in children of all ages with obstructive apneas or primary respiratory insufficiency and adequate pulmonary compliance. EPAP can replace the normal positive end expiratory pressure (PEEP) generated by the larynx during coughing, talking or crying. EPAP levels may be increased in the rare patient with NMD and severe hypoxemic insufficiency or air trapping. EPAP is rarely needed for children with primary respiratory impairment and normal lung compliance, however it is often beneficial for older children with SMA Type I.

Optimized clearance of airway secretions

For pediatric patients who cough sufficiently enough to eliminate secretions, chest physical therapy and assisted coughing are used as for adult patients. Chest percussion with postural drainage can help mobilize peripheral airway secretions but causes oxy-hemoglobin desaturation and imposes respiratory work that can also fatigue respiratory muscles. These problems can be alleviated, at least for patients with cystic fibrosis, by the use of nasal peak inspiratory pressure (PIP) combined with PEEP. In a study of 16 cystic fibrosis patients aged 13 to 14 years, who performed forced expiratory maneuvers, respiratory rates were significantly lower and tidal volumes, maximal inspiratory and

expiratory pressures, and SatO₂ significantly higher when nasal PIP plus PEEP was used. Furthermore, among the patients treated with PIP plus PEEP, 15 patients reported less fatigue, and 10 of 16 patients reported that expectoration was easier with nasal PIP.

The critical level for effective coughing in adult airways, as measured at the mouth, appears to be 160 liters per minute (lpm). However, no one has determined the analogous level for children. Lower total flows may be effective in the airways of small children because cough effectiveness is more a function of air velocity than air flow. In infants with ineffective cough, expectoration can be facilitated, and fatigue eased, by providing deep insufflations and n-IPPV or high-span n-BiPAP. Infants younger than 1 year learn how to first close the glottis to hold the IPAP and then quickly open it to expel secretions.

MECHANICAL INSUFFLATION- EXSUFFLATION (MI-E)

Mechanical assisted cough devices such as the CoughAssist™ (J.H. Emerson Co., Cambridge, MA, USA) deliver deep insufflations followed immediately by deep exsufflation. The insufflation and exsufflation pressures and the delivery times are independently adjustable. Abdominal thrusts are applied in conjunction with the exsufflation, except after a meal. MI-E can be provided via an oral-nasal interface, a simple mouthpiece, or an invasive airway tube (e.g. tracheostomy tube). When delivered via the latter, the cuff, when present, should be inflated. Whether used via the nose or mouth or via invasive, indwelling airway tubes, routine airway suctioning misses the left lung in approximately 90% of cases; hence, 80% of pneumonias occur in the left lung. MIE via an airway tube provides the same exsufflation flows in the left and the right airways without the discomfort or airway trauma of tracheal suctioning and can be effective when suctioning is not. Furthermore, patients invariably prefer MI-E to suctioning for comfort and effectiveness and find it less tiring. Therefore, deep suctioning, whether via airway tube or via the upper airway, can essentially be discontinued for most children.

The CoughAssist™ (Fig. 4) can be manually or automatically cycled. Manual cycling facilitates coordination of inspiration and expiration with



Figure 2. The CoughAssist™ device (J.H. Emerson Co., Cambridge, MA, USA).

insufflation and exsufflation between the care giver and the user, but requires hands to deliver an abdominal thrust, to hold the mask on the patient, and to cycle the machine. Automatic mode enables the patient to work alone with the machine and increase their cough efficacy without the help of a caregiver (Fig. 5). Although the machine can be managed automatically by programming the insufflations, exsufflations, and pause times, the manual mode allows for better synchronization, and makes it easier for patients to coordinate their insufflation and cough with the machine. This is especially true for infants, whereby the cycles should follow their rapid respiratory frequency and chest movement.

A single treatment session comprises roughly five cycles of MI-E followed by a short period of normal breathing or ventilator use to avoid hyperventilation. Multiple treatments are given in one sitting until no further secretions are expelled and any secretion- or mucus-induced oxygen desaturations are reversed. For patients with chest colds, treatment may be required as frequently as every few minutes over a 24 hour period. Although no medications are usually required for effective MI-E in children with weak muscles, liquefaction of sputum using heated aerosol treatments may facilitate exsufflation when secretions are inspissated.



Figure 3. An example of hand placement in thoracic expiratory mobilization on a child, used for airway secretion clearance and lung expansion.

MI-E is labor intensive and often difficult for non-professional caregivers in both acute and chronic settings. Moreover, MI-E of children with advanced NMDs is nearly impossible without the use of tracheostomy tubes, unless their families and caregivers provide virtually all of the care during upper respiratory tract infections. After taking full care of the hospitalized patient, hospital staff can not simply instruct the family just before discharge and then expect them to be able to prevent another episode. Although the home or ICU patient's family often has the time and motivation to use MI-E along with abdominal thrusts as often as every 15 minutes, and to use oximetry as feedback to maintain normal saturation (without supplemental oxygen), the respiratory physiotherapy and nursing staff can not be expected to do this.

Caregivers provide the positive pressure of MI-E timed to diaphragm movement (abdominal protrusion) via oral-nasal interface to 9- to 30-month old infants on a daily basis to allow maximal lung expansion and to accustom them to the technique so that they will use MI-E effectively during chest infections. MI-E via the upper airway can be used effectively for children as young as 11 months: even at this age patients can avoid crying or closing their glottis. Between 2.5 and 5 years of age most children become able to cooperate and cough on cue with MI-E. Children that are too young to cooperate with manually and mechanically assisted coughing, or those who are not introduced to these methods before a cold develops into pneumonia and respiratory failure, are hospitalized and usually

intubated (a catheter is passed via the nose or mouth into the lungs for respiratory support and airway secretion evacuation). It is often the case for small children that until they are old enough to cooperate, each time they develop a chest infection, they need to be hospitalized and intubated.

When airway secretions need to be cleared in small children unable to cooperate with MI-E, MI-E with an exsufflation-timed abdominal thrust (manually assisted coughing [MAC]) is used via an oral-nasal interface on manual mode to correlate the insufflation and exsufflation with the child's inspiration and expiration. MAC is avoided for the first 1.5 hours after a meal; hence, if assisted cough is needed, only MI-E, or MAC without aggressive manual thrusting, is performed. Although timing MI-E to an infant's breathing and crying may be helpful, when the patient does not cooperate, MI-E can only be effective when used via translaryngeal or tracheostomy tube with the cuff inflated.

In addition to the standard hand placements for applying thrusts to the chest and abdomen to increase cough flows, other placements can be used to apply thrusts to specific lung regions. Likewise, thrusts can be applied to stretch specific areas of the anterior and posterior chest walls. There are guidebooks that demonstrate these hand placements and thrusting techniques in children (Fig. 3).

When MI-E is delivered with oral-nasal interfaces, pressures of +20 to -20 cm H₂O are used initially, and then augmented quickly, as tolerated, to the more effective settings of +40 to -40 cm H₂O. The maximal efficacy of MIE at pressures of +40 to -40 cm H₂O has been demonstrated in experimental models and in both adult and pediatric populations. Although these values are generally adequate for most patients, higher settings are often required when compliance decreases (due to obesity or scoliosis) or resistance increases. When used via pediatric translaryngeal or tracheostomy tubes, a severe drop-off in flows and in pressures often demands that full lung insufflation and subsequent emptying last for at least 4 seconds each. Pressures much greater than 40 cm H₂O are usually required to achieve the clinical goal of full chest expansion and subsequent complete emptying of the lungs in 2 to 4 seconds. However, in infants, even the maximum capabilities of the CoughAssist™ can be suboptimal for effective cough flows across the tubes.



Figure 4. A 3 year old boy with SMA Type 2 being treated with oscillating pressure under a chest shell to help clear airway secretions.



Figure 5. CoughAssist™ used with a face mask.

Although there have not been any extensive studies on the use of MIE in small children, there are published reports that this treatment enables consistent extubation of NMD patients following general anesthesia—despite their inability to breathe on their own—and ventilation of them with non-invasive IPPV. It has also permitted hospital staff to avoid intubation or to quickly extubate patients with acute respiratory failure (ARF) and with profuse airway secretions due to intercurrent chest infections. MI-E in a protocol with manually assisted coughing, oximetry feedback, and home use of non-invasive IPPV was shown to effectively hospitalizations, respiratory complications, and mortality in pediatric NMD patients. However, it may be ineffective for patients that cannot cooperate sufficiently to keep their airway open, or those with a fixed upper airway obstruction, or those whose upper airway dilator muscles cannot maintain sufficient patency to allow for a peak cough flow (PCF) > 160 lpm.

MI-E is very effective for resolving ARF in NMD patients, but is rarely ever needed for stable patients with intact bulbar function that can air stack to maximum lung volumes and that can close their glottis against high pressures with an abdominal thrust. However, even in stable patients, routine use of MI-E may be advisable, just to enable them to practice the technique so that they can apply it during upper respiratory tract infections, when it is needed the most.

CHEST PHYSIOTHERAPY TECHNIQUES

Approaches to preventing retention of airway secretions include the use of medications to reduce

mucus hypersecretion or to liquefy secretions as well as facilitation of mucus mobilization. Complimentary methods include chest physiotherapy, which has been shown to be very effective at preventing pulmonary complications in infants that have accumulated bronchopulmonary secretions. The principles of chest physiotherapy techniques in adults can be applied in children.

