CHAPTER 22

Noninvasive mechanical ventilation in chronic respiratory failure: ventilators and interfaces

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The present chapter deals with the technical aspects of ventilators and interfaces used in noninvasive ventilation (NIV) of patients with chronic respiratory failure (CRF). Before going into details, it might be helpful to highlight one important clinical issue: patients with CRF are more or less in a respiratory stable condition and are not dependent on ventilatory support 24 hours a day; however, patients with CRF have limited ventilatory capacities, thus the use of NIV as an intermittent treatment should be clinically beneficial and lead to stabilisation of the ventilatory failure. Therefore, in contrast to invasive mechanical ventilation (IMV), cessation of NIV does not cause an immediate life-threatening risk. Complications of IMV, such as failure of the ventilator, changes in ventilator settings, accidental disconnection from ventilator or accidental decannulation, may lead to acute deterioration of clinical status, acute hospitalisation or even death. Therefore, to minimise these complications, ventilators in IMV are equipped with many surveillance devices and alarms [1]. In contrast, such a surveillance system is not necessary when NIV is used to treat CRF, thus avoiding unnecessary irritation to the patient. Accordingly, a recently published study investigated the technical performance of nine portable pressure ventilators (which are also used as NIV ventilators in the home) and found that most of the portable pressure ventilators evaluated were able to respond to high ventilatory demands, even outperforming the intensive care unit (ICU) device [2].

The objective of the first section of the present chapter is to discuss the principal characteristics of ventilators that have been designed for use in patients with CRF requiring NIV. In the second section, the interfaces of NIV are discussed.

Ventilators

Historical development

From an historical point of view, negative pressure ventilation (NPV) was the first mode of NIV to be widely applied to CRF patients (i.e. during the 1950s poliomyelitis epidemic). NPV takes place by exposing the chest to subatmospheric pressure during

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inspiration. During expiration the pressure around the chest wall changes to atmospheric pressure in order to allow passive exhalation [3]. In the past, body ventilation was provided with different models, e.g. tank respirator or cuirass type device driven by a negative pressure cycled machine.

Apart from some specialised centres that have maintained the tradition of using NPV as a treatment for CRF, this mode of ventilation has steadily lost its former impact over the last decades and has been almost completely substituted by positive pressure ventilation (PPV) modes. The main reasons for this trend were the large, cumbersome NPV-devices, the lack of accessibility by the patient, the need for considerable experience to operate the device and, finally, the danger of inducing upper airway obstruction [4]. These shortcomings were emphasised by a monocentre retrospective study which investigated, over a 46-yr period, long-term NIV of patients with neuromuscular disorders [5]. It was shown that, compared with NPV, a greater number of patients with PPV (67%) reported positive outcomes (i.e. improved sense of wellbeing, independence and perform daily activity). However, there were still patients with CRF who did not tolerate PPV but did well with NPV; therefore, NPV should be considered as an alternative means of ventilation in case of PPV intolerance.

**Terminology and classification of modes**

The existing set of terminology describing the modes of NIV can sometimes be confusing. The most frequently used modes and abbreviations are shown in table 1. The answers to the following basic questions may facilitate communication and simplify the terminology dealing with NIV. 1) Is the NIV mode pressure-targeted ventilation (PTV) or volume-targeted ventilation (VTV; the frequently used term “volume control” may be inaccurate, since the volume leaving the ventilator is not really controlled; this is due to leakage that can occur during the delivery of air to the patient)? 2) Should positive pressure be applied during inspiration, expiration or both? 3) Does NIV work in the assist (triggering), assist-control (triggering with back-up rate) or cycled (control) mode with a fixed breathing frequency?

Before going into details about the two main types of NIV modes (volume and pressure target-ventilation), it should be noted that the drive of breathing by the patient and ventilators can be set up in the following ways.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
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<tr>
<td>ASB</td>
<td>Assisted spontaneous breathing</td>
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<tr>
<td>ASV</td>
<td>Adaptive servo ventilation</td>
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<tr>
<td>ASSPCV</td>
<td>Assisted-pressure controlled ventilation</td>
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<tr>
<td>BIPAP</td>
<td>Biphase positive airway pressure</td>
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<tr>
<td>CPAP</td>
<td>Continuous positive airway pressure</td>
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<td>IPPV</td>
<td>Intermittent positive pressure ventilation</td>
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<tr>
<td>NIV</td>
<td>Noninvasive ventilation</td>
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<td>NPPV</td>
<td>Noninvasive positive pressure ventilation</td>
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<td>PAV</td>
<td>Proportional assist ventilation</td>
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<tr>
<td>PCV</td>
<td>Pressure controlled ventilation</td>
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<td>PEEP</td>
<td>Positive end-expiratory pressure</td>
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<td>PSV</td>
<td>Pressure support ventilation</td>
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<td>SIMV</td>
<td>Synchronised intermittent mandatory ventilation</td>
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<td>VCV</td>
<td>Volume controlled ventilation</td>
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Assist mode. When the ventilator detects and supports the patient’s spontaneous breath, this process is called “triggering”. When NIV is set to assist mode (e.g. pressure support ventilation (PSV), proportional assist ventilation (PAV) or assist VTV), it is possible to achieve both a patient-adapted breathing pattern and a high synchrony of ventilation between the patient and the ventilator. However, triggering requires considerable inspiratory work of breathing, which does not end abruptly with the ensuing mechanical pressure support of the inspiration cycle. Flick et al. [6] showed through electromyogram (EMG) recordings that inspiratory work of breathing persisted after triggering diaphragmatic activity. Moreover, it could be demonstrated that the oxygen consumption of the respiratory muscles were clearly higher in the assisted mode of intermittent positive pressure ventilation (IPPV) than in the controlled mode [7].

