Patient-Ventilator Asynchrony During Noninvasive Ventilation

A Bench and Clinical Study

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**Background:** Different kinds of ventilators are available to perform noninvasive ventilation (NIV) in ICUs. Which type allows the best patient-ventilator synchrony is unknown. The objective was to compare patient-ventilator synchrony during NIV between ICU, transport—both with and without the NIV algorithm engaged—and dedicated NIV ventilators.

**Methods:** First, a bench model simulating spontaneous breathing efforts was used to assess the respective impact of inspiratory and expiratory leaks on cycling and triggering functions in 19 ventilators. Second, a clinical study evaluated the incidence of patient-ventilator asynchronies in 15 patients during three randomized, consecutive, 20-min periods of NIV using an ICU ventilator with and without its NIV algorithm engaged and a dedicated NIV ventilator. Patient-ventilator asynchrony was assessed using flow, airway pressure, and respiratory muscles surface electromyogram recordings.

**Results:** On the bench, frequent auto-triggering and delayed cycling occurred in the presence of leaks using ICU and transport ventilators. NIV algorithms unevenly minimized these asynchronies, whereas no asynchrony was observed with the dedicated NIV ventilators in all except one. These results were reproduced during the clinical study: The asynchrony index was significantly lower with a dedicated NIV ventilator than with ICU ventilators without or with their NIV algorithm engaged (0.5% [0.4%-1.2%] vs 3.7% [1.4%-10.3%] and 2.0% [1.5%-6.6%], \( P \leq .01 \)), especially because of less auto-triggering.

**Conclusions:** Dedicated NIV ventilators allow better patient-ventilator synchrony than ICU and transport ventilators, even with their NIV algorithm. However, the NIV algorithm improves, at least slightly and with a wide variation among ventilators, triggering and/or cycling off synchronization.

**Abbreviations:** AI = asynchrony index; ICUv− = ICU ventilator with the noninvasive ventilation algorithm turned off; ICUv+ = ICU ventilator with the noninvasive ventilation algorithm turned on; NIV = noninvasive ventilation; NIVv = dedicated noninvasive ventilation ventilator; PEEP = positive end-expiratory pressure; TD = triggering delay; Tiexcess = insufflation time in excess; Tsim = simulated active inspiration time; Tvent = time between the beginning of a simulated inspiratory effort and the end of the ventilator's insufflation

Noninvasive ventilation (NIV) has become a standard of care for the management of many causes of acute respiratory failure.\(^1\)\(^-\)\(^3\) During NIV, the unavoidable presence of leaks around the mask\(^4\) can interfere with the ventilator performance. Expiratory leaks can mimic an inspiratory effort for the ventilator, leading to auto-triggering;\(^5\) and inspiratory leaks can mimic a sustained inspiration, leading to delayed cycling.\(^6\) Not surprisingly, patient-ventilator asynchronies have, therefore, been reported to occur with a high incidence during NIV in critically ill patients.\(^7\)

Different ventilators are now used to conduct NIV in ICU: ICU ventilators,\(^2\) dedicated NIV ventilators,\(^8\) and also transport ventilators when needed.\(^9\)\(^-\)\(^11\) Most ICU ventilators were initially built to work without any leak, at least in adults, and are prone to be disrupted...
by the presence of leaks during NIV.\textsuperscript{12} To address this issue, manufacturers have implemented NIV algorithms (so called “NIV modes”) on the latest generation of ICU ventilators to compensate and better manage the leaks. Both bench\textsuperscript{12,13} and clinical\textsuperscript{14} studies assessing the performance of NIV algorithms on ICU ventilators have shown mixed results, partly due to large variations among the ventilators, making it difficult to draw an overall conclusion. Dedicated NIV ventilators stem from bilevel home ventilator technology, which has been particularly oriented toward leakage management and comfort. Some bench studies suggested that a dedicated NIV ventilator could produce better performance and synchronization than ICU ventilators in the presence of leaks.\textsuperscript{13,15} However, no bench model concerning ventilator synchronization during NIV has been clinically validated, raising the question of their clinical relevance in critically ill patients. Consequently, the kind of ventilator that allows the best synchronization during NIV in the ICU is still unknown. In some areas, NIV is mainly delivered with dedicated NIV ventilators,\textsuperscript{2} whereas in other countries ICU ventilators are almost exclusively preferred,\textsuperscript{2} and this distribution reflects local habits rather than an evidence-based approach.