Mucus mobilization can be facilitated by the use of special breathing techniques, manual or mechanical chest vibration, direct oscillation of the air column, and postural drainage, all with or without directed assisted coughing. The goal is to transport mucus from the peripheral airways to the central airways, from which it can be more easily eliminated. Gravitational forces can enhance mucus transport when bronchi are vertically positioned. Postural drainage is the facilitation of airway drainage by having the patient assume gravity-assisted positions. Knowledge of the anatomy of the tracheobronchial tree is vital to effective treatment. Each lobe to be drained must be aligned so that gravity can facilitate progression of the secretion to the upper airways. This is probably most effective for relatively large quantities of mucus with low adhesiveness. Nine postural positions have been described for draining the large bronchi. Localization of airway mucus is essential. The goal is vertical positioning of the secretion-encumbered bronchi for sufficient time to allow drainage (generally, approximately 20 minutes). The time required probably depends on the quantity, viscoelasticity and adhesiveness of the mucus. This intervention is more efficient when complemented with manual chest mobilizations,

vibrations and breathing exercises. Mucus mobilization implies certain disadvantages: postural drainage is relatively time-consuming and may require use of a specially modified bed or table. Vibration is a sustained co-contraction of the upper extremities of a caregiver to produce a vibratory force that is transmitted to the thorax over an involved lung segment. It is applied throughout exhalation concurrently with mild compression of the infant's chest wall. Vibration is proposed to enhance mucociliary transport from the peripheral of the lungs fields to the larger airways. Since vibration is used in tandem with postural drainage and percussion, many studies do not distinguish the effects of vibration from those of other elements.

The chest wall or abdomen can be vibrated externally by rapidly applying oscillating pressure (high frequency chest wall oscillation [HFCWO]) through a vest (e.g. the thAIRapy™ vest, American Biosystems, Inc., St Paul, MN, USA), by cycling oscillating pressures under a chest shell (e.g. the Hayek oscillator, Breasy Medical Equipment, Inc., Stamford, CT, USA) (Fig. 2), or by using chest vibrators. Vibration is either applied during the entire breathing cycle or only during expiration. HFCWO may act as a physical mucolytic, reducing both the spinnability and viscoelasticity of mucus and enhancing clearance by coughing. Moreover, it has demonstrated efficacy in assisting mucus clearance in patients with disorders associated with mucus hyper-secretion and preserved muscle function, such as cystic fibrosis (CF). HFCWO is an external, non-invasive respiratory modality proven effective for mobilizing airway secretions from the small peripheral airways and improving mucus rheology in patients with CF. Indeed, it has become a major component of airway clearance techniques for these patients.

Mechanical vibration can be performed at frequencies up to 40 Hz. Oscillation at 16 Hz can be applied orally by high-frequency positive-pressure ventilation or jet ventilation. One such air column oscillator, based on high frequency jet ventilation, has been developed by the Bird Corporation (Exeter, UK). This hand-held device delivers 30 mL sine wave oscillations through a mouthpiece at 20 Hz. Lower frequency air column oscillators include the Intrapulmonary Percussive Ventilator (IPV), and the Percussionator, Impulsator, and Spanker Respirators

(Percussionaire Corp., Sandpoint, ID, USA). They can deliver nebulized medications while providing intrapulmonary percussive ventilation: mini-bursts of high-flow air delivered to the lungs at 2 to 7 Hz. This technique has been shown to be as effective as standard chest physiotherapy and to assist mucus clearance in patients with secretion encumbrance from various etiologies, such as CF, acute exacerbations of COPD and Duchenne muscle dystrophy. IPV can be used with a mouthpiece or face mask, or endotracheal or tracheostomy tube. The primary aims of this technique are to reduce secretion viscosity, promote deep lung recruitment, improve gas exchange, deliver a vascular "massage", and protect the airway against barotrauma. The main contraindication is the presence of diffuse alveolar hemorrhage with hemodynamic instability. Relative contraindications include active or recent gross hemoptysis; pulmonary embolism; subcutaneous emphysema; bronchopleural fistula; esophageal surgery; recent spinal infusion; spinal anesthesia or acute spinal injury; presence of a transvenous or subcutaneous pacemaker; increased intracranial pressures; uncontrolled hypertension; suspected or confirmed pulmonary tuberculosis; bronchospasm; empyema; large pleural effusion; and acute cardiogenic pulmonary edema.

Another method of promoting airway clearance is use of positive expiratory pressure (PEP) breathing. PEP creates a backpressure to stent the airways open during exhalation and promotes collateral ventilation, allowing pressure distal to the obstruction to accumulate. This method of clearing the airways prevents their collapse, easing mobilization of secretions from the peripheral airways toward the central airways. Application of PEP breathing is based on the hypothesis that mucus in peripheral small airways is mobilized more effectively by coughing or forced expirations if the alveolar pressure and volume behind mucus plugs are increased. A mask or mouthpiece apparatus provides a controlled resistance (10 to 20 cm H₂O) to exhalation and requires a slightly active expiration; tidal volume inspiration is unimpeded. PEP increases the pressure gradient between open and closed alveoli, thus tending to maintain patency in alveoli. It also increases functional residual capacity (FRC), thus reducing the resistance in collateral and small airways. As a voluntary maneuver, PEP requires

children to cooperate; therefore, it is difficult to apply in very small infants. Nonetheless, exhalation can be coordinated through PEP when infants are crying.

The Flutter® is a device which provides a form of intermittent PEP. The patient exhales through a small pipe, which provides PEP, oscillation of the airways (at 6 to 20 Hz) and accelerated expiratory flow rates to loosen secretions and move them towards the central airways. Mobilization of mucus is thought to occur via widening of the airways by increased expiratory pressure and air flow oscillations generated by the oscillation ball located inside the device. However, carefully controlled studies need to be conducted before this technique can be widely recommended. The RC Cornet® is a device based on the same physiological principles as the Flutter®. It features a curved plastic tube containing a flexible, latex-free valve hose. During expiration through the RC Cornet®, a PEP and oscillatory vibration of the air within the airways are generated. Since it functions independently of gravity, it can be used in any position. The flow, pressure and frequency of the oscillations can be adjusted to the patient's needs. As with the Flutter®, secretions mobilized to the central airways are cleared by coughing or huffing.

As demonstrated in clinical practice, these three techniques have major effects on sputum viscoelasticity. Viscoelasticity has been reported to be significantly lower in patients treated with these devices compared to standard treatment. This reduction has been hypothesized to improve mucociliary and cough clearability; however, interestingly, there have not been any published studies that compare the differences in the quantity of expectorated sputum during treatment with each of these devices.

CONCLUSION

Most physiotherapy interventions for ventilated children take place in the hospital, above all, in the pediatric intensive care unit (PICU). NIV is critical to the management of respiratory insufficiency in PICU patients, and its success depends on the establishment of a good respiratory physiotherapy program.

Many PICU patients need to be intubated because of acute illness. A good extubation protocol

depends on the total achievement of the goals described in this chapter. After extubation, airway secretions continue to be removed by some combination of physiotherapy techniques for a few days until the airways are determined clear by auscultation. The family must continue to provide most airway secretion management, and therefore, must be trained in managing MI-E, respiratory resuscitation—including manual resuscitation—and respiratory support. The family needs this knowledge and these skills to avoid future hospitalizations and to resuscitate children susceptible to bradycardias or sudden respiratory arrests associated with mucus plugging or fatigue.

Transmitted sounds from the throat and pharyngeal secretions are not a reason to initiate chest physiotherapy; nocturnal n-BiPAP and diurnal insufflations should be continued, and the patient can be discharged whether or not they can breathe autonomously. Most patients with good secretion clearance, and lung expansion associated with good alveolar ventilation, can wean from full-time ventilator use to nocturnal-use at 1 or 2 weeks post-discharge.

In conclusion NIV is a very efficient technique for the respiratory management of children; however in most cases, secretions are excessive and NIV alone is likely to fail. Respiratory physiotherapy is crucial for these patients. It should be based on the intervention goals described in this chapter to enable efficient treatment while the child is hospitalized, and prevent hospitalizations while the child is at home, where family members must be trained to meet said goals, and therefore, maximize the child's potential for pulmonary rehabilitation.

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Healthcare assistance, quality control and clinical training for non-invasive ventilation of acute pediatric patients

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INTRODUCTION

Pediatric intensive care units (PICUs) should be equipped for non-invasive ventilation (NIV). This chapter provides an overview of the human and material resources required for administration of NIV and for training and research in this technique. These resources are the same as those employed for conventional mechanical ventilation (CMV). Sharing of clinical and research experiences among health professionals from the field enables continuous learning.

MATERIAL RESOURCES

Hospital infrastructure

NIV in acute pediatric patients can be initiated in any hospital ward (e.g. ER, pediatric ward or PICU). The location depends on the specific characteristics of each hospital. In the majority of Spanish hospitals, NIV is started in the PICU. It can also be administered in extra-hospital environments such as the home or during transport.

The space required for administering NIV is similar to that of any PICU bed. The main requirements are agreeable surroundings for the patient, sufficient space for the required equipment (e.g. ventilator, monitor, and IV pumps), and standard gas outlets (three for oxygen, one for air, and two for vacuum) and utilities (e.g. electrical

outlets with surge protectors, lighting, air conditioning, and heating). Furthermore, since NIV has proven utile for immunologically compromised patients, a room equipped for isolating a patient in this condition may also be valuable.

Equipment

1. Monitoring of physiological parameters: clinical evaluation of ventilated patients requires that their respiratory rate and oxygen saturation be continuously monitored. If possible, transcutaneous CO₂ should also be monitored. Electrocardiograms and blood pressure measurements are only required for patients at risk for hemodynamic complications.
2. NIV-specific material:
 - a. Ventilators: Ideally, an NIV-specific ventilator would be used. A home ventilator without oxygen blender can be used to initiate treatment. However, any ventilator for CMV that is equipped with an NIV module can be employed. In certain cases CMV ventilators can be used as long as the problems inherent to their use in NIV are resolved (see Chapter 13).
 - b. Tubing: The tubing used depends on the ventilator. If a non-vented interface is used, then the tubing should include an exhalation or leak control valve or, for ventilators lacking an expiratory loop, a Plateau valve. If the

ventilator used does not include pressurized oxygen or lacks an oxygen blender, then the tubing should also be equipped with an oxygen connection.