Control mode. In control mode, there is a preset automatic cycle based on either volumetric ventilation (i.e. volume controlled ventilation (VCV)) or barometric ventilation (i.e. pressure controlled ventilation (PCV)). In PCV, fixed inspiratory and expiratory pressure levels, breathing frequency and inspiratory and expiratory times are preset. Ventilators for VCV are characterised by the presetting of fixed inspiratory volume, fixed breathing frequency and inspiratory and expiratory times. In pure control mode, the breathing frequency of the ventilator is generally set to a high level in order to avoid the patient’s spontaneous efforts. Only this procedure enables actual passive ventilation. In general, preset-controlled volume and pressure modes are preferable in patients with an unreliable respiratory effort, massively overloaded respiratory muscles, apnoea and hypopnoeas, and failure of PSV.

Assist-control mode. This mode is a combination of assisted and controlled modes. Depending on the spontaneous breathing frequency, the patient may either trigger to receive inspiratory support (i.e. pressure or volume targeted), or be passively ventilated with the chosen back-up frequency.

Concerning pressure ventilators, this mode is often called “spontaneous/timed”, whereas in volumetric ventilators, the mode is called “assist-control ventilation”. In principle, the synchronised intermittent mandatory ventilation (SIMV) mode also belongs to this category.

The two main types of NIV-ventilator in CRF: VTV and PTV

Most of the initial studies in the 1990s used VTV as the preferred mode of NIV in CRF [8, 9]. In line with these findings, a study by Simonds et al. [10] reported that the broad majority of patients (n=170) used VTV, while only ten patients used PTV. Furthermore, a group study by Leger et al. [11] revealed the exclusive use of VTV among the 276 patients studied.

However, due to various reasons, PTV has been increasingly prescribed in recent years and its usage surpassed that of volume respirators by the end of the 1990s [12–14]. This trend is shown in figure 1 [15]. Here, during the observation period from 1990–1999, the entire group of 530 CRF patients were adapted to NIV in the Kloster Grafschaft hospital (Schmallenberg, Germany). The number of new NIV patients per year continuously increased from 13 in 1990 to >100 patients in 1998 and 1999. Apart from in 1990, when NIV was exclusively started with VTV, PTV dominated the years that followed. Within the PTV users, the application of PTV in the assist mode decreased, while PTV in the control or assist-control mode increased (fig. 1).

In general, PTV and VTV are still characterised by some typical advantages and disadvantages which are listed in table 2. In two prospective randomised cross-over
studies, no advantages in sleep quality, gas exchange or quality of life over a 4-month period were reported when comparing VTV with PTV in the treatment of CRF [16, 17]. However, reduced patient comfort and increased gastrointestinal side-effects were reported with VTV application [16] while leak compensation is superior in PTV [18, 19]. This trend is particularly obvious in the case of chronic obstructive pulmonary disease (COPD)-induced CRF, where the high airway pressures that arise from the high airway resistance in VTV may partly underlie the development of gastrointestinal side-effects and reduced comfort. In Europe today, PTV is the more commonly used mode in the treatment of CRF, with two-thirds of the 21,526 patients on home mechanical ventilation using this mode of ventilation (fig. 2) [14]. University hospitals are increasingly using PTV, since the percentage of VTV is higher both in non-university hospitals and the long-established centres using NIV [14, 20].

**VTV.** Most VTV ventilators in NIV have a one-line circuit with an integrated demand valve; therefore, CO$_2$-rebreathing is not a problem. Furthermore, most VTV ventilators on the market deliver the inspiratory volumes via a piston or bellow without integrated PEEP; however, newer devices are blower-driven and capable of internal PEEP adjustment.

VTV ventilators deliver a fixed tidal volume, while the associated airway pressures result from airway resistance, lung and thoracic compliance, flow rate and inspiratory cycle. Although the method of triggering is not consistently specified, VTV is mostly applied in the assist-controlled mode. As mentioned, the use of VTV as a mode of NIV is currently decreasing compared with PCV.

However, VTV as an NIV-mode is still used frequently in CRF due to neuromuscular diseases [14, 21], and in some countries VTV is still used as often as PTV [14]. Volume ventilation may be preferred by some patients with neuromuscular diseases who sometimes need high tidal volumes for ventilation, coughing and increasing the volume of their voice during NIV. According to the need to attain maximal lung insufflations for assisted coughing, adolescent and adult patients with respiratory muscle dysfunction used portable volume-cycled ventilators, rather than pressure-cycled ventilators. This former disadvantage of PTV is now redeemable, since the currently available generation of PTV ventilators deliver higher maximum inspiratory pressures (i.e. 40 cm H$_2$O). VTV with a high flow capacity and pressure limitation may cope adequately with leaks;
however, in general, PTV still provides better compensation for such leaks. Finally, it should be mentioned that SIMV, a subtype of volume-cycled ventilators, is also available as an NIV mode. However, this is not recommended, since SIMV is associated with increased work of breathing [22].

