ICU Ventilators Versus BiPAP Ventilators in Noninvasive Ventilation

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Tamer Fahmy and Sameh Salim

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5.1 Introduction

In contrast to the closed-circuit ventilation of invasive ventilation, noninvasive ventilation (NIV) is an open-circuit ventilation where leaks are inherent and, paradoxically, essential to its success. The success of NIV, whether in the acute setting, weaning, or long-term therapy is dependent on all three aspects for its use, appropriate patient selection, suitably fitting interface, and a specifically designed machine. The choice of a ventilator may be crucial for the success of NIV in the acute setting, because intolerance and excessive air leaks are significantly correlated with NIV failure [1].

T. Fahmy, MD, PhD (✉) • S. Salim, MD
Critical Care Medicine, Cairo University Hospitals, Giza, Egypt
e-mail: tfahmy@kasralainy.edu.eg, tamfahmy@gmail.com

A.M. Esquinas (ed.), *Noninvasive Mechanical Ventilation: Theory, Equipment, and Clinical Applications*, DOI 10.1007/978-3-319-21653-9_5

5.2 Leaks and Ventilator Performance

In contrast to unintentional leaks creating difficulties with ventilation, intentional leaks are "venting leaks." They should be created in the system in two instances. The first is to prevent the accumulation of CO_2 and rebreathing due to the dead space present in the interface, which may reach up to 800 ml in total face masks [2]. This accumulated air should be vented via exhalation ports in the interface. In the second instance, single-limb circuits should contain either a port for continuous intentional leaks or an exhalation valve. The intentional leaks are constant and controllable. Other sites of leaks, including that between the interface and the patient's face and mouth leaks with nasal masks, are sudden, variable, and unpredictable.

Leaks are less marked during expiration than during inspiration, because upper airway pressure decreases markedly when mechanical insufflation switches off to permit expiration. However, positive end-expiratory pressure (PEEP) may still promote expiratory leaks, where its level is proportional to the occurrence of leaks. Such leaks interfere with proper ventilation by affecting the trigger, pressurization during insufflations, and cycling off to exhalation. This ultimately leads to poor ventilation, lack of patient compliance, and prolongation or failure of NIV. Expiratory leaks can mimic an inspiratory effort for the ventilator, leading to auto-triggering, and inspiratory leaks can mimic a sustained inspiration, leading to delayed cycling [3].

If leak flow reaches the trigger threshold, auto-triggering occurs. Because of this, the frequency of auto-triggering does not depend on the magnitude of the increase in leak. On the other hand, if the leak is large enough, the ventilator may not detect respiratory efforts, leading to miss-triggering [3]. Vignaux et al. [4] demonstrated that auto-triggering was present in 13 % of patients, and delayed cycling in 23 % of patients during NIV. Auto-triggering per se may also induce miss-triggering if inspiratory time is prolonged, because of auto-triggering overlapping the patient's next inspiratory effort. In other words, cycle asynchrony can produce trigger asynchrony. Additionally, leaks can lead to aerophagia, odynophagia, dry mouth, eye irritation, and nasal symptoms, and noise may result, all of which reduce therapeutic compliance [5].

Ventilators used in NIV must be capable of detecting and properly estimating leaks and compensating for such leaks. Indeed, the response of these ventilators will vary according to the degree of leak, their capability to compensate, ventilation target (pressure vs volume targeted ventilation), and the type of intrinsic lung disease (obstructive vs restrictive pattern).

5.2.1 Leak Estimation and Compensation

The leak volume, as estimated from the difference in inspiratory and expiratory volumes, occurs during both inspiration and expiration. In the past, tidal volume has been estimated from the expiratory volume. However, given the observation that volume is also lost during expiration, tidal volume (Vt) can be underestimated from expiratory volume, and, consequently, crucial inspiratory leakage might be overestimated [6, 7]. Conceivably, the expired-volume method for measuring Vt might underestimate the Vt if leaks occur during expiration and therefore may induce overcompensation.

The simplest way to estimate the patient's Vt during leaks is to measure expiratory Vt and to consider that Vt is underestimated in case of expiratory leakage [7]. Ventilators with an expiratory valve have no expiratory circuit and no pneumotachograph connected to the patient interface. Consequently, these ventilators cannot measure expiratory Vt and, therefore, the patient's real Vt during leaks [7]. By measuring pressure and flow inside the ventilator, while taking into account the ventilator turbine speed throughout the entire respiratory cycle and detecting the beginning and end of inspiration, the ventilators with single-limb circuits with intentional leak are able to rebuild the patient's flow pattern and to establish a "baseline" breathing pattern corresponding to the patient's zero flow [7].

