30 Negative and Positive Noninvasive Pressure Ventilation

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Abstract

Mechanical ventilation replaces or supplements the respiratory muscles' activity. Invasive mechanical ventilation is performed using a device that bypasses the upper airways, such as the nasal/orotracheal tube or the tracheostomy tube. Noninvasive mechanical ventilation (NIV), on the other hand, uses an interface that does not bypass the upper airways, thus avoiding some of the complications associated with intubation and improving patient comfort. Noninvasive ventilation techniques can be used using positive or negative pressure ventilators.

Negative pressure ventilation, most widely used during the first half of the twentieth century, had some disadvantages such as patient discomfort, difficult ventilation in subjects with variable anatomical conformations, and poor handling of the equipment. This led to a progressive replacement, after the 1970s, of negative pressure ventilators with new positive pressure ventilation systems.

Keywords

Positive pressure ventilation · Negative pressure ventilation · Interface · Acute respiratory failure

Abbreviations

ACPE	Acute cardiogenic pulmonary edema
ALI	Acute lung injury
ARF	Acute respiratory failure
CNEP	Continuous extrathoracic negative pressure
COPD	*Chronic* obstructive pulmonary disease
CPAP	Continuous positive airway pressure
NEEP	Negative end-expiratory pression
NIV	Noninvasive mechanical ventilation
NPV	Negative pressure ventilation
OSAS	*Obstructive* sleep apnea syndrome
PCV	Pressure-controlled ventilation
PEEP	Positive end-expiratory pression
PSV	Pressure support ventilation
VCV	Volume-controlled ventilation

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A. M. Esquinas (ed.), *Pulmonary Function Measurement in Noninvasive Ventilatory Support*,
https://doi.org/10.1007/978-3-030-76197-4_30

30.1 Introduction

Mechanical ventilation replaces or supplements the respiratory muscles' activity. Invasive mechanical ventilation is performed using a device that bypasses the upper airways, such as the nasal/orotracheal tube or the tracheostomy tube.

Noninvasive mechanical ventilation (NIV), on the other hand, uses an interface that does not bypass the upper airways, thus avoiding some of the complications associated with intubation and improving patient comfort.

Noninvasive ventilation techniques can be used using positive or negative pressure ventilators.

Negative pressure ventilation, most widely used during the first half of the twentieth century, had some disadvantages such as patient discomfort, difficult ventilation in subjects with variable anatomical conformations, and poor handling of the equipment. This led to a progressive replacement, after the 1970s, of negative pressure ventilators with new positive pressure ventilation systems.

30.2 Discussion and Analysis of the Main Topic

30.2.1 Negative Pressure Ventilation

Negative pressure ventilation (NPV) was the first ventilatory technique used in the clinical setting.

In the 1930s and 1940s it was used during polio epidemics. Subsequently it was replaced by orotracheal intubation and positive pressure ventilation due to the lack of protection of the airways and their collapse in patients with paralysis of the pharyngeal muscles.

In recent years, however, it has again been used successfully in patients with acute respiratory failure secondary to obstructive and restrictive lung and chest wall diseases.

The mechanism of action consists in artificially generating a sub-atmospheric pressure during inspiration: the negative pressure expands the chest wall and reduces the alveolar pressure; the pressure gradient between the opening of the airways and the alveoli generates an inspiratory flow which determines the alveolar ventilation. The exhalation occurs passively through the elastic forces of the respiratory system.

Negative pressure ventilator consists of a rigid container that encloses the chest wall and a pump capable of generating sub-atmospheric pressures inside the container.

There are three types of negative pressure ventilators:

- Steel lung, in which the rigid container (in plastic or aluminum) encloses the entire body surface of the patient with the exception of the head. It applies pressure changes to the entire body surface of the patient and requires only one seal with respect to the external environment.
- Poncho, consisting of a rigid support, which encloses the thoracic cage and abdomen of the patient and a nylon suit which, once worn, completely envelops the rigid support and is sealed at the neck, wrists, pelvis, and ankles of the patient.
- Armor, consisting of a hard plastic shell to be placed around the rib cage and upper abdomen, the only parts exposed to pressure variations.