**PTV.** In contrast to VTV, all of the currently available PTV ventilators are compressor/blower driven. One-line circuit models with or without an integrated demand valve are available.

PTV ventilators cycle between preset inspiratory positive airway pressure (IPAP) and expiratory positive airway pressure (EPAP), thus providing PSV [23]. This allows the patient to control inspiratory and expiratory times while providing a preset pressure, which, along with patient’s effort, determines the inspiratory flow and tidal volume. IPAP and EPAP can be adjusted independently in order to augment alveolar ventilation and maintain upper airway patency during sleep. PSV may facilitate an acceptable patient−ventilator synchrony, while the addition of external PEEP reduces dynamic hyperinflation by offsetting intrinsic PEEP [24]. Therefore, PSV may help the patient to

<table>
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<th>Aspect</th>
<th>PTV</th>
<th>VTV</th>
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<tr>
<td>Constant inspiratory volume</td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td>Constant inspiratory pressure</td>
<td>++</td>
<td>-</td>
</tr>
<tr>
<td>Improvement in sleep quality</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Improvement in gas exchange</td>
<td>+</td>
<td>+</td>
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<tr>
<td>Improvement of quality of life</td>
<td>+</td>
<td>+</td>
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<tr>
<td>Leak compensation</td>
<td>++</td>
<td>-</td>
</tr>
<tr>
<td>Gastrointestinal side-effects</td>
<td>+</td>
<td>-</td>
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<tr>
<td>Comfort</td>
<td>+</td>
<td>-</td>
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Advantages range from + to ++ and disadvantages are shown as -.

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Table 2. – Advantages and disadvantages of pressure-targeted ventilators (PTV) and volume-targeted ventilators (VTV)

Fig. 2. – Percentage per country of pressure- (■) and volume- (□) targeted positive pressure ventilators used for home mechanical ventilation (n=21,526) [14].

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feel more comfortable. A further advantage of portable PTV devices is the absence of unnecessary alarms (depending on the product) in clinically stable patients. In addition, the PSV equipment is generally lighter and less expensive.

An important advantage of PSV and PCV is the compensation for mild-to-moderate mask or mouth leaks [18, 19]. In the presence of leak the pressure in the patient–ventilator-circle drops and PTV increases inspiratory flow to compensate for the drop in pressure.

CO$_2$-rebreathing has been documented in PSV, and the risk of CO$_2$-rebreathing is greater with a single delivery circuit that lacks an active exhalation valve [25, 26]. A recent study from Schettino et al. [27] dealt with CO$_2$-rebreathing and the influences of the exhalation port position and mask design in the PSV-mode. In that bench study, a lung model with a single-limb circuit was used. In that setting, the full mask with the exhalation port positioned within the mask, demonstrated less CO$_2$-rebreathing than either the closed full-face mask, with a whisper swivel, or the total face mask [27]. Furthermore, high respiratory rates and low external PEEP increased the risk of CO$_2$-rebreathing caused by the shorter expiratory time and lower CO$_2$ washout of the circuit. A minimal EPAP (>2–4 cmH$_2$O) is therefore necessary to avoid CO$_2$-rebreathing in a single tube circuit without valves, in order to wash out CO$_2$. However, to the best of the present authors’ knowledge, no study has shown that CO$_2$-rebreathing is clinically significant.

A further critical issue of PSV is the detection of the patient’s inspiration. There are ventilators fitted with both a fixed and variable trigger. In the past, ventilators were often pressure-triggered. More-recent studies have found that flow-triggered devices appeared to be more sensitive than pressure-triggered devices [28]. Another technical challenge is “pressurisation”, in other words, the ability of the ventilator to meet the flow demand of the patient. Flow demand mainly depends on the underlying pathophysiology (e.g. resistance and compliance), the given level of pressure support and inspiratory pressure rise time; the shorter the rise time, the lower the level of work of breathing [29]. Depending on the type of ventilator, the pressure rise time is either adjustable or fixed. It may be possible that in an individual case (e.g. an obese patient with severe airway obstruction) a ventilator does not have enough power to yield adequate pressure.

Both expiratory trigger and resistance may have a clinically relevant impact on expiratory effort and the possibility of desynchronisation between the patient and ventilator [30, 31]. During PSV, cycling to exhalation is triggered by a decrease in inspiratory flow from a peak to threshold value. A time limit of inspiration is usually added because the aforementioned technique becomes inoperative when mask leaks are present. Furthermore, systems using active exhalation valves have shown significant variation in their valve resistance to exhalation. Increased resistance associated with difficulties in exhalation can significantly increase the work of breathing.

Compared with PSV, the aforementioned issues (i.e. CO$_2$-rebreathing, inspiratory and expiratory triggering) are less critical in the PTV assist-controlled and controlled modes, since they are dominated by automatic cycling.