- c. Interfaces: A wide variety of interfaces (e.g. nasal, oral-nasal or face masks, and nasal tubes) should be available to enable optimal fitting for each patient. It is important to organize these according to type and size. Many interfaces are designed for only one use; however, most hospitals tend to clean and reuse them. If this is the case, then the interfaces must be carefully stored with their respective harnesses (since mismatching can lead to poor attachment) and inventoried to facilitate any required replacement. One useful classification system is to separate the interfaces by age group (neonates, infants, toddlers, children, adolescents and adults) and then by model (type, manufacturer and size), which enables rapid location of any interface in stock.
 - d. Active humidifiers: Any simple humidifier can be connected to the respiratory circuit through the tubing.
 - e. Other accessories: Oxygen connections, Plateau valves, filters, jet or ultrasonic nebulizers, aspirator for secretions, assisted cough device (CoughAssist®), etc.
3. Manual resuscitation bag connected to an oxygen source and kept at the patient's bedside.
 4. Material for endotracheal intubation and CMV in the event that NIV fails.

HUMAN RESOURCES

NIV treatment of children in the PICU should be performed by all medical personnel: doctors, respiratory therapists, nurses and auxiliary staff. Furthermore, multidisciplinary healthcare teams should be created to evaluate and care for the ventilated child and to ensure proper monitoring of the child after they have been discharged from the hospital, especially those who are to receive home mechanical ventilation (HMV). Said team should include intensive care physicians, pulmonary specialists, physical therapists and nutritionists.

The healthcare team will decide when the patient is admitted to and discharged from the PICU,

determine the type of ventilation to be used and the material required, program the respirator, help set up the material, and be in charge of clinical monitoring of the patient.

The team should also develop NIV protocols and evaluate the treatment results. It may consider designating one doctor and one nurse from the ward to share the responsibilities of maintaining ventilation equipment in optimal order, updating the treatment protocols, supervising team member training, and keeping close records, upon which QC will be based. These two professionals will be in charge of coordinating training, teaching, treatment evaluation and research in NIV. Another valuable option, especially for small PICUs with low patient volume, is periodic rotations of doctors or nurses in other hospitals. This ensures good NIV training and enables sharing of experiences among professionals, which is extremely useful in the medical profession.

The team nurses or respiratory therapists will be responsible for continuous care of the patient. They will also be required to learn the treatment protocols and how to operate the equipment, help set up the materials, become familiar with aspects of the treatment that may cause failure during initiation of NIV, and be able to quickly and independently solve any problems that arise. It is crucial that nursing supervisor(s) collaborate with the nurses in maintaining NIV materials, conducting training activities, and fomenting teamwork among the medical staff.

Auxiliary personnel should collaborate closely with the nurses in patient care.

Just as in CMV, safe delivery of NIV requires that well-trained hospital staff be present 24 hours a day, 365 days a year. NIV training should encompass indications, contra-indications and disadvantages of the technique, as well as early recognition of signs that the patient is clinically deteriorating or that the treatment is failing, in order to prevent any delays in endotracheal intubation and subsequent initiation of CMV.

It is well known that the first 6 to 8 hours of NIV imply an additional workload for hospital personnel, especially nurses or respiratory therapists. In the majority of Spanish hospitals, NIV is initiated by intensive care staff (whether in the ICU or PICU); this work requires a high level of personal motivation and force. Therefore, hospital wards that use NIV should anticipate problems in this time frame and take

adequate measures to resolve any problems. If preventative measures are not taken, then there is a strong chance that the treatment will fail and hospital staff will lose their motivation, and consequently, a highly useful ventilatory support option for many patients could be lost.

As with any technique in the PICU, NIV demands that all personnel be capable of delivering this technique at any time; the importance of adequate training can not be reiterated enough.

QUALITY CONTROL

The majority of published studies report an efficacy rate of nearly 75% for NIV in intensive pediatric patients. However, this rate can drop substantially in function of the patient's age and pathology; this is especially apparent in infants younger than 12 months and in patients with Type I acute respiratory failure (ARF).

Evaluating the efficacy of NIV involves more than simply counting the number of patients for whom intubation has been avoided and confirming that the morbidity and mortality are not higher in intubated patients that had first received NIV compared to those that did not: secondary variables must also be measured. These include the average length of hospital stay for patients that have received NIV alone compared to that of clinically similar patients (i.e. by factors including age, type and stage of pathology) that had first been treated with CMV, as well as the frequency of nosocomial infections.

Although the aforementioned variables can be used to compare NIV against the gold standard of CMV, the best way to evaluate NIV is by assessing the quality of the treatment itself and how it has progressed within a given ward.

A record of the efficacy of NIV is undoubtedly the best form of quality control for evaluating this technique within a PICU, although a record of complications can also be useful. Despite the limited body of literature on quality control in NIV, the authors of this chapter have proposed the following four quality indices for NIV of critical pediatric patients:

Initial failure index (IFI)

The IFI is the percentage of patients for whom NIV fails within the first hour. It is calculated by dividing the number of these patients by the total

number of patients treated with NIV, and then multiplying the result by 100%. The authors of this chapter consider that the IFI should be < 10% (ideally < 5%) after the first year doing NIV.

The authors believe that failure of NIV within the first hour is typically due to inappropriate indication, an inadequate interface or ventilator, or a poorly adjusted interface—all of which are associated with inexperienced or untrained personnel—and therefore, think that once a ward adopts NIV, it should closely monitor its IFI. As the ward gradually acquires experience and confidence with NIV, it can begin to treat evermore complex patients or patients that are borderline contraindicated (and consequently, whose condition can temporarily worsen). Hence, the IFI can serve as a red flag in reviewing individual cases, evaluating patient selection protocols, and preventing excessively optimistic use of NIV, which can be pernicious for patients.

Early failure index (EFI)

The majority of NIV failures occur between the first and twelfth hours. The causes of failure include rapid progression of the disease, inadequate etiological treatment of the cause of ARF, patient-ventilator desynchronization (due to multiple factors), and non-compensated hypoxemia (e.g. due to slow recruitment or to use of a ventilator lacking an oxygen blender).

The EFI is the percentage of patients for whom NIV fails between the first and twelfth hours of treatment. It is calculated analogously to the IFI. Its maximum value should be 10 to 15%, which is the overall intubation rate reported in the majority of publications. Although these articles typically do not mention whether intubation occurred before or after the first hour of NIV, the authors of this chapter have determined that experienced wards have an IFI < 5% (see Table I).

The EFI serves to track the progress of NIV in wards that have already learned the technique and have an acceptable IFI. It can also be useful for evaluating the efficacy of NIV in hypoxemic patients with a PaO₂/FiO₂ of nearly 200 that are treated with more than two hours of NIV despite having clinical factors consistent with a poor prognosis (e.g. age < 12 months or no decrease in respiratory rate after the first hour of NIV).

Table I. Quality control indices for non-invasive ventilation (NIV)

Center	Year	IFI	EFI	LFI	# NIV Patients
Bilbao (Cruces)	2004	0%	50%	0%	4
	2005	0%	6%	6%	16
	2006	5%	0%	5%	19
	2007	5%	0%	15%	25
Oviedo	2004	0%	13.63%	4.54%	22
	2005	3.12	3.12	15.62	32
	2006	6.66%	6.66%	2.22%	45
	2007	1.85%	5.55%	11.11%	54
Lisboa (F Fonseca)	2005	0%	14%	7%	14
	2006	0%	12%	5%	42
	2007	4%	12%	16%	25
Salamanca	2004	0%	23%	0%	13
	2005	0%	9%	18%	22
	2006	7.7%	15.4%	7.7%	26
	2007	0%	10.5%	0%	19
Castelló	2005	0%	0%	50%	3
	2006	10%	15%	10%	19
	2007	0%	0%	25%	8
Albacete	2005	0%	0%	50%	4
	2006	0%	7.7%	7.7%	13
	2007	0%	12%	0%	16
Sabadell	2004	14.2%	14.2%	0%	8
	2005	0%	0%	0%	3
	2006	11%	0%	0%	9
	2007	0%	0%	14%	14
Barcelona (HSJD)	2002	6.6%	6.6%	6.6%	15
	2003	0%	11%	3.7%	27
	2004	0%	14.7%	11.7%	34
	2005	0%	9.8%	15.7%	51

IFI: initial failure index; EFI: early failure index; LFI: late failure index; NIV: non-invasive ventilation; HSJD: Hospital Sant Joan de Deu

Late failure index (LFI)

Many NIV failures also occur after the twelfth hour and are often due to the same reasons that cause failure between the first and twelfth hours, such as inadequate humidification and progression of the disease (e.g. appearance of new atelectases in bronchiolitis).

The LFI is the percentage of patients for whom NIV fails after the twelfth hour. It is also calculated analogously to the IFI. The LFI should be approximately 5-15%; hence, the EFI and the LFI should sum to approximately 20%, which is the

overall intubation rate (see above and Table I). The cut-off between EFI and LFI could be set at 18 or 24 hours instead of 12 hours; this is open to debate and will ultimately depend on analysis of data from different wards.

Delayed failure index (DFI)

Some patients are at risk for delayed failure of NIV, namely, those given NIV either as rescue treatment for failed extubations during weaning or as elective therapy for weaning from CMV and avoiding tracheostomy. Albeit no data on this patient

group have been published, the delayed failure index (DFI) may be > 50%. Based on the authors' experience, DFI can range from 75% in the general population to 100% in post-operative cardiac patients.

The duration of NIV in these patients is highly variable, and treatment may remain relatively unstable for several days; hence, the actual number of hours is not very important in determining delayed failure. For many of these patients NIV implies an extended stay in the PICU until they can be treated definitively with CMV.

The authors believe that a DFI of < 75% is possible in the subgroup of patients for whom NIV as rescue treatment is used as last resort.

The authors present here data from eight intensive care units (seven Spanish and one Portuguese) with varying levels of expertise in NIV that support the use of these indices in quality control of NIV. Nonetheless, these indices should be validated in the near future.