Khairani et al. [7] evaluating the ability of home ventilators to maintain the minimum Vt in volume-targeted pressure support ventilation (VT-PSV) in seven different NIV ventilators using different circuits. They concluded that ventilators that can be used with a single-limb circuit with intentional leak outperform devices that use double circuits or expiratory valves, where the latter could even paradoxically exacerbate the Vt drop during unintentional leak when used in VT-PSV mode. All but one of the studied ventilators with a double-limb circuit and all studied ventilators with an expiratory valve misinterpreted leaks as an increase in Vt and therefore decreased their inspiratory pressure to the minimal preset level, thereby paradoxically exaggerating the fall in Vt.

5.3 Comparison Between Ventilators

Three major types of ventilators have been commonly used for NIV over the past two decades: regular intensive care unit (ICU) ventilator (with no NIV capabilities or algorithm), ICU ventilator with NIV algorithm, and dedicated NIV ventilators. In general, in ICU ventilators without algorithms for leak compensation, a minimal amount of leak can be attained because the ventilator can only minimally compensate for the decline in pressure. If leaks are greater, the ventilator leak alarm will be activated, and the leaks will abort the breath due to disconnection. The failure to operate alarm is activated at higher levels. In the latter case, the system alarm for disconnection may be modified to a higher level, however, this still cannot be compensated for. ICU ventilators are more powerful and have more adjustable features (trigger type and sensitivity, slope of pressurization, cycling criteria) and monitoring capabilities. Their downside is cost, size, and the knowledge required for their safe use.

NIV ventilators, on the other hand, are portable devices with a turbine-type blower capable of delivering a high inspiratory flow rate (>100 l/min), are easier to use, and are less costly [8]. Most of the first generation bi-level ventilators, however, had important technical limitations, including limited pressure-generation ability, poor performance if respiratory-system load increased, risk of CO_2 rebreathing, and lack of ventilatory monitoring, alarms, or battery [1]. Although there have been many updates, NIV ventilators still cannot administer high inspired O_2 concentrations, nor can they reliably provide high (>20 cmH_2O) levels of pressure support. These two factors could prove to be a limitation in patients with hypoxemic respiratory failure, in whom high levels of FiO_2 and PEEP are required. In addition, CO_2 rebreathing can occur with some circuits, and they often lack monitoring capability [8].

Several bench and clinical studies have compared ventilator operability as well as patients' synchrony with different ICU ventilators (with and without leak compensation algorithms) and dedicated NIV ventilators (portable and ICU ventilators). In a randomized, crossover clinical study, Lofaso et al. [8] compared a home device to a device specially designed for intensive care use in seven intubated patients during weaning from mechanical ventilation. The main differences between the two devices were trigger sensitivity and initial flow acceleration. For the same level of pressure support, there were no significant differences in arterial PCO_2, Vt, respiratory rate, or minute ventilation between these two devices. However, the esophageal pressure-time product was 30 % higher with the home device. They concluded that differences exist between devices in terms of occurrence of rebreathing, speed of attainment of stable pressure support level, and expiratory resistance. These differences characterizing the delivery of pressure support may have clinical impact on the inspiratory effort of patients.

Didier et al. (2002) compared an NIV ventilator with three different ICU ventilators in a bench study they found its inspiratory trigger responded as quickly as the ICU ventilators tested, while its speed of pressurization was equal to some ICU ventilators, even at high inspiratory demand, provided the level of pressure support was kept below 20 cmH_2O. At higher levels, the proportional solenoid valve of the ICU machines was clearly at an advantage over the turbine-type blower of the home device [8].

In a bench study, Ferreira et al. (2009) [9] evaluated the ability of nine different ICU ventilators to function in the presence of leaks compared with NIV ventilators. They found that as the leak was sequentially increased, all ventilators, except for one dedicated NIV and another ICU ventilator, needed adjustment of sensitivity and/or inspiratory termination criteria to maintain synchrony, and some ventilators transitioned to backup ventilation. They found that only those two ventilators were able to synchronize with the lung simulator at all leak levels without adjustment. However, the dedicated NIV ventilator outperformed the ICU ventilator.

In a bench and a clinical study, Carteaux et al. (2012) [3] compared 19 different ICU ventilators with dedicated NIV ventilators. They found that in NIV conditions, most dedicated NIV ventilators allowed better patient-ventilator synchronization than ICU ventilators, even when the NIV algorithm was engaged, especially regarding the risk of auto-triggering. Most dedicated NIV ventilators exhibited a synchronization performance in the presence of leaks equivalent to ICU ventilators in the absence of leaks. Moreover, the NIV algorithm usually improved, at least slightly, the triggering and/or cycling synchronization of ICU and transport ventilators in the presence of leaks. The authors suggested that each ICU ventilator should be examined individually regarding its ability to manage NIV conditions. In contrast, dedicated NIV ventilators exhibited more homogeneous behavior during our bench evaluation, with an ability to avoid auto-triggering or delayed cycling while keeping a short triggering delay despite leaks.