Compliance might also be improved by allowing the patient to maintain control of the breathing pattern. PAV has been proposed as a mode of synchronised partial ventilatory support, in which the ventilator pressure output is proportional to instantaneous patient effort, thus unloading the resistive and elastic burden [32, 33]. Studies in patients with acute respiratory failure (ARF) have shown that PAV is well-tolerated and just as effective as PSV [34, 35]; however, PAV currently remains as an experimental mode of ventilation. The majority of studies, investigating the short-term application of PAV in patients with CRF, has revealed some interesting pathophysiological insights [36, 37]. PAV has been shown, especially during physical activity, to be more efficient than PSV.
in assisting the diaphragm and in increasing minute ventilation [37]. Since NIV has been postulated as a promising therapy option for rehabilitation programs in CRF [38–40], PAV could be, in this case, one of the preferred modes of ventilation; however, further studies are needed to investigate this suggestion. Long-term studies, investigating the application of PAV as an NIV mode in sleep or the effect of long-term application in CRF, are yet to be performed.

Finally, it should be mentioned that in both intensive care medicine and anaesthesiology, the biphasic positive airway pressure (BiPAP) mode is associated with a different mode of the Evita ventilator (Draeger, Lübeck, Germany). This mode consists of a phasic change between two preset demand-valve CPAP values (“P-low” and “P-high”) during which spontaneous breathing remains unrestricted at each CPAP value. The mechanical support is defined by: 1) the difference between the two pressure levels and 2) the variable duration of both pressure levels.

To conclude this section, it should be added that some manufacturers of home ventilators have recently focused on providing a combination of both PTV and VTV in the same machine. The role of these hybrid modes of ventilation have not yet been sufficiently explored to warrant their use in NIV but a pilot study has indeed shown promising results [41]; in that study, patients with obesity-hypoventilation syndrome were randomised in a cross-over design to either the BiPAP spontaneous/timed or the hybrid combination of BiPAP spontaneous/timed with average volume-assured pressure support (AVAPS). Each mode was applied for 6 weeks of home mechanical ventilation. The authors reported that with the addition of the AVAPS mode there was a significantly greater reduction of transcutaneous carbon dioxide tension ($P_{tc,CO_2}$) during the night; however, sleep quality and quality of life did not benefit from the addition of the AVAPS mode when compared with BiPAP spontaneous/timed alone [41]. Similar findings were reported by JANSSENS et al. [42], who reported that the AVAPS mode led to a slight improvement in alveolar ventilation but did not significantly affect the objective indices of sleep structure; however, this new mode was associated with a subjective feeling of reduced sleep quality, increased leaks and increased ventilator pressures. Since these were the first studies to investigate the hybrid mode of ventilation in CRF, it remains unknown as to whether these new modes do actually offer any long-term advantages over the modes in current use.

**Choice of ventilator and setting**

Regarding the choice of ventilator and ventilator setting, an individualised approach to each patient appears, in general, to be a useful practice [43, 44]. From a practical point of view this means that the ventilator type and its setting should be determined by each patient’s degree of comfort, coupled with the patient’s ability to increase minute ventilation, improve gas exchange and diminish the work of breathing. Indeed, this constitutes the ideal aim of every specialist in the field of respiratory medicine. However, data that deal with these topics are virtually non-existent in literature, while evidence-based recommendations are also lacking.

Furthermore, despite the described differences between the NIV modes, it still remains open as to whether these differences are of clinical importance. In view of this, HILL [45] stated 15 yrs ago that, based upon the data available at the time, considerations such as leak compensation and reliably delivered volumes, did not appear to be major determinants of NIV success; this statement remains valid to the present day.

Accordingly, data regarding the validity of PTV versus VTV in NIV are available. These data generally emerged from physiological studies, which were conducted mainly over short time periods in small groups of patients [46–48]. A disadvantage of these
previous studies was the introduction of additional variables such as assist-control VTV versus PSV [47, 48], thus making the comparison between the two ventilation modes more unreliable.

Several studies have compared the long-term efficacy of different NIV modes in CRF [12, 16, 17, 49, 50]. CRINER et al. [12] investigated the efficacy and compliance of long-term NIV in 40 patients with CRF; here, the aforementioned trend from VTV to PTV was demonstrated. After initial evaluation, 34 patients received NIV via PTV (i.e. BiPAP) while only six patients required NIV via VTV. During the 6-month follow-up, 14 patients ceased NIV due to incompliance; in the compliant patients, blood gases and functional status improved on a chronic basis. Also, on a long-term basis, SCHÖNHOFER et al. [49] conducted a prospective study of the effect of volume- and pressure-cycled ventilation modes of NIV in patients suffering from CRF. After 4 weeks of treatment with VTV in the time-cycled mode, the effect was compared with that of PTV, which was also performed in the same mode over a 4-week period. From these results, the authors concluded that VTV proved superior to PTV in one-third (10 out of 30) of their patients, since this subgroup deteriorated during the PTV period and had to return to VTV. However, the majority of patients (20 out of 30) remained stable during the subsequent PTV period. Subjective scores and carbon dioxide tension values provided a distinction between long-term responders and nonresponders to PTV. It could be speculated that the amount of reduced work of breathing accounted for the discrepancies between the two modes. In contrast to the study of SCHÖNHOFER et al. [49], SMITH et al. [50] reported that in a mixed collective of 10 CRF patients who deteriorated under VTV, the exchange of the ventilator to PTV led to a reversal of the deterioration observed under VTV.