Lastly, a record of NIV complications is an invaluable tool for establishing preventative strategies and improving treatment, as exemplified in the drop in cases of skin necrosis due to pressure from NIV interfaces.

ACADEMIC ACTIVITIES

Teaching and training

Ventilatory assistance for acute pediatric patients is a complex discipline which requires a firm base in pediatric medicine, a strong domain of treatment technology, and the skills to perform the diagnostic and therapeutic procedures indicated for respiratory failure patients. This is especially true in the case of relatively recent treatment strategies such as NIV.

Hence, healthcare professionals seeking to learn NIV or update their knowledge on this technique require well organized training programs. Those requiring training include intensive care physicians, pulmonary specialists, physical therapists, pediatrics residents, and nurses. Once trained, these professionals can teach other personnel in their ward through specific training courses and help develop treatment strategies by sharing their NIV experiences with their peers.

Hospital wards should develop in-house academic programs for NIV similar to those used for other techniques. These would include clinical meetings with presentation of clinical cases, literature reviews, and updating of protocols and equipment. Multidisciplinary meetings are especially valuable. These should encompass intensive care physicians, pulmonary specialists, physical therapists, radiologists and any other specialists that have contributed to the patients' care.

Proper training will expand the range of indications of NIV, increase the rate of treatment success and improve early application of this technique, while reducing the frequency of major complications and decreasing the workload on hospital staff that must start and maintain NIV treatment.

Research

Continued research on NIV should provide valuable scientific results that will enable new or improved practical applications (see Table II), and therefore, should be stimulated. However, there is a need for common protocols for multicenter studies and clinical trials, which would be of great interest to professionals in the field. Creation of these protocols could be facilitated by assembling national-level work groups with international connections.

Table II. Future areas of NIV research.

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- The immediate effects of NIV in various pathologies.
 - The mid-term and long-term effects of NIV in various pathologies.
 - NIV safety.
 - Technical variables (interfaces and triggers).
 - Structured training for healthcare professionals.
 - Impact of NIV on development (namely, pulmonary function).
 - Guidelines for diagnosis, treatment, and patient care in NIV.
-

In these groups professionals could share their experiences, and then use them as the basis for protocols. Therefore, each ward should maintain records on its NIV treatment for use in research as well as for quality control. These records should be simple, practical and well-supported by IT.

The results from NIV research should be communicated through the appropriate channels (e.g. journals, conferences and training courses), not only those related to intensive care, but also those dealing with pediatric specializations and with adult medicine.

It is crucial that pediatric ARF patients receive early non-invasive ventilatory support according to criteria distinct from those used for intubation. This requires that healthcare professionals be familiarized with all of the available resources and latest criteria for NIV treatment of ARF.

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Ethical aspects of non-invasive ventilation

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INTRODUCTION

The aim of treating a sick child is to cure them, or, if this is not possible, than at least to improve their condition. Medical technology for treating diseases and prolonging patients' lives is continually progressing. Indeed, the prognoses for many patients, especially those with chronic conditions, are constantly improving as therapeutic techniques become more advanced. However, it is now more important than ever to carefully assess a new technique before adopting it, establishing its therapeutic boundaries and evaluating its suitability for each patient so that unnecessary or ineffective treatments can be avoided.

In most treatment scenarios, healthcare professionals have developed a clear strategy which has been accepted by the child's parents. In these situations, the benefits clearly outweigh the risks.

Starting non-invasive ventilation (NIV) is a valuable option for children with diverse pathologies, primarily acute ones; it is an effective treatment that obviates the need for more aggressive forms of ventilation assistance. However, in certain pathologies, especially chronic ones, NIV can range from highly effective to futile: for some patients, it may improve the quality of their life and that of their family, whereas for others, it may simply extend the time during which they remain in a compromised state, diminishing their quality of life and that of their family, without offering any hope of curing their pathology.

Defining the point at which a child's quality of life becomes unacceptable due to intellectual or

physical limitations can be extremely difficult. Healthcare professionals must carefully inform the patient and their family of all treatment options with their respective benefits and risks. Only the patient—or their family, in the case of very young or otherwise incapable children—can then decide what they are willing to sacrifice or endure in the name of medical treatment.

Another important and potentially controversial ethical issue at the social justice level is the economic and social costs that starting and maintaining certain therapies or techniques places on the public healthcare system. This is especially relevant to the Spanish system, which is being stretched thinner and thinner as it endeavors to continue offering high quality health services. Social justice dictates that all patients should have equal access to these services and that if resources are limited, then the system must give priority to those patients for whom a given treatment will prove most effective.

INDICATIONS OF NON-INVASIVE VENTILATION

There is strong evidence that the drop in mortality rates of pediatric patients is partly due to improvements in neonatal and pediatric intensive care. However, technological advances have brought increased morbidity with severe sequelae that sometimes imply major intellectual, cognitive and physical (especially respiratory) limitations among survivors. Furthermore, modern techniques enable therapeutic options that can prolong the lives of children with various pathologies but that place

these children and their families in overwhelmingly stressful situations.

There are two ethical principles from good clinical practice which are particularly relevant to NIV: beneficence (doing everything possible for the patient's well-being) and non-maleficence (avoiding harm to the patient). There may be cases in which ventilatory support keeps the patient alive at the cost of a severe loss in quality of life which affects not only them, but their family and society as well. NIV may be an excellent treatment option for some patients, especially when used only for part of the day, whereas for others, it may put heavy demands on them and their families.

NIV is often proposed for patients who can not be weaned off of conventional mechanical ventilation (CMV). In these scenarios, the treatment options comprise extubating the child and allowing their pathology to run its natural course, or transitioning the child to NIV. In the latter case, a stipulation can be placed whereby the patient will not be returned to CMV should the treatment prove ineffective. NIV may be employed as elective therapy for patients whose pathology and its natural progression are known.

NIV is indicated for various pathologies, and its therapeutic scope has broadened as healthcare professionals gain experience with this technique and its related equipment (see Chapters 3 and 21). The benefits of NIV are most apparent for diseases in which respiratory failure is temporary or relatively stable.

For certain conditions (e.g. laryngeomalacia, tracheobronchomalacia, bronchopulmonary dysplasia [BPD], and certain facial malformations) ventilatory assistance enables decreasing or even eliminating work of breathing, which in turn allows for better growth and development of the airways, whose structures can then gradually mature. NIV is especially beneficial for patients with facial deformations that are treated by surgery: it can be used until their airways are sufficiently developed for undergoing surgery. In many of these cases NIV can be stopped after a given period of time.

NIV provides clear clinical benefits for patients whose respiratory failure is stable, such as those with scoliosis.

The most challenging questions regarding indication of NIV typically arise over patients whose

condition is very severe or progressively deteriorating. This is most clearly illustrated in neurological or neuromuscular diseases, especially Type I spinal muscular atrophy (SMA).

Type I SMA is an extremely severe progressive neuromuscular disease (NMD) which involves a near total loss of voluntary muscle activity, but which does not affect upper cerebral activities (e.g. sensory organ or intellectual activities). Patients with this disease remain incapacitated and require ventilatory assistance to survive. Explaining the prognosis of an SMA patient to their family can prove challenging: these patients suffer from muscular debilitation so grave that they can not even maintain effective breathing, yet their cognitive function remains normal. As reflected in the literature, there is no general consensus on the best method of ventilatory assistance for infants with SMA, which in turn influences parents' decisions as well as the availability of human and material healthcare resources. Authors that are against the use of NIV for these patients claim that it is futile and only serves to lengthen the child's suffering, whereas those in favor affirm that it improves the child's quality of life and ameliorates the family's sense of powerlessness to stop the disease.

NIV has recently been employed to treat cystic fibrosis patients. Initially its use was limited to temporary ventilation support during lung transplants, but it is now applied early on in cystic fibrosis patients and has demonstrated good results.

NIV can also prove valuable for cancer patients suffering from intercurrent respiratory compromise which, if treated by CMV, would lead to a very poor prognosis. Indeed, NIV is an ideal option for these patients since it improves their clinical state while limiting lung damage. Alternatively, NIV can make terminal patients more comfortable during end-of-life care.

When assessing indication of NIV, healthcare professionals may consider experimental use of this technique. In these cases, they must take into account all of the ethical stipulations that dictate experiments involving humans—specifically, pediatric patients—and, in the absence of other options, consider using NIV as compassionate treatment.

For very severely ill or progressively deteriorating patients the only alternative to NIV is CMV via tracheotomy. This is an invasive method whereby

access to the airways is created surgically via the trachea—which carries inherent risks—and which implies a greater probability of tracheopulmonary infections, requires more frequent aspiration of secretions, limits the patient's oral communication and feeding, and may demand greater dependence on mechanical ventilation.

Homecare is easier for children treated with NIV than for those treated with CMV. This obviates prolonged hospital stays (often in intensive care) and their negative consequences on the child's psychological and emotional development.

When assessing the suitability of an NIV treatment program for a given child, healthcare professionals should consider the following general objectives:

1. Prolong their patient's life.
2. Optimize cardiopulmonary function.
3. Reduce morbidity.
4. Improve the quality of life of the patient and their family.
5. Maintain age-appropriate growth and development.
6. Optimize the cost to benefits ratio of the medical care.

DECISION MAKING

In medical decision-making, the principle of autonomy dictates that capable adult patients must consent to or decide on their care. A doctor must always follow the choice of their patient, regardless of what their own decision would be.

When discussing treatment options with third parties for patients who are not capable of expressing their own opinion—as occurs in pediatric medicine—the main challenge is to determine the best interests of these individuals. Furthermore, decision making in pediatrics can be very complex for patients that, despite legally being minors, have some degree of autonomy because of their age or level of maturity. The parents or caregivers of pediatric patients are responsible for deciding on medical intervention. Their authority, which is legally and ethically indisputable, is based on trust and expressed on behalf of the (incapable) patient, and is presumed to reflect the will and best interests of the patient. Parents are granted this authority precisely because they want the best for their children.