The pumps can be located inside the container (steel lung) or outside (poncho and armor). These pumps allow a pressure-controlled and time-cycled ventilation so that the inspiratory flow and the tidal volume are not constant but depend on the mechanical characteristics (elastance and resistance) of the patient's respiratory system.

The pumps currently available allow you to set the level of sub-atmospheric pressure to be delivered during inhalation, the pressure level to be maintained inside the container during exhalation and the times of the respiratory cycle. Maintaining a sub-atmospheric pressure around the chest wall during exhalation (negative end-expiratory pression/NEEP) has physiological effects equivalent to those of PEEP (positive end-expiratory pression) during positive pressure ventilation.

The main factors determining the effectiveness of negative pressure fans are:

- Pump power (the maximum negative pressure generated varies from −60 to −100 cmH_2O depending on the models).
- Type of pressure wave generated by the pump (pumps that generate a square wave determine a tidal volume greater than those that produce a sine wave).
- Surface of the chest wall exposed to pressure changes.
- Number of seals required.

The following ventilation modes are currently possible:

- Negative cyclic pressure: ventilator delivers the sub-atmospheric pressure level set by the operator for the set time, during exhalation, which occurs passively, t pressure around the chest wall returns to the atmospheric level.
- Negative/positive pressure: ventilator delivers a sub-atmospheric pressure during inspiration and a positive pressure (greater than atmospheric pressure) during exhalation.
- Continuous extra thoracic negative pressure: ventilator delivers constant sub-atmospheric pressure throughout the respiratory cycle while the patient breathes spontaneously. The physiological effects of CNEP are similar to those of CPAP (continuous positive airway pressure).
- Negative pressure/NEEP: ventilator delivers two predetermined levels of negative pressure, respectively during inhalation and exhalation.

30.2.1.1 Clinical Applications

COPD (chronic obstructive pulmonary disease) patients can be treated with NPV by means of a steel lung in order to improve the ventilatory pattern (increase in tidal volume and minute ventilation, reduction in respiratory rate, reducing the work of the respiratory muscles) [1].

In patients suffering from neuromuscular diseases and chest wall deformities, the use of NPV allows you to rest the respiratory muscles, improve the breathing pattern, and slow the evolution of chronic respiratory failure [2].

Several studies show that the use of NPV is useful in pediatric patients and in neonatal respiratory distress syndromes.

30.2.1.2 Side Effects

The main side effect is the tendency to collapse of the upper airways: during NPV, the pressure inside the upper airways during inspiration becomes sub-atmospheric; this phenomenon facilitates the collapse of the upper airways at the pharyngeal level.

In addition, the patient's airways are not protected with a consequent potential risk of aspiration in case of vomiting.

30.2.2 Positive Noninvasive Ventilation

30.2.2.1 Background

The first work on the use of positive pressure ventilation dates back to 1912, when Bunnel [3] used a face mask to maintain lung expansion during thoracic surgery.

A series of studies conducted by Barach et al. [4] during the 1930s showed that continuous positive pressure (CPAP) applied using a face mask could be useful in the treatment of acute cardiogenic pulmonary edema and other forms of acute respiratory failure.

In the 1990s, the evidence of a reduction in complications related to nasal/orotracheal intubation [5] and the reduction of mortality and morbidity in selected patients with acute respiratory failure led to the explosion in the use of noninvasive ventilation methods.

30.2.2.2 Instruments and Techniques

The NIV uses an interface and different types of ventilation. Interfaces are devices that guarantee the connection between patient and ventilator allowing the release of pressurized gases in the airways. The available interfaces are nasal and oronasal masks, and helmets and nasal olives. Selecting an appropriate interface is crucial to the success of the NIV.

A *nasal mask* is a plastic device that is placed on the patient's nose. The tightness is guaranteed by means of a soft cushion and anchoring systems (fastening straps). It is preferred in cases of chronic administration of NIV due to its high tolerability. It is not indicated in the early stages of ALI (acute lung injury) as the patient breathes through the open mouth.

Nasal olives are soft silicone or rubber plugs which, by not exerting any pressure on the root of the nose, can be useful in patients who develop irritation or skin ulcers on the face.