More recently, PTV and VTV were compared in two prospective randomised cross-over studies [16, 17]. In one of the studies, 12 CRF patients with chest wall deformities underwent a four-week single-blinded randomised cross-over study in either VTV or PTV. In conclusion, the authors suggested that pressure- and volume-ventilation are equivalent in terms of the effects on nocturnal and daytime physiology, resulting daytime function and health status [17]. In line with these findings, WINDISCH et al. [16] investigated, in a similar prospective randomised cross-over study, PTV and VTV in 10 patients with obstructive (n=5) and restrictive (n=5) CRF. After 6 weeks of home mechanical ventilation in the assist-controlled mode, an equivalent improvement in gas exchange and sleep quality was seen overnight. However, PTV was better tolerated by the patients, whereas more gastrointestinal side effects were associated with VTV; these findings therefore contribute to the trend towards the use of PTV over the last 15 yrs [16].

Finally, it should be mentioned that the glottis function plays an important role in NIV, since the glottis is known to narrow substantially or even close completely, in response to NIV. This may induce deterioration in the quality of both NIV and sleep [51, 52]. Furthermore, it has been shown that a substantial increase in glottis resistance can occur with the use of different modes of NIV [53, 54], leading to narrowing of the glottis reflex and inducing (amongst others) mouth leaks. It was found that, by altering the delivery of tidal volume, inspiratory flow and ventilatory frequency or positive inspiratory pressure (as well as manipulating the ventilatory mode), the glottis response can be regulated, thus improving ventilatory efficacy. This warrants further trials with CRF patients, since glottis function may act as a practical determinant of ventilator mode and setting, respectively.

**General issues concerning technical equipment**

The major advantage of NIV is its applicability outside the hospital, e.g. in the patient’s home. Compared with long-term invasive mechanical ventilation at home [1],
which often needs accessory equipment, the technical equipment and design of NIV ventilators should remain simple and be easy to handle. Therefore, NIV ventilators would not need the following technical details in general: a second, back-up ventilator; humidification; external battery; non-rebreathing valve; PEEP; supplemental O\textsubscript{2}; pressure and volume monitoring; and alarms for high and low pressure and failure of the battery.

Routine care for patients receiving NIV at home should include the following: patients and caregivers should be properly trained by technicians, specialised nurses or respiratory therapists from the home care company, in the use of the ventilatory equipment prior to hospital discharge. Once assigned to NIV for home mechanical ventilation, patients should be visited at home at least during the first week; subsequent visits would then be dependent on the patient’s needs. During these visits, the ventilator should be checked for proper function. Preventative maintenance is performed according to the manufacturer’s specifications. The home-care company must guarantee a 24 h technical service, in order to answer emergency calls and repair technical dysfunctions of the ventilatory equipment. After a certain period of usage (e.g. every 5,000 h), the ventilators are to be removed from the home for complete preventative maintenance at the factory. Additional services which are organised by the healthcare providers (such as mask consultation) offer further support for the patient.

A thorough investigation into the frequency of home ventilator failure revealed that such failures were relatively uncommon, with nearly all suspected failures being resolved at home [55]. Caregivers’ misuse, tampering or damage led to half of the reported failure. True mechanical failures occurred in only 40% of the reports. No patient suffered any adverse clinical effects, resulting from the failure. However, in a more recent, European survey [56], the quality control of equipment in home mechanical ventilation showed some interesting facts that should be considered: 1) ventilator service was mainly carried out by external companies (62% of centres), with a service occurring every 3–12 months; 2) interaction between servicing companies and prescribers was limited (only 61% of centres were consistently informed of major incidents); 3) participation of centres in equipment quality control was poor; and 4) only 23% of centres were sufficiently aware of the vigilance systems [56]. In line with previous findings, that report revealed that regular assessment of actual ventilator performance at the patient’s home is an important quality-control procedure for detecting any malfunctions which could otherwise compromise both the compliance and outcome of home mechanical ventilation [57].

**Interfaces**

The interface between the patient and ventilator is crucial for the success of NIV; a patient may refuse NIV on the grounds of an uncomfortable mask, or a poorly fitting interface may reduce the efficacy of NIV. Custom sizing and fitting of the mask may require several attempts in order to accommodate the facial architecture. Despite the clinical impact, the choice of different interfaces has received little scientific attention; hence, no general consensus exists in regard to the management of interfaces.

**Spectrum of interfaces**

As seen historically, the quality of interfaces has markedly improved over the past 25 yrs. In the early 1990s, the percentage of custom-made nasal and facial masks in use was high, due to a lack of sufficient fitting and comfortable commercial masks [15].
Today, a variety of commercial masks are available and more frequently used than custom-made masks (figs 3 and 4). Commercial manufacturers continue to improve mask design and develop gauging tools in order to help the clinician choose the correct mask and size for the patient.