Pediatric patients do not have any recognized authority over their health until they reach legal adult age. However, if the acquisition of autonomy is viewed as a gradual process that occurs over several years, then in terms of decision making, an infant can not be equated with a 7 year old, nor can a child of 7 be equated with an adolescent of 14. From a legal perspective minors should not all be grouped together as being incapable of making choices concerning their health: each patient should be treated on an individual basis and be granted decision-making power in function of their level of maturity. However, as a general rule, children under 12 can be considered as incapable of making decisions, and those over 14, as capable. It is hard to establish a general rule for patients between 12 and 14; each patient should be carefully evaluated to determine their level of maturity. Apart from age and maturity, the consequences of the procedure to be realized must also be taken into account, such that a higher level of maturity is demanded for situations with greater risks (e.g. initiating CMV).

The patient (when capable), their family, and the professionals responsible for their healthcare must assess the advantages and disadvantages of the procedure together.

It is important to highlight the potential for conflicting opinions between parent and child. For capable children these situations can be especially difficult if some type of compromise is not reached; indeed, they may require the intervention of the hospital's ethics committee or the Department of Justice. Regardless of their age or capacity for decision making, the child's dignity must always be respected, and they must always be informed of their condition in an age-appropriate fashion.

From the very beginning of treatment, doctors act based on the principle of beneficence, applying their knowledge to improve the child's wellbeing. The only possible restrictions on their involvement could be the wishes of the child themselves (when capable) or of the parents or caregivers (for non-capable children). Furthermore, during conflicts of opinion between the doctor and patient, there are limits to autonomy: the priority is always the best interest of the child.

The concept of quality of life is difficult to define for children, and doctors, patients (when capable of expressing themselves) and parents do not always

Table I. Bioethical evaluation of non-invasive ventilation according to the principles of Beauchamp and Childress

Principle	Role of non-invasive ventilation (NIV)
Beneficence	Improves the clinical condition of respiratory failure patients; Improves their comfort level and quality of life; Enables verbal expression and good interaction with surroundings; Shortens hospital and PICU stays.
Non-maleficence	Has few side effects; Obviates intubation and tracheostomy; Has lower risk of ventilator-induced pulmonary lesions and of respiratory infections.
Autonomy	A treatment option that children and/or their parents can choose once informed of its indications, advantages, disadvantages and alternatives.
Distributive justice	Enables distribution of resources (i.e. invasive methods are dedicated to most severe patients); Easy to use in home care, which leads to savings in the hospital resources.

Table II. Questions to ask when determining the suitability of NIV for a given patient

Question	Comments
Can the patient benefit from NIV?	Valuation of the technique (principle of beneficence)
How can harm to the patient be avoided during NIV?	Risks inherent to the technique (principle of non-maleficence)
Has the patient and/or family participated in decision-making on the type of ventilation to be used?	Respect the patient's autonomy. The child and their family should be well-informed.
What quality of life is expected for the patient before, during and after treatment?	It is only ethically acceptable to ventilate the patient if the treatment is expected to be beneficial according to objective and subjective terms that fall under the concept of quality of life.

share the same definition. Surveys on quality of life for children treated with ventilatory support typically refer to CMV, as information on NIV remains scarce.

Doctors may have a more distanced perspective, implying less personal feelings, whereas families often can not remove the emotional element from their decision making. Social, cultural and religious factors also influence families' treatment choices. An important aspect to consider when valuating the family's opinion is their need to feel that they have done everything possible to maintain their child in the best conditions possible. In the event of an early death, healthcare professionals must ensure that the family does not feel responsible, even if they had understood the gravity of the child's prognosis.

Life is one of the most precious things on Earth, but it is not the only one; it is not absolute. The quality of a life prolonged by ventilatory support must be deemed sufficiently good to justify the treatment. This demands that the doctor have the deepest knowledge possible of the pathology affecting the child and of the natural course of the

disease. Doctors must remain up to date on current therapies, since medical decisions can vary in function of experience and available resources.

Usually there is no ideal treatment option; different decisions may be equally correct from a moral perspective. Each case is different and each family is unique. Health professionals must recognize the rights of the parents to define what is best for the child, and, as long the principle of maleficence is not violated, must accept the parents' decision even if they do not agree with it. Furthermore, they must accompany the parents during the decision making process and comfort them over their decision, regardless of whether the family has opted for a particular treatment or decided against it.

Despite the difficulty inherent in defining quality of life, NIV can offer certain clear benefits that facilitate decision making: improved nocturnal sleep with a consequent increase in diurnal activity; decreased rate of respiratory infections; fewer hospital admissions; and greater physical autonomy (e.g. eating and speaking).

Accurate information is critical to decision making. It should be clearly and sincerely communicated to all parties involved (including the child, if capable), with all the treatment risks and benefits carefully explained. Healthcare professionals must ensure that in every conversation with the patient, family and/or caregivers, the information is well understood; if needed, they must be willing to expand on or repeat what they have said if requested.

THE ROLE OF SOCIETY

NIV is dictated by a series of contextual factors that, depending on the patient, can either facilitate or complicate its clinical application. Material resources are limited; hence, the public health administration and healthcare institutions must develop strategies to organize and distribute these resources in function of their priorities. The bioethics principle of justice stipulates that all individuals should have equal access to health resources (since each person deserves the same consideration and respect), and the premise of distributive justice deems that limited resources must be maximized. Hence, NIV should be provided to those patients that stand to benefit the most.

NIV can be considered a highly efficient resource, since its use for both chronic and acute patients implies major savings as compared to CMV: NIV equipment is cheaper, simpler and longer lasting, and NIV is relatively easy to administer in the home, which reduces workloads on hospital staff. Home mechanical ventilation (HMV) programs should be encouraged as much as possible for both NIV and CMV patients.

In terms of resource distribution, doctors must evaluate each patient to determine which form of mechanical ventilation would be most appropriate—and therefore, how resources will be used—according to fair criteria. They must also try and obtain all the materials that they deem necessary for their patients, endeavoring to convince the hospital administration of the various benefits of NIV—namely, in terms of beneficence, non-maleficence and quality of life for the patient, as well as cost-effectiveness as a health service. Doctors must always efficiently manage their available resources. For example, NIV systems should be used for as

many patients as possible. This in turn may require the development of specific treatment programs, training courses, technical protocols and clinical guidelines.

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Summary and algorithms

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INTRODUCTION

The demands that non-invasive ventilation (NIV) places on hospital staff require that hospital wards develop clear treatment protocols. This chapter aims to establish general clinical guidelines, based on the evidence presented throughout this book, that should be adapted to each patient and each ward. Furthermore, the protocols and algorithms presented here should be frequently updated, as continued interest in NIV leads to greater technical expertise and clinical experience among professionals in the field.

INDICATIONS (CHAPTER 3)

The indications of NIV in respiratory failure are becoming increasingly clear and are based on the criteria for pediatric acute respiratory failure (ARF) (see Table I). These can be extrapolated to establish a general classification for the different acute and chronic pathologies which can be treated with NIV (Table II).

From a practical perspective, when using NIV the type of ARF should be classified according to certain physiopathological criteria:

Type I ARF. Type I ARF is characterized by imbalance between ventilation and perfusion (V/Q mismatch) without alveolar hypoventilation. It first appears as hypoxemia with no increase in arterial carbon dioxide pressure (PaCO₂). Patients may exhibit condensations when examined by chest X-rays.

Type II ARF. The main feature of Type II ARF is alveolar hypoventilation. It is defined by the presence

of hypercapnia (PaCO₂ > 45 mm Hg) with a normal alveolar-arterial oxygen gradient (A-a O₂). Patients may present with hypoxemia due to hypoventilation. Chest X-rays do not reveal any condensations (excluding atelectases).

Following the classification above, the authors of this chapter propose that pathologies should be grouped as shown in Table III (modified from Teague & Dobyns et al.). Acute bronchiolitis can be classified under each type of ARF in function of its clinical characteristics. It is important to remember that atelectasis observed in chest X-rays is not necessarily indicative of Type I ARF. Despite causing V/Q mismatch in the affected area, it may occur in Type II ARF, specifically, as the consequence of pre-existing hypoventilation. Furthermore, atelectasis in Type I ARF may be generated in adjacent segments by pneumonia.

CONTRA-INDICATIONS (CHAPTER 3)

Early detection and pre-assessment of contra-indications to NIV is crucial for avoiding erroneous treatment of patients that should instead be treated with conventional mechanical ventilation (CMV). These contra-indications are constantly updated; indeed, certain conditions which only a few years ago were considered absolute are now considered relative (e.g. pneumothorax and recent gastric surgery). In fact, the British Thoracic Society guidelines accept the use of NIV for patients with contradictions as long as intubation is planned or the treatment is palliative. Nonetheless, there are certain absolute conditions which must be carefully evaluated (Table IV).