Miyoshi et al. (2005) [10] evaluated the effects of gas leak on triggering function during NIV with dedicated NIV and ICU ventilators using a lung simulator. They found that the dedicated NIV ventilators triggered properly at several levels of leak (up to 44.2 l/min at 5 cmH_2O of PEEP) and that triggering was more effective than with the ICU ventilators (but not in NIV mode).

Oto et al. (2013) [11], in a lung model of chronic obstructive pulmonary disease (COPD) and acute respiratory distress syndrome (ARDS) evaluated seven different ICU and NIV ventilators at different levels of leaks up to 36 l/min. They found that ventilators performed better during decreasing than increasing leak, and that ventilators performed better with lower than with higher PEEP. Moreover, miss-triggering occurred more frequently and longer times were required to stabilize Vts in the COPD model than in the ARDS model. On the other hand, auto-triggering occurred more frequently in the ARDS model than in the COPD model. The ventilators may automatically decrease trigger sensitivity according to the level of leak to avoid auto-triggering, but as the leak decreases, the trigger sensitivity increases. This can lead to miss-triggering, particularly if the change is larger than the inspiratory effort. If the change in leak is smaller than the inspiratory effort, miss-triggering is unlikely, though higher patient effort is required to reach this threshold. The authors further added that because all the ventilators measure one or several cycles and adjust trigger/cycling for the subsequent cycles following a leak level change, it is not possible to synchronize on the exact breath that the leak changes. Due to this technical constraint, leak compensation on current acute care ventilators is limited in its ability to provide synchrony.

Nakamura et al. (2014) [2] found that only one of eight tested ICU ventilators was suitable for NIV using a total face mask with large leaks. Four were considered totally nonoperational due to inappropriate turning-off (misinterpretation of disconnection) or auto-triggering, whereas three of the remaining four had problems compensating for the large leaks through the exhalation ports, resulting in inability to keep PEEP and inspiratory pressure, delayed inspiratory triggering, or delayed cycling to expiration.

To increase safety, various manufacturers have limited the leak compensation for ICU ventilators to values equal to or lower than 30 l/min (or 0.5 l/s), values above which the disconnection alarm of the ventilator goes off [13]. However, the authors mentioned in the limitations of their study that some of the failed ICU ventilators upgraded their NIV software to a higher level of leak compensation after the commencement of their study.

To conclude, in different comparative studies:

- There is a wide range of heterogeneity among ICU ventilators in the leak compensation algorithms, while dedicated NIV ventilators are more homogenous. Because the manufacturers have not revealed the exact triggering and cycling algorithms used during system leak, it is difficult to explain the discrepancies among the different studies.

- Dedicated NIV ventilators outperform ICU ventilators in NIV, especially in patient–ventilator synchrony.
- NIV algorithms mostly improve ICU ventilator performance in NIV, however, modifications still have to be carried out to prevent triggering and cycling asynchrony.

5.4 Variation with Different Modes

In addition to the inherent characteristic of the device, the mode and setting also affect the leak compensation mechanisms within the same ventilator. Three different controls are being used in NIV: volume-targeted, pressure-targeted, and volume (average) assured pressure support. The response to different degrees of leak widely differs among these modes/controls.

When a leak is introduced, the peak inspiratory pressure decreases in the system and delivered Vt decreases. In volume-targeted ventilation, compensation is far less effective than in pressure-targeted ventilation [12]. This is expected with most volume-targeted ventilators, where the inspiratory flow is fixed and cannot increase, accounting for its poor leak compensation capabilities [12]. This cannot be overcome by increasing the inspiratory time, as this would also increase the duration of leak at higher pressures. Although increasing the Vt could partially compensate for leaks, this strategy for leak compensation is less effective than using pressure-targeted ventilators. Thus, volume-targeted ventilators would not be the first choice for noninvasive positive-pressure ventilation in patients with substantial air leakage.

On the other hand, when leak occurs in pressure-targeted ventilation, inspiratory flow will increase to maintain system pressurization for an extended time, increasing the inspiratory time. However, this compensatory effect depends on the rate of lung filling and emptying and the absolute inspiratory duration. Prolonging the inspiratory time to the point of inverting the inspiratory-expiratory ratio is counterproductive at higher rates (e.g., 30/min) because of incomplete emptying of the lung, resulting in higher end-expiratory pressure and therefore lower differential pressure [12].