Fig. 3. – Proportion of interfaces for different diseases categorised by country for a) lung, b) thoracic and c) neuromuscular home mechanical ventilation (HMV) users (n=21,526) [14]. ■: nasal masks; ◼: facial masks; □: tracheostomy. #: no data were available for Polish lung users.
In the aforementioned European survey of home mechanical ventilator users, the majority of interfaces are represented by nasal and facial masks, with the majority of patients using nasal masks (fig. 3) [14]. However, as shown in figure 3, there are still patients on home mechanical ventilators who are tracheostomised. The use of this invasive interface is dependent on the underlying disease, whereby the highest rate of the tracheostomised patients suffer from neuromuscular diseases (24%). Fewer patients with lung diseases, like COPD (8%) or restrictive thoracic disorders (5%), require tracheostomy [14]. This distribution also depends on the country of the patient. For example, the respective proportions of tracheostomised patients with neuromuscular diseases in Poland (90%) and the Netherlands (50%) are much higher compared with other countries (fig. 3).

The varieties of interfaces that are currently in frequent use are given in figure 4; approximately 20–30 types of both nasal and face masks are on the market, each being characterised by their own advantages and disadvantages. A comparison of these most-frequently used interfaces is described in table 3. In special indications, total face masks, nasal pillows and mouthpieces are also used (fig. 4).

Commercial interfaces

There are only a few reports which directly compare the success rate of nasal masks, facial masks and other devices. In a study by Navalesi et al. [58], patients with chronic hypercapnic respiratory failure showed an overall better tolerance of the commercially available nasal masks compared with both the facial masks and nasal pillows (p<0.005). However, the full-face masks were associated with the most favourable reduction in arterial carbon dioxide tension ($P_{a,CO_2}$). A recently published study reported that nasal masks are just as effective as full-face masks in terms of sleep quality and gas exchange in CRF patients. Here, the nasal masks were often attached with a chin strap in order to compensate for oral leaks [59]. In line with these findings, the nasal mask was considered to be more comfortable than the face mask during CPAP therapy for sleep apnoea [60]. However, nasal masks dominate as the type of interface used in CRF [14, 61].

![Fig. 4. – Variety of interfaces. a) Commercial nasal mask, b) custom-made nasal mask, c) commercial full-face mask, d) full-face mask with nasal pillows, e) mouthpiece and f) total face mask.](image-url)
contrast, due to various reasons, oronasal masks are used more often in the treatment of ARF [61, 62].

In order to avoid leaks, masks are often fitted tightly; however, this can induce pressure sores which, in turn, may lead to reduced tolerance. Pressure sores mostly appear on the nasal bridge and different dressings have therefore been evaluated to prevent nasal bridge abrasion. The proper fit of the nose mask can be improved by applying mask cushions or by padding the bridge of the nose. Variations include the bubble type- or gel-masks.

Patients with an intolerance of such nasal interfaces (i.e. masks or nasal pillows) might be more willing to try masks that cover both the nose and mouth. Accordingly, Criñer et al. [63] found that the total face mask was likely to improve comfort, minimise air leakage and improve ventilation in patients who were previously unable to tolerate NIV via nasal or oronasal masks.

Recently, helmets were introduced as a new interface in NIV. In two studies by Antonelli et al. [64, 65], the helmet was a promising tool in the treatment of acute hypoxemic respiratory failure [64]; however, in patients with CRF, the reduction of \( P_{a,\text{CO}_2} \) with the helmet was not as favourable as that achieved with treatment by the full-face mask [65]. Recently, a study by Navalesi et al. [66] showed, in patients with COPD and CRF, that the helmet and facial mask were equally tolerated and that both were effective in ameliorating gas exchange and decreasing inspiratory effort. However, the helmet was less efficient in decreasing inspiratory effort and worsened the patient–ventilator interaction. Currently, the helmet cannot be recommended as an interface for long-term NIV.

**Customised interfaces**

Despite the wide use of commercially available masks there are some potential side effects such as a large mask volume, nasal bridge pressure sores or significant leakages. In this case, custom-made nasal or facial masks may be an alternative (fig. 4). In a short-term physiological study, a volumetric ventilator was used to compare commercially available and custom-made nasal masks during NIV [67]; the nasal mask showed a higher effectiveness of NIV, most probably since it has a smaller dead space and reduced air leakage compared with the custom-made mask. In a French population study, masks were constructed by modelling a mixture of silicone and catalyst to the patient’s face. The entire mask-making procedure took approximately 30 min and the masks were then

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Oronasal mask</th>
<th>Nasal mask</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mouth leak</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Mouth breathing</td>
<td>Possible</td>
<td>Decreases NIV quality</td>
</tr>
<tr>
<td>Dental status</td>
<td>Independent</td>
<td>Dependent</td>
</tr>
<tr>
<td>Application of airway pressure</td>
<td>Higher</td>
<td>Lower</td>
</tr>
<tr>
<td>Dead space</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Dynamic of ABG improvement</td>
<td>Quicker</td>
<td>Slower</td>
</tr>
<tr>
<td>Communication</td>
<td>Reduced</td>
<td>Possible</td>
</tr>
<tr>
<td>Eating and drinking</td>
<td>No</td>
<td>Possible</td>
</tr>
<tr>
<td>Expectoration</td>
<td>No</td>
<td>Possible</td>
</tr>
<tr>
<td>Risk of aspiration</td>
<td>Elevated</td>
<td>Reduced</td>
</tr>
<tr>
<td>Risk of aerophagia</td>
<td>Elevated</td>
<td>Reduced</td>
</tr>
<tr>
<td>Claustrophobia</td>
<td>Elevated</td>
<td>Reduced</td>
</tr>
<tr>
<td>Comfort</td>
<td>Lower</td>
<td>Higher</td>
</tr>
</tbody>
</table>

ABG: arterial blood gas; NIV: noninvasive ventilation.
usable for around 6 months [11]. The most-recent trend involves the use of semi-
customised masks consisting of a prefabricated frame in which quick-drying filler is
injected and then moulded to the unique facial contours of each patient.