Table I. Criteria for respiratory failure in children

Clinical criteria	Physiological criteria
Weak cough, retention of respiratory secretions	Vital capacity < 15 mL/kg
Increased use of accessory muscles	Maximum inspiratory force < 20 cmH ₂ O
High respiratory frequency (based on age)	PaCO ₂ > 45 mm Hg and pH < 7.35
Paradoxical breathing	PaO ₂ /FiO ₂ < 300 mmHg
Incompetent swallowing	SatO ₂ < 97% for ambient air
Reduced activity level or diminished function	

mL: milliliters; kg: kilograms; cm H₂O: centimeters water; mm Hg: millimeters mercury; PaCO₂: arterial carbon dioxide pressure; PaO₂: arterial oxygen pressure; Sat O₂: oxygen saturation; FiO₂: inspired fraction of oxygen

Table II. Processes causing acute or chronic respiratory failure in pediatric patients for which non-invasive ventilation (NIV) is indicated

Acute respiratory failure (ARF)	Chronic respiratory failure (CRF)
A. Decompensated central nervous system (CNS) diseases: <ol style="list-style-type: none"> 1. Apneas in pre-term/full-term infants 	A. Respiratory sleep disorders: <ol style="list-style-type: none"> 1. Obstructive sleep apnea syndrome (OSAS)
B. Decompensated respiration due to chest wall or spinal abnormalities <ol style="list-style-type: none"> 1. Obesity-hypoventilation syndrome 	B. Neuromuscular diseases (NMDs) that affect respiratory musculature <ol style="list-style-type: none"> 1. Diseases of the 2nd motor neuron (e.g. spinal muscular atrophy [SMA]) 2. B30 3. Diseases of or damage to the phrenic nerve 4. Myasthenia gravis and other congenital myasthenic syndromes 5. Myopathies (e.g. congenital, mitochondrial, metabolic, or inflammatory; and deposition diseases) 6. Muscular dystrophies (MDs)
C. Upper airway diseases: <ol style="list-style-type: none"> 1. Upper airway (e.g. laryngitis, and laryngotracheitis) 	C. Upper airway diseases: <ol style="list-style-type: none"> 1. Tracheomalacia
D. Lung diseases <ol style="list-style-type: none"> 1. Asthma 2. Bronchiolitis 3. Pneumonia 4. Atelectasis 5. Acute pulmonary edema (APE) 	D. Respiratory diseases of the lower tract or parenchyma <ol style="list-style-type: none"> 1. Bronchopulmonary dysplasia (BPD) 2. Cystic fibrosis 3. Bronchiectasis
E. Other situations <ol style="list-style-type: none"> 1. Apneas after tonsillectomy 2. Postoperative period after corrective surgery for scoliosis 3. Pulmonary complications from sickle cell disease 4. Early extubation 5. As ventilatory support during sedation procedures 6. Severe respiratory failure in terminal illness (i.e. palliative indication) 	

CONDITIONS FOR NON-INVASIVE VENTILATION (CHAPTER 4)

NIV can be delivered nearly anywhere if a portable ventilator is used. However, a hospital environment is preferred for treating acute patients and for controlling changes in ventilation parameters in chronic patients, whereas extra-hospital treatment should be reserved for chronic patients who have already begun NIV. Choosing

the ward in which NIV should be started depends on the patient, the available materials and the personnel (Table V).

MATERIALS

Positive pressure NIV of pediatric patients requires various materials that often differ from, or are used differently than, those for adult patients:

Table III. Physiopathological classification of acute respiratory failure (ARF)

Type I ARF	Type II ARF
ALI/acute respiratory distress syndrome (ARDS)	Respiratory center: <ul style="list-style-type: none"> • Drugs (opiates, barbiturates and anesthetics) • Central congenital hypoventilation syndrome (CCHS)
Neonatal distress syndrome	Upper motor neuron: <ul style="list-style-type: none"> • Spinal column trauma • Syringomyelia • Demyelinating diseases • Tumors • Anterior horn neurons • Poliomyelitis • Werdnig-Hoffmann syndrome
Bronchoaspiration	Lower motor neuron: <ul style="list-style-type: none"> • Post-thoracotomy lesion of the phrenic nerve • Guillan-Barré syndrome
Acute bronchiolitis	Neuromuscular junction: <ul style="list-style-type: none"> • Botulism, multiple sclerosis (MS) and myasthenia gravis • Antibiotics that block neuromuscular function • Organophosphorous compound poisoning • Tetanus
Cardiogenic pulmonary edema	Pleura and chest wall: <ul style="list-style-type: none"> • Lesions from chest wall burns with retraction • Massive pleural effusion, and morbid obesity • Muscular dystrophy (MD) and pneumothorax
Cystic fibrosis	Increased airway resistance: <ul style="list-style-type: none"> • Obstruction of the larynx (e.g. laryngitis, diphtheria, epiglottitis, aspiration of foreign bodies, post-extubation edema, and paralysis of the vocal chords) • Lower airway obstruction (e.g. emphysema, asthma, and acute bronchiolitis)
Pulmonary embolism (air, fat or blood)	
Interstitial pulmonary disease	
Post-obstructive pulmonary edema	
Radiation	
Sepsis	
Severe pneumonia (of bacterial, viral, fungal or parasitic origin)	
Inhalation of poisons or toxic gases	
Multiple transfusions	
Trauma (pulmonary contusion)	

ALI: acute lesion injury; ARF: acute respiratory failure; ARDS: acute respiratory distress syndrome.

Table IV. Contra-indications to the use of non-invasive ventilation (absolute contra-indications are shown in bold)

1. Neurological: <ul style="list-style-type: none"> • Inability to protect airway: compromised bulbar function, paralysis of the vocal chords, and altered level of consciousness • Severe psychomotor retardation 	4. Respiratory: <ul style="list-style-type: none"> • Severe respiratory failure (relative) • Undrained pneumothorax • Fixed obstruction of the upper airway • Upper airway surgery • Abundant heavy secretions • ARDS with PaO₂/FiO₂ < 150
2. Craniofacial alterations: <ul style="list-style-type: none"> • Facial trauma or burns • Facial surgery 	5. General: <ul style="list-style-type: none"> • Severely compromised clinical state • Hemodynamic instability or shock • Post-operative arrhythmias following cardiac surgery • Congenital cardiopathies affecting pulmonary flow
3. Gastrointestinal (GI): <ul style="list-style-type: none"> • Upper digestive tract surgery (esophageal or upper GI) • Profuse vomiting • Active digestive hemorrhaging • Obstruction of the intestinal tract 	

ARDS: acute respiratory distress syndrome; PaO₂: arterial oxygen pressure; FiO₂: fraction of inspired oxygen.

Table V. Criteria, materials and hospital staff requirements for use of non-invasive ventilation in the pediatric intensive care unit or in the intermediate care or general wards

	PICU	Intermediate-care or general ward
Criteria	ARF with $FiO_2 < 0.4$ pH < 7.30 at any time General ward staff is inexperienced Patient and/or family are non-cooperative Apneas	ARF with $FiO_2 < 0,4$ Initial pH > 7.30 General ward staff is experienced hospitalización 24 hour continuous care by experienced staff Patient and/or family are cooperative
Materials	Non-invasive specific ventilator with oxygen blender Conventional ventilator with non-invasive module Interface (preferable oral-nasal) For NMD patients: assisted cough device	Non-invasive specific ventilator with oxygen blender Interface (oral-nasal or nasal) For NMD patients: assisted cough device
Hospital staff	Trained physician Trained nurse For NMD patients: respiratory physiotherapist (if unavailable, nurse to patient ratio of 1:1)	Trained physician Trained nurse

PICU: pediatric intensive care unit; ICW: intermediate care ward; ARF: acute respiratory failure; FiO_2 : fraction of inspired oxygen.

Table VI. Choice of interface in function of the patient's age and type of acute respiratory failure

RF	Age	Preferred interface	Alternatives
Type I	Neonate	Short double nasal prong	Nasopharyngeal tube Nasal mask
	Infant	Large nasal mask used as an oral-nasal mask	Nasal mask Short nasal prong Helmet
	1 to 6 years	Oral-nasal mask	Nasal mask Nasopharyngeal tube
	6 to 12 years	Oral-nasal mask	Nasal mask Helmet
	> 12 years	Oral-nasal mask	Full face mask Helmet Nasal mask
Type II	Neonate	Short double nasal prong	Nasopharyngeal tube Nasal mask
	Infant	$FiO_2 < 0.5$: nasal mask, or short nasal prong $FiO_2 > 0.5$: Large nasal mask used as an oral-nasal mask	Short nasal prong Nasopharyngeal tube Helmet
	1 to 6 years	Oral-nasal mask	Nasal mask Nasopharyngeal tube
	6 to 12 years	$FiO_2 < 0.5$: nasal mask $FiO_2 > 0.5$: oral-nasal mask	Oral-nasal mask
	> 12 years	$FiO_2 < 0.5$: nasal mask $FiO_2 > 0.5$: oral-nasal mask	Oral-nasal mask Full face mask

ARF: acute respiratory failure; FiO_2 : fraction of inspired oxygen.

- a. Ventilators.
- b. Interfaces.
- c. Attachment systems.
- d. Tubing and associated equipment.

Table VII. Overview of mechanical ventilators

Ventilator type	Supports	NIV Modes	Oxygen blender	Inspiratory sensitivity	Expiratory sensitivity	Compensación de fugas	Monitoring
CPAP (assembled by hand)	Yes	Yes CPAP	Yes	No	No	No	Pressure
CPAP (specific)	Yes	Yes CPAP	Yes	No	No	No	Pressure
NIV ventilator for home use	Some models	Yes CPAP Pressure Volume	Someones	Automatic by flow	Automatic	Yes	Pressure
NIV ventilator for hospital use	Some models	Yes CPAP Pressure Volume	Yes	By flow Generally automatic	Generally automatic	Yes	Pressure Volume Apneas
Conventional (invasive) ventilator with standard modes	Yes	Yes CPAP Pressure Volume	Yes	Yes* Pressure and flow	Yes*	No	Pressure Volume* Apneas
Conventional (invasive) ventilator with NIV mode	Yes	Yes CPAP Pressure	Yes	Yes Pressure and/or flow Automatic or manual	Yes Automatic or manual	Yes	Pressure Volume Apneas

*IMV: invasive mechanical ventilation; CPAP: continuous positive airway pressure. *Does not work well in NIV*

Table VIII. Accessories required for non-invasive ventilation.

Hydrocolloid dressings	Tubing
Humidifier	Nebulizer
Oxygen T-piece	Plateau valve
Oxygen lines	Pressure lines
Flow meter	

an oxygen blender (see Table VII). Other influential factors are the need for synchronization or for a specific NIV mode.

Accessories

Auxiliary materials depend on the patient, ventilator and interface. Table VIII summarizes the accessories required for NIV of acute patients.

INTERFACES (CHAPTER 5)

Choosing the right interface for each patient primarily depends on their age and their type of respiratory failure, as well as on the availability of materials in the ward (Table VI). The interface should be applied according to the algorithm shown in Fig. 18, chapter 5.