Oronasal masks cover both the nose and the mouth. They are preferred in the emergency department as dyspneic patients mostly breathe through the mouth. They interfere with language, with expectoration, and with nutrition, making them less tolerable in the long term. When the opening pressure of the upper esophageal sphincter (25.30 mmHg) is exceeded, the introduction of a nasogastric tube is recommended to reduce gastric distension. A particular type of oronasal mask is the total face mask which also incorporates eyes, avoiding pressure on the root of the nose, and, consequently, reducing the risk of skin ulcers.

The *helmet*, made of transparent latex free material, has a plastic ring that joins it to a soft collar that adheres to the patient's neck. It is secured to the armpits by padded straps. The patient has the possibility to drink through a straw and to feed on a liquid diet. Its advantages include good tolerability, even in pediatrics, low risk of skin lesions, and better comfort. The limitations of the helmet are the difficult assessment of the patient's effective ventilation. With this interface, in fact, a part of the tidal volume delivered by the ventilator stretches the helmet and does not participate in gas exchanges. The internal volume of the helmet varies between 6 and 8 L. Another limit is the possibility of rebreathing which, however, is modest if sufficient levels of gas flow are guaranteed.

30.2.2.3 Ventilation Modes in NIV

30.2.2.3.1 CPAP (Continuous Positive Airway Pressure)

CPAP is a ventilation that maintains a constant positive pressure in the airways without providing any assistance in the inspiratory phase to the patient. Mechanical ventilators or continuous-flow systems can be used for the application of CPAP. The continuous flow systems consist of flow generators (flowmeters), a reservoir able to reduce pressure oscillations within the system during the respiratory cycle phases and a PEEP valve able to ensure the maintenance of a constant pressure.

CPAP determines an improvement in oxygenation in many pathological conditions associated with the presence of edema or alveolar exudate. The improvement in oxygenation depends on various physiological mechanisms: the increase in functional residual capacity determined by CPAP with a reduction in the shunt rate and the shift of the patient's respiratory activity to a steeper area of the pressure/volume curve with reduced work by the patient, and, consequently, the oxygen consumption.

Furthermore, CPAP has important effects on heart; in fact, in patients with heart failure, positive intrathoracic pressure determines reduction of ventricle's transmural pressure and afterload.

30.2.2.3.2 PSV (Pressure Support Ventilation)

PSV is an assisted ventilation: the patient maintains the ability to initiate the breath by activating a trigger, which can be pressure or flow, and terminating it by a flow trigger. The main parameters to be adjusted are the pressure level of the inspiratory phase and the level of PEEP. Other parameters to set are the sensitivity level of the inspiratory trigger and the expiratory trigger (by varying the percentage of the peak inspiratory flow at which the ventilator opens the expiratory valve).

A typical starting setting in PSV during NIV is a supportive inspiratory pressure of 8–12 cmH_2O and a PEEP of 3–5 cmH_2O. In the presence of major air leaks, the cycling mechanism between inhalation and exhalation may be ineffective.

30.2.2.3.3 Controlled Mechanical Ventilation

Controlled mechanical ventilation can be pressure (PCV) or volume (VCV). In PCV the ventilator delivers sequences of high and low pressure

(PEEP). The tidal volume delivered to the patient will be the function of lung and rib cage compliance and flow resistance. In VCV, the tidal volume is set by the operator and the resulting pressures are a function of thoraco-pulmonary compliance.

30.2.2.4 Practical Applications

The starting point for the application of NIV is the identification of the patient suffering from signs and symptoms of respiratory distress:

- Increased dyspnea.
- Respiratory rate > 24 breaths/min.
- Use of accessory respiratory muscles and/or the presence of paradoxical breathing.
- Respiratory acidosis and/or hypoxemia ($PaCO_2$ > 45 mmHg with pH < 7.35 and/or PaO_2/FiO_2 < 200).

At the same time, patients with contraindications to NIV should be excluded:

- Patients in respiratory arrest.
- Severe hemodynamic instability (hemodynamic shock, ongoing myocardial infarction).
- Lack of protective reflexes in the upper airways (coughing and swallowing mechanism inadequate).
- Severe state of agitation or lack of cooperation.
- Traumatic or surgical facial injuries such as to prevent the application of the interface.
- Severe upper gastroesophageal bleeding.
- Undrained pneumothorax.
- Vomiting.