**Mouthpieces**

Bach et al. [68] reported on the use of mouthpieces as an interface that precludes the
necessity of tracheotomy in patients with neuromuscular disease. A commercially
available mouthpiece interface covers the lips and is held in place by straps. Here the
mouthpiece, like the nasal mask, facilitates both communication and secretion
clearance. A simple mouthpiece may be kept adjacent to the mouth for easy accessibility
during the day, with a lip seal added for nocturnal use; the addition of a bite plate may
also facilitate the use of an oral interface. However, this type of interface has been
associated with adverse effects, e.g. air leakage, dry mouth, risk of aspiration, altered
dental occlusion and temporomandibular joint problems.

A recently published study by Toussaint et al. [69] recommends NIV with a
mouthpiece as the interface of choice for additional daytime NIV in end-stage Duchenne
patients. Here, patients who underwent NIV with a nasal mask and were normocapnic
during the night, but developed end-diurnal hypercapnia, were additionally ventilated
with a diurnal mouthpiece. A 7-yr follow-up of 42 patients has been performed and
revealed NIV with a mouthpiece as a safe means of improving daytime gas exchange,
prolonging survival and stabilising vital capacity. The authors also recommended the
addition of a self-supporting harness to aid NIV with a mouthpiece.

**Dead space**

The increase in dead space, as well as the inherent CO$_2$-rebreathing associated with
mask use, is a crucial aspect. Criner et al. [63] found the following values for dead
spaces: total face mask, 1,500 mL; oronasal mask, 250 mL; and nasal mask, 105 mL.
Studies in this field are quite rare, but one study of Schettino et al. [27] dealt with CO$_2$-
rebreathing, the position of exhalation port and the design of the mask. In that bench
study, a lung model with a single-limb circuit was used. Within this setting, the full-face
mask, with its exhalation port fitted in the mask, demonstrated less CO$_2$-rebreathing
compared with either the closed full-face mask with a whisper swivel or the total face
mask. A further study investigated the dynamic dead space in 19 commercially available
face masks in a lung model; here, with the use of a face mask, the total dynamic dead
space during spontaneous ventilation was increased above physiological dead space
from 32 to 42% of tidal volume [70]. NIV in either bilevel or CPAP mode that exerts
continuous pressure throughout the expiratory phase led to a reduction in total dynamic
dead space to approach physiological dead space with most face masks, whereas NIV in
PSV mode led to less of a reduction, namely from 42 to 39%. Face masks using
expiratory ports over the nasal bridge resulted in beneficial flow characteristics within
the face mask and nasal cavity. Here, a decrease in total dynamic dead space to less than
physiological dead space from 42 to 28.5% of tidal volume was demonstrated [70]. In
conclusion, more studies on this subject are needed to verify the above findings.

**Air leakage**

The two major sites of air leakage are: 1) between the skin and the mask and 2) through
the mouth. Leaks, especially mouth leaks, play a major role in the ineffectiveness of NIV.
Leaks should be monitored and quantified and, for the multiple reasons that have been already mentioned, the potential for leaks should also influence the choice of mask (nasal or oronasal). The effect of a high rate of leakage on the efficiency of ventilation during sleep should be monitored, in addition to the potential effect on arousal and the role of nasal airway resistance.

Leaks may decrease the quality of both ventilation and sleep. Bach et al. demonstrated, through the use of volume ventilators for NIV, that severe leakage (i.e. a loss of 33% of the tidal volume) occurred for a median of 55% of sleep time and was associated with significant hypoventilation. In line with these findings, Meyer et al. [72] found severe mouth leak during sleep. In that study, a single limb bilevel device was used to allow for the possible compensation of leaks. In contrast to the study by Bach et al. [71], oxygenation was well maintained, despite prevalent leaking. Based on polysomnographic studies, it was found that leaks >24 L·min⁻¹ were associated with frequent arousals during sleep stages 1, 2 and rapid eye movement (REM) and this contributed to sleep fragmentation; arousals were infrequent during slow-wave sleep.

Indeed, leak-induced deterioration of sleep and ventilation may be compensated by adequate interfaces. For example, CRF patients who wore mouth tape during NIV demonstrated a marked reduction in leakage, improved ventilation (i.e. decrease of $P_{CO_2}$) and improved sleep quality (i.e. reduction of arousal index and increase of REM sleep), when, compared to patients without mouth taping [73]. In order to prevent mouth leaks that are associated with wearing a nose mask, the addition of chin straps can be helpful, and this combination has been shown to be just as effective, in terms of gas exchange and sleep quality, as the full-face mask in patients with CRF [59].

Although several mechanisms may be potentially involved in the development of nasal discomfort during NIV, mouth leaks are particularly important because they cause unidirectional inspiratory nasal airflow and progressive drying of the nasal mucosa. This mechanism is also known to promote the release of inflammatory mediators and increase nasal airway resistance [74, 75], which increase mouth breathing and promote further leakage, respectively.