VENTILATORS (CHAPTER 6)

The principal criterion for choosing a ventilator is the patient's oxygen needs: hospital staff should determine the patient's FiO₂ requirements and check whether the ventilator in question is equipped with

TREATMENT PROTOCOL FOR ACUTE PATIENTS (CHAPTER 8)

No sufficiently strong evidence exists for establishing class A or B recommendations. Hence, the authors of this book have referred to the protocols published to date as well to expert opinion. Based on the preceding chapters, the authors of this chapter propose the following algorithms for acute patients (Figs. 1 and 3).

PATIENT CARE (CHAPTER 9)

The efficacy of NIV is highly dependent on the technical and theoretical expertise of the healthcare

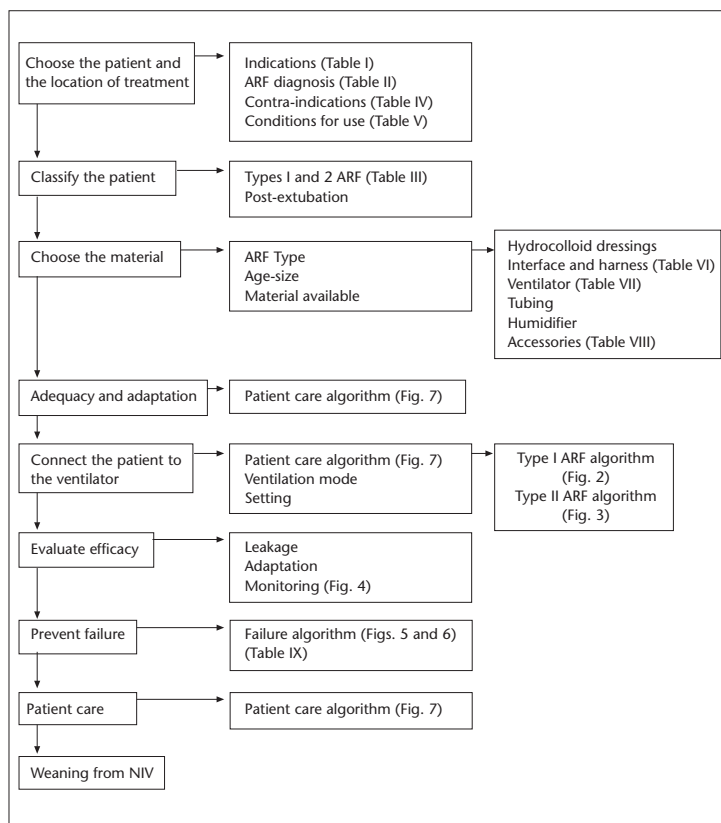


Figure 1. General algorithm (ARF: acute respiratory failure; NIV: non-invasive ventilation).

professionals involved, as well as the quality of patient care, including troubleshooting of complications that may arise during ventilation. NIV patient care is summarized in Figure 4.

MONITORING (CHAPTER 10)

Monitoring in NIV encompasses close observation of different parameters in the patient (e.g. clinical, analytical and functional) and in the ventilator. The objective is to ensure effective treatment, detect any side effects or other complications early on, and then, if required, apply the necessary clinical criteria to decide whether ventilation should be continued, modified or stopped.

Figure 5 shows the protocol for monitoring NIV patients before and during treatment. This algorithm is based on clinical monitoring and on arterial blood gas levels.

1. Clinical monitoring. This is used before and during treatment to detect any contra-indications to NIV or any changes in NIV mode parameters.

2. Arterial blood gases. Since NIV is non-invasive, there is a risk that hospital staff will not monitor the patient sufficiently. To avoid this, the patient's ARF must be classified physiopathologically (see Table III), as recommended by current guidelines for adult patients and according to the data reported by Mayordomo-Colunga et al. For patients with ARDS (according to the data of Antonelli et al.), a $\text{PaO}_2/\text{FiO}_2 > 175$ after one hour of NIV is a predictive factor for treatment success, whereas a $\text{PaO}_2/\text{FiO}_2 < 175$ indicates that CMV should be considered even if the patient does not strictly meet intubation criteria. Hence, blood gases should be closely monitored before, and 1 hour after, NIV has begun to avoid unnecessarily prolonging failed NIV or allowing the patient to enter into a contra-indicated state ($\text{PaO}_2/\text{FiO}_2 < 150$).

3. Pulse oximetry. NIV patients should be should be systematically and regularly monitored by pulse oximetry, the results of which are the best indicator of their level of oxygenation. Moreover, for adult patients with either acute pulmonary lesions (ALI)

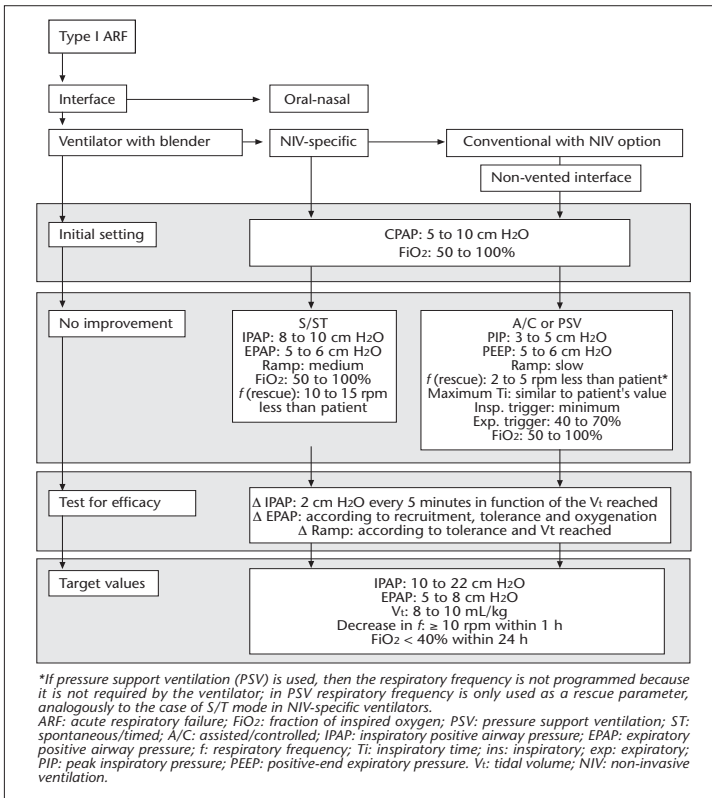


Figure 2. Algorithm for Type I acute respiratory failure (ARF).

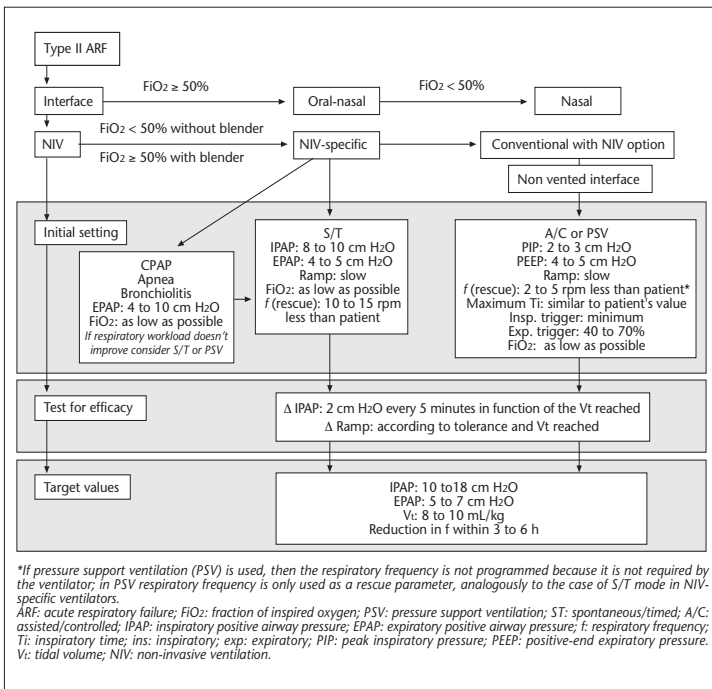


Figure 3. Algorithm for Type II acute respiratory failure (ARF).

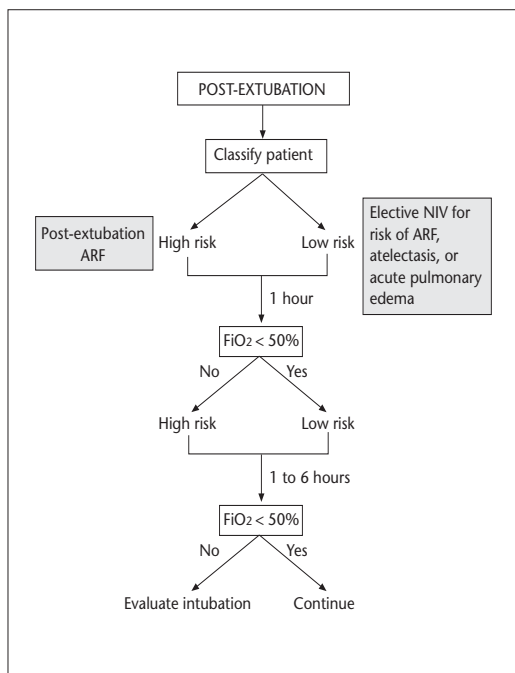


Figure 4. Algorithm for analyzing failure of non-invasive ventilation in post-extubation patients. PaO₂: arterial oxygen pressure; FiO₂: fraction of inspired oxygen; ARF: acute respiratory failure.