Two counterproductive mechanisms occur. First, increasing pressure also increases leakage further, and the patient may not tolerate it, or it may further lead to aerophagia. Second, increasing the inspiratory time, especially with high rates, leads to expiratory asynchrony, requiring the patient to use the expiratory muscles to cycle off. Hence, this compensatory mechanism leads to increasing the inspiratory time, and at high rates would lead to air trapping, cycling off expiratory asynchrony, and intolerance to NIV [12]. Additionally, if pressure increases, in NIV-dedicated ventilators, inspiratory oxygen fraction obtained in these cases depends on factors such as the mixing of air supplied by the system and the oxygen in the circuit. If greater flow is needed to pressurize the circuit, high oxygen concentrations are harder to reach, even with high flow supplements [5].

This patient response varies among different ventilators and modes. If the patient-ventilator interface develops a large air leak during the attempted delivery of a pressure-targeted, flow-cycled breath, the ventilator will prolong inspiration because it does not sense the drop in flow required to terminate inspiration [13]. The ventilator may not be able to generate enough flow to maintain adequate inspiratory pressure. The patient will then "pull" against the ventilator circuitry, increasing the work of breathing. In contrast, a subset of patients may experience discomfort when exposed to an inspiratory flow exceeding demand [13].

The mechanism of expiratory asynchrony is terminated by a decrease in inspiratory flow up to a maximum duration of 3 s. Therefore, inspiratory time increases during leak because inspiratory flow fails to drop sufficiently to cycle the ventilator [12]. If airway resistance or lung elastance increases, normally Vt can be delivered only in volume targeted ventilation, and decreases in pressure controlled.

5.4.1 Volume (Average Volume) Assured Pressure Support

These devices increase the delivered Vt by increasing inspiratory flow during inspiration. However, when working within a single-circuit configuration without monitoring of the expiratory volume, it may expose to inefficient compensation especially when inspiratory leaks are present [14]. Some have used a proprietary system to adjust their leak compensation, which uses pressure-targeted ventilation to obtain optimal control of both inspiratory positive airway pressure (IPAP) and inspiratory time (Ti) to determine which of these adjustments is most effective for leak compensation [14]. The original feature of their leak compensation mode is that a Ti increase is combined with an IPAP increase to maintain sufficient minute ventilation based on monitoring of the patient's exhaled Vt. The ventilator takes the amount of leakage into account, cycle by cycle, and increases inhaled Vt to obtain an exhaled Vt value as close as possible to the set security Vt [14]. One important limitation of this system is that expiratory leaks may lead to errors by decreasing the exhaled Vt detected by the ventilator. The result may be inappropriately large increases in Ti, inspiratory flow, and IPAP, possibly producing lung overinflation [14]. They concluded that their leak-compensation system is probably less effective in compensating for expiratory leaks than inspiratory leaks and may be ineffective when the entire exhaled Vt leaks around the interface [14, 15].

In the presence of a mild leak during NIV, whether with an ICU ventilator or a dedicated NIV ventilator, either volume-controlled or volume-assured ventilation can be used. However, as the leak increases, pressure-targeted ventilation may be preferred to compensate for the leaks, as long as the pressure still allows (less than 20–25 cmH_2O) and the inspiratory time can still be increased. To best compensate for air leaks, pressure-targeted ventilators should have high and sustained maximal inspiratory flow capabilities.

Conclusion

Because leakage is a prerequisite in the application of NIV, ventilators used for NIV should be specifically designed to overcome this leak. The degree of leak compensation should be enough to build-up the baseline pressure set on the ventilator. ICU ventilators with NIV capabilities or bi-level positive airway pressure units usually have leak compensation between 30 and 60 l/min. Some ICU ventilators may have higher compensation, reaching more than 100 l/min. The set baseline expiratory pressure must not be less than 4 to allow for continuous venting of CO_2 and to prevent rebreathing; therefore, leak compensation must be capable of maintaining that minimum pressure during expiration.

In order for a ventilator to maintain synchrony in the presence of leak, the ventilator must automatically adjust the trigger sensitivity and/or cycling time [11]. Furthermore, in any mode the ventilator should have an algorithm for differentiating the leak from the decrease in base flow for triggering to prevent triggering dyssynchrony (missed efforts and auto-triggering). Similarly, in case of pressure support mode, the ventilator should also be able to discriminate between the leak and the expiratory trigger criteria (cycling) to allow for inspiratory synchrony and the following breath trigger level. In addition, the ventilator should be designed to have a secondary cycling mechanism in case of failure to sense the expiratory trigger level, so that the inspiratory time is not unduly prolonged (i.e., longer than 1.5 s). In such cases, the ventilator will switch from pressure-support mode to pressure control (time cycled). In order for a ventilator to maintain synchrony in the presence of increasing leaks, the ventilator must be able to acclimate by adjustment of both triggering and cycling, ideally automatically [9].

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