It is also necessary to identify NIV predictors of success or failure in order to recognize patients who may benefit from noninvasive ventilation and avoid unnecessary applications, delaying the start of invasive ventilation. The severity of acidosis can be a starting point. Brochard et al. [6] demonstrated that success in NIV in COPD patients is less likely with a more acidemic starting pH.

Once the patient has been identified, the choice of interface is essential for the success of NIV. The first choice falls on the face mask, which guarantees a more effective delivery of positive pressure in patients who, in the initial stages of respiratory distress, have mainly mouth breathing. The second choice, in case of intolerance to the mask or side effects due to decubitus, must be oriented on the helmet keeping in mind the problems related to the CO_2 rebreathing, especially in hypercapnic patients; therefore monitoring of patients undergoing NIV is essential for the achievement of clinical results and for improvement of symptoms.

Clinical parameters to be assessed will be the level of consciousness, reduction in expiratory work (respiratory rate, chest wall movement, use of accessory muscles) and patient-ventilator synchrony. Other instrumental parameters to be considered will be the tidal exhaled volume (more significant in patients undergoing NIV), pressure and flow curves, hemodynamic parameters (heart rate and arterial pressure), continuous ECG, and continuous oximetry blood gas analysis (basic and after 1–2 h).

If the response to NIV is insufficient, invasive mechanical ventilation should be considered early.

30.2.2.5 Indications

- COPD exacerbation.
- Asthma.
- Acute heart failure.
- Community-acquired pneumonia.
- Weaning from mechanical ventilation.
- Patient not to be intubated/not resuscitated.
- Post-operative.
- OSAS (obstructive sleep apnea syndrome).
- Trauma.
- Restrictive neurological diseases.

The major scientific evidence concerns the use of NIV in patients suffering from ALI caused by exacerbation of COPD. During NIV, the combination of external PEEP and inspiratory pressure support reduces the respiratory work, which is increased in the patient with COPD, counterbalancing the auto-PEEP.

The first study conducted by Meduri et al. [7] in 1989 shows improvements in respiratory exchanges with reduction in intubation rates. In another randomized study, comparing NIV and conventional therapy, Kramer et al. [8] confirmed a reduction in the need to intubation and showed a significant improvement in PaO_2, heart rate, and respiratory rate, without a significant decrease in $PaCO_2$.

Several studies have shown a higher rate of NIV failure with the need to tracheal intubation in patients starting with more severe respiratory insufficiency ($PaCO_2 < 7.25$), without evidence of problems associated with late onset of invasive ventilation. Finally, emerges that NIV should be considered the first-line therapeutic option in patients with COPD exacerbations.

NIV is routinely used in patients with ACPE (acute cardiogenic pulmonary Edema) both in the emergency department and in the ICU.

In these patients, NIV can be delivered either by CPAP or by ventilatory assistance under pressure (PSV), offering a series of positive effects, such as reduction of preload with an improvement in heart failure, reduction in respiratory work, and related consumption oxygen secondary to an improvement in lung compliance. This improvement is secondary to an extrathoracic redistribution of lung water, an increase in residual functional capacity, and a shift on a steeper area of the pressure/volume curve.

Several studies such as a review and meta-analysis by Collins et al. [9] showed a reduction in the need for intubation and in mortality compared to medical therapy (oxygen, diuretics, and nitrates) associated with the early onset of NIV.

Recently, a prospective randomized study conducted by Gray et al. [10] (3CPO trial) did not demonstrate any difference in terms of the need for tracheal intubation and mortality despite the improvement in blood gas parameters and dyspnea.

The ERS/ATS clinical practice guidelines [11] recommend (not firmly) NIV as a preventive strategy for avoiding intubation in hypoxemic acute respiratory failure (ARF) only when performed by experienced teams in highly selected cooperative patients with community-acquired pneumonia or early ARDS without any associated major organ dysfunction.

Severe COVID-19 causes significant numbers of patients to develop respiratory symptoms that require increasing interventions. Initially, the treatment for severe respiratory failure included early intubation and invasive ventilation as this was deemed preferable to be more effective than noninvasive ventilation (NIV). However, emerging evidence has shown that NIV may have a more significant and positive role than initially thought. NIV includes continuous positive airway pressure (CPAP) and bi-level positive airway pressure (BiPAP).