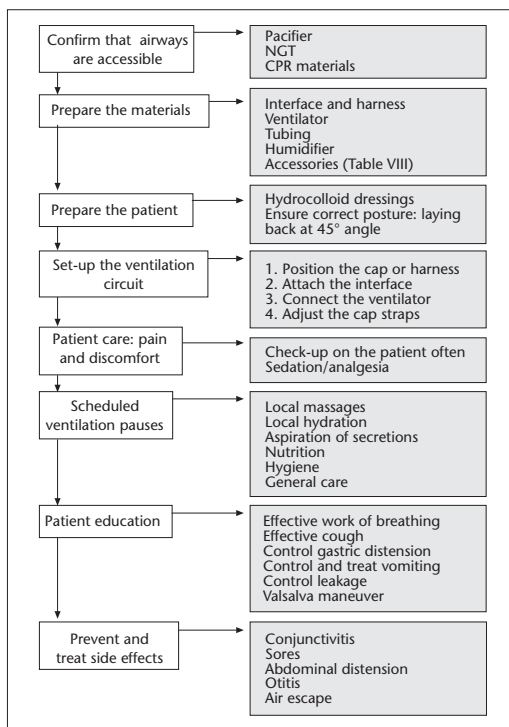


Figure 5. Algorithm for patient care in non-invasive ventilation (NGT: nasogastric tube; CPR: cardiopulmonary resuscitation).

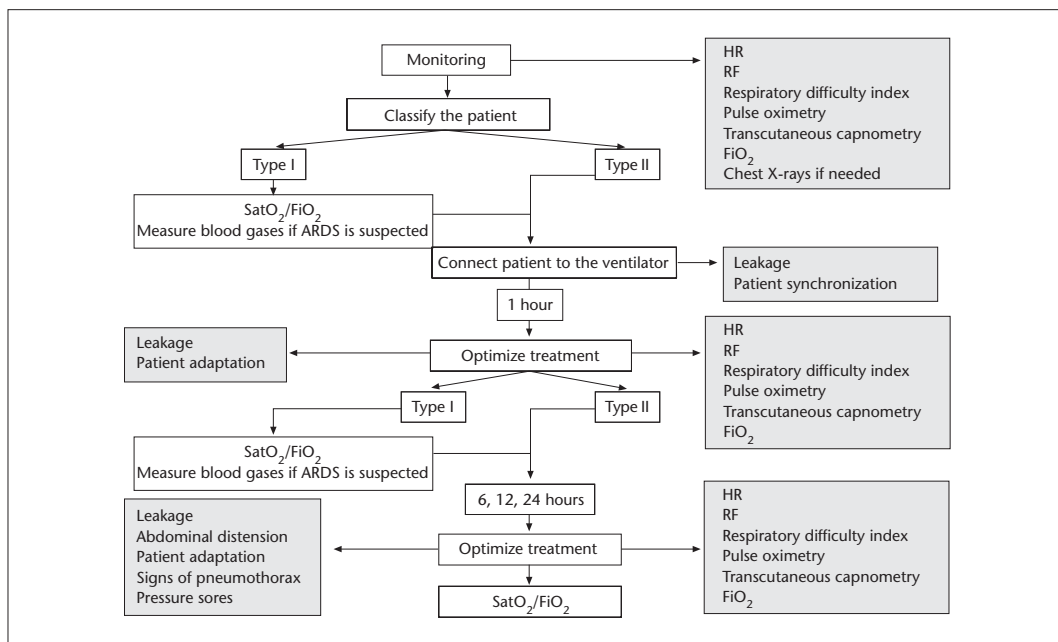


Figure 6. Algorithm for monitoring non-invasive ventilation. HR: heart rate; RF: respiratory frequency; FiO₂: fraction of inspired oxygen.

Table IX. Systematic checklist for possible failure of non-invasive ventilation

1. Desynchronization
 - a. Inadequate interface
 - b. NIV-specific ventilator:
 - Leakage in the interface
 - Inspiratory trigger not activated
 - Inadequate respiratory circuit
 - Inadequate ramp
 - c. Conventional ventilator:
 - Insufficient leakage compensation
 - Correct expiratory trigger
2. Confirm adequate etiological treatment for the cause of RF
3. Facilitate drainage of secretions via physiotherapy
4. Check for any new complications:
 - a. Pneumothorax
 - b. Aspiration pneumonia
5. Persistent hypoxemia:
 - a. Switch to a ventilator with oxygen blender
 - b. Determine if the EPAP should be increased
 - c. Increase the FiO₂
6. Persistent or newly arising hypercapnia:
 - a. Check for leakage in the interface
 - b. Confirm that the circuit has leakage control
 - c. Correct any re-inhalation:
 - Increase the EPAP
 - Change to Plateau valve
 - Use an interface with less dead space (if possible)
 - d. Prevent desynchronization:
 - Adjust the respiratory frequency and the I/E ratio
 - Adjust the inspiratory and expiratory triggers (if possible)
 - Determine if the EPAP should be increased
 - e. Ensure adequate ventilation:
 - Check chest wall expansion
 - Increase the IPAP or delivered volume
 - Determine if the mode or ventilator should be changed

FiO₂: fraction of inspired oxygen; EPAP: expiratory positive airway pressure; IPAP: inspiratory positive airway pressure; I/E: inspiratory to expiratory; RF: respiratory failure

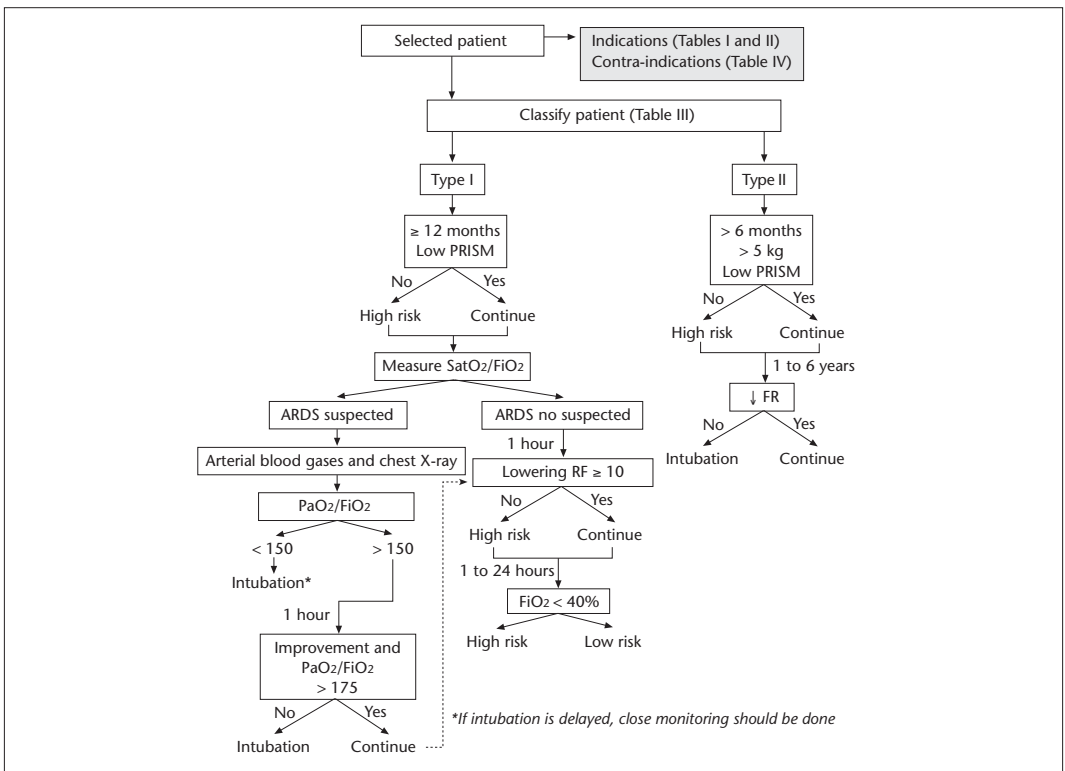


Figure 7. Algorithm for analyzing failure of non-invasive ventilation in Types I and II acute respiratory failure. RF: respiratory frequency; PaO₂: arterial oxygen pressure; FiO₂: fraction of inspired oxygen; Rx: radiografía tórax.

or ARDS—the patients included under the most severe cases of Type I ARF—and a transcutaneous $\text{SatO}_2 < 98\%$, the hemoglobin saturation quotient ($[\text{SatO}_2]/\text{FiO}_2$) has proven utile for indirect measurement of $\text{PaO}_2/\text{FiO}_2$, according to the formula: $\text{PaO}_2/\text{FiO}_2 = [(\text{SatO}_2/\text{FiO}_2 - 64)]/0.84$. Hence, this index can be useful for measuring the level of intrapulmonary shunt in patients before and during NIV treatment.

4. Capnometry. For acute indications of NIV, determination of CO_2 levels via capnography (side-stream or micro-stream) or conventional transcutaneous capnometry allow evaluation of the patient's minute volume, and therefore, of their response to NIV, especially in Type II ARF patients.

FAILURE ANALYSIS (CHAPTER 13)

Any ward that adopts NIV must have protocols for evaluating its success or failure. Various studies have been performed in which the authors attempted to identify predictive factors for failure of NIV in adult patients. However, very few studies of this type have been done for infants, and those that do exist are either based on retrospective data or focus on single pathology (bronchiolitis).

Patients generally respond clinically to NIV within the first hour of treatment: a positive response consists of reductions in tachypnea and in chest retractions, whereas a negative response, whether due to poor adaptation or the underlying pathology, leads to increased work of breathing, ultimately obligating the patient to be intubated. The parameters which have proven most utile for determining the success of NIV comprise a decrease in FiO_2 , a decrease in respiratory frequency, an increase in delivered tidal volume, improved pH, and improved $\text{PaO}_2/\text{FiO}_2$.

To identify NIV patients at a high risk for treatment failure, and for whom CMV should therefore be considered, the authors of this chapter have developed the algorithms shown in Figures 6 and 7, which incorporate clinical and arterial blood

gas data. Furthermore, it is essential to use a checklist (see Table IX) to recognize all factors (whether or not they can be corrected) that cause NIV to fail.

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