Furthermore, Richards et al. [74] found that increased nasal resistance can be prevented by the addition of humidification. Their findings showed that, because of the high flows, a cold burst of humidification only increased the relative humidity by 6–9% and thus had no effect on improving airway resistance. However, a hot water bath humidifier increased the relative humidity to >97%, and changes in nasal resistance were either greatly attenuated or abolished. Although no consensus has been found concerning the optimal level of air humidification, it is an issue that deserves much more attention in NIV.

Due to the lack of trials dealing with air humidification during NIV of CRF patients, it seems to be feasible to apply to NIV in CRF the central findings of studies of air humidification during CPAP treating sleep apnoea. Both physiological and long-term clinical trials support the impact of air humidification.

Thus, in physiological studies it has been clearly shown that even during mouth leak, heated humidification can significantly increase relative humidity in the airways [76]. Furthermore CPAP treatment in sleep apnoea was associated with the highest rate of compliance (i.e. hours of CPAP usage) and optimal degree of satisfaction when supplemented with heated humidification, compared to both non-heated humidification and no humidification [77].

Finally, the question of when a face mask should be used instead of a nasal mask could be answered by considering the degree of leak monitoring. Compared to patients with CRF, those with ARF are more closely monitored for ineffective ventilation and mouth leaks. This may account for the reason why oronasal masks are preferred in ARF [61, 62]. Nevertheless, mouth leaks can also be a major problem in CRF. Hence,
monitoring the presence of mouth leaks, especially during sleep, should help to optimise mask management.

Conclusions

Although there is an immense variety of both ventilators and interfaces for NIV currently available, this form of therapy is a life-changing treatment in which patients may still feel uncomfortable during ventilation. Therefore, further dedication to this matter is needed to ensure the ongoing improvement of ventilators and interfaces.

Many specialists (i.e. physicians, respiratory therapists and skilled nurses), working in hospitals, specialised centres or home-care companies are well-qualified to adapt patients to NIV. However, the choice of the ventilator, the interface and the ventilator are usually based on intuition rather than evidence. Finally, monitoring the patient–ventilator interaction or air leaks during sleep is rarely performed and the knowledge about these phenomena, therefore, remains low.

Even though almost 15 years have passed since M. Meyer and Hill [8] published their review article, the concluding sentence “…several issues relating to the use of NIV are unresolved. The optimal interface and ventilator design have not been determined, and these may differ among patients” remains true.

Summary

Negative pressure ventilation (NPV) was the first reported form of noninvasive ventilation (NIV) to be widely applied to chronic respiratory failure (CRF). However, during the past decades, NPV has gradually lost its former impact and, apart from in a few centres, has been almost completely replaced by positive pressure ventilation (PPV) modes.

The existing plethora of terminology describing NIV modes can sometimes be confusing, especially with respect to ventilators. Pressure-targeted ventilation (PTV) and volume-targeted ventilation (VTV) are the main modes of NIV; Both types can be used in an assisted or controlled setting.

PTV has surpassed VTV in recent years as the treatment option for CRF. Both modes have been successfully applied to NIV in CRF. However, PTV has become the preferred mode due to the higher comfort level for the patient, as well as the lower costs and the compensation it provides for mild-to-moderate mask or mouth leaks.

Recently, hybrid modes of PTV and VTV were introduced.

The choice of ventilator and its setting should address different pathophysiological aspects of the underlying disease, of which is variable amongst CRF patients; in patients with COPD, the expiration time should be set at a higher level to avoid air trapping, while higher pressures may be useful to achieve a sufficient tidal volume. Furthermore, the addition of an positive end-expiratory pressure (PEEP) may be helpful to offset intrinsic PEEP in these patients. Various studies have shown that a controlled mode of ventilation is useful and well tolerated by all patients, irrespective of the underlying disease. When a controlled mode of ventilation is favoured, an assist-controlled mode is suggested to increase the patients’ subjective tolerance.

However, an individualised approach to each patient is beneficial and further studies investigating ventilator settings are needed to continually improve recommendations.

The interface between patient and ventilator is crucial for the success of NIV. In various studies, different interfaces have been used with success. However, despite its
high clinical impact, the choice of different interfaces has received little scientific attention. A variety of masks are now available, and manufacturers continue to improve mask design. The majority of interfaces is represented by commercial or custom-made nasal masks and oronasal masks. In special indications, nasal pillows or mouthpieces are used. It is suggested that nasal masks should be used prior to oronasal masks in CRF, since there are fewer limitations and communication with the patients is more convenient. In contrast, if patients are mouth breathers, an oronasal mask is favoured. In patients using nasal masks, leaks can occur through an open mouth, especially during night; these leaks can lead to NIV insufficiency, where both the quality of ventilation and sleep may be reduced. In this case, changing the interface to an oronasal mask should be considered. In general, mechanical ventilation can lead to dryness of the upper airway. Therefore, nasal resistance may be an important reason for reduced compliance, which may be compensated by additional humidification.

**Keywords:** Chronic respiratory insufficiency, hypoventilation, interfaces, mechanical ventilators, noninvasive positive-pressure ventilation.

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