NIV can be reserved for patients with mild ARDS, with close monitoring, airborne precautions, and preferably in single rooms. In patients with suspected or diagnosed COVID-19 requiring NIV, helmets may be the best solution for CPAP or NIV because of minimal or no dispersion from leaks and easy to filter/scavenge exhausted gas. Due to the scarcity of this interface it is probable that traditional oronasal masks will be the most commonly used. In this case a suboptimal NIV set-up with interface with inappropriate seals and improper circuitry will not be tolerable. If NIV is the option, try "protective-NIV" with lower tidal volumes between 6 and 8 mL/kg [12].

Although there is a role for noninvasive respiratory therapie77s in the context of COVID-19 ARF, more research is still needed to define the balance of benefits and risks to treatment of COVID patients.

30.2.2.6 Adverse Events and Complications

The most frequent complications are related to the interface, the flow delivered by the ventilator, and the patient-ventilator interaction.

The various interfaces can cause, as a result of the pressure they exert on the face, discomfort, erythema, or ulceration.

Air leaks can cause conjunctival irritation, while the pressure generated by ventilation can cause pain in the sinuses and ears. Patient ventilator asynchrony is a common cause of NIV failure and is often related to patient agitation or excessive air loss.

30.3 Conclusion Discussion

The indication best supported by the literature for the use of NIV is acute respiratory failure linked to the exacerbation of COPD. After the COVID 19 pandemic, more and more evidence is accumulating to justify its use in patients with ALIs of other etiology.

Key Major Recommendations

- In patients suffering from neuromuscular diseases and chest wall deformities, the use of NPV allows you to rest the respiratory muscles, improve the breathing pattern, and slow the evolution of chronic respiratory failure.
- NIV should be considered the first-line therapeutic option in patients with COPD exacerbations.
- NIV can be reserved for patients with mild ARDS.
- NIV is routinely used in patients with ACPE.

References

1. Corrado A., Gorini M., Villella G, et al. Negative Pressure Ventilation in the treatment of acute respiratory failure: an old non-invasive technique reconsidered. Eur Respir J 1996; 9:1531–1544.
2. Corrado A, Gorini M. Negative-pressure ventilation: is there still a role? Eur Respir J. 2002;20:187–97.
3. Bunnel S. The use of nitrous oxide and oxygen to maintain anesthesia and positive pressure for thoracic surgery. JAMA. 1912;58:835–8.
4. Barach AL, Martin J, Eckman M. Positive-pressure respiration and its application to the treatment of acute pulmonary edema. Ann Intern Med. 1938;12:754–95.
5. Elliot MW, Steven MH, Phillips GD, et al. Noninvasive mechanical ventilation for acute respiratory failure. BMJ. 1990;300:358–60.
6. Brochard L, Mancebo J, Wysocki M, et al. Noninvasive ventilation for acute exacerbation of chronic obstructive pulmonary disease. N Engl J Med. 1995;333:817–22.
7. Meduri GU, Conoscenti CC, Menashe P, et al. Noninvasive face mask ventilation in patients with acute respiratory failure. Chest. 1989;95:865–70.
8. Kramer N, Meyer TJ, Meharg J, et al. Randomized, prospective trial of noninvasive positive pressure ventilation in acute respiratory failure. Am J Respir Crit Care Med. 1995;151:1799–806.
9. Collins SP, Mielniczuk LM, Whittingham HA, et al. The use of noninvasive ventilation in emergency department patients whit acute cardiogenic pulmonary edema: a systematic review. Ann Emerg Med. 2006;48:260–9.
10. Gray A, Goodacre S, Newby DE, et al. Noninvasive ventilation in acute cardiogenic pulmonary edema. N Engl J Med. 2008;359:142–51.
11. Rochard B, Brochard L, Elliot MW, et al. Official ERS/ATS clinical practice guidelines: noninvasive ventilation for acute respiratory failure. Eur Respir J. 2017;50:1602426.
12. Winck JC, Ambrosino N. COVID-19 pandemic and non-invasive respiratory management: every Goliath needs a David. An evidence based evaluation of problems. Pulmonology 2020;26(4):213–220.