The purpose of this study was to compare patient-ventilator synchronization during NIV using ICU and transport ventilators with or without their NIV algorithm, and finally dedicated NIV ventilators. We designed a bench model to assess ventilator synchronization with a simulated inspiratory effort in different leak conditions, simulating the different challenges to be faced by the ventilator. Furthermore, we conducted a clinical study in critically ill patients to compare the incidence of patient-ventilator asynchrony between ICU ventilators with and without their NIV algorithm engaged, and a dedicated NIV ventilator.

**Materials and Methods**

This study involved a bench part and a clinical part. An extensive description of both the bench and clinical protocols is provided in e-Appendix 1.

**Bench Study**

All 19 ventilators tested are reported in Table 1 and included eight ICU ventilators, five transport ventilators, and six dedicated NIV ventilators. The test lung, an Active Servo Lung 5000 (ASL 5000; IngMar Medical, Ltd), was used to simulate a moderate inspiratory effort in the presence of an 80 mL/cm H\textsubscript{2}O respiratory system compliance and 10 cm H\textsubscript{2}O/L/s resistance to mimic a mild obstructive condition. The simulated respiratory rate was 15 breaths/min and the inspiratory time 0.8 s. Three leak conditions were generated (Fig 1A): absence of leak, continuous leak (to reveal triggering asynchronies during expiratory leak), and inspiratory leak (to reveal cycling-off asynchronies). For this last experiment, the leak started at a pressure corresponding to a water column of 7 cm H\textsubscript{2}O, as detailed in e-Appendix 1. The inspiratory leak was characterized by a nonlinear pressure-flow relationship with a flow varying from 0 to 22 L/min for a pressure from 7 to 15 cm H\textsubscript{2}O. The continuous (expiratory) leak was characterized by a flow of 16 L/min at 5 cm H\textsubscript{2}O pressure.

Ventilators were set in pressure support ventilation, with a pressure support level at 15 cm H\textsubscript{2}O and a positive end-expiratory pressure (PEEP) at 5 cm H\textsubscript{2}O. ICU and transport ventilators were tested with and without their NIV algorithm engaged, except the Elisee 250, whose NIV algorithm cannot be turned off. Data were acquired at 512 Hz from ASL 5000 and stored in a laptop computer for subsequent analysis (Acqknowledge 3.7.3; BIOPAC Systems, Inc). Inspiratory triggering synchronization was assessed using the triggered delay, the triggering pressure-time product, and the incidence of auto-triggering, expressed as a percentage and calculated as follows: auto-triggering incidence ($\%$) = (auto-triggered cycles/total ventilator cycles) $\times$ 100. The pressurization was assessed using the pressure-time product at 300 milliseconds. Cycling synchronization was assessed by determining ventilator insufflation time in excess (T\textsubscript{excess}), expressed as a percentage, and calculated as follows: T\textsubscript{excess} = [(T\text{vent} - T\text{sim})/T\text{sim}] $\times$ 100, where T\text{vent} is the time between the beginning of the simulated inspiratory effort and the end of the ventilator’s insufflation, and T\text{sim} the simulated active inspiration time. Delayed cycling was defined by a T\text{vent}$\geq$2 T\text{sim} and premature cycling by a T\text{vent}$\leq$2/3 T\text{sim}.

**Clinical Study**

A prospective, randomized, crossover study was conducted in two university hospital ICUs. The protocol was approved by the ethics committee CPP-Ile-de-France IX (number: 08-021), and informed consent was obtained from all patients. We included 15 patients in the ICU receiving NIV in pressure support ventilation mode with PEEP via a standard oronasal mask. The ventilator settings chosen by the clinician in charge of the patient were kept identical for the study. Three consecutive NIV sessions were applied in a random order, using the same oronasal mask: (1) use of an ICU ventilator whose NIV algorithm has been turned off
Table 1—Bench Study: Characteristics of the ICU, Transport, and NIV Ventilators Tested in the Bench Study

<table>
<thead>
<tr>
<th>Ventilator</th>
<th>Supplier</th>
<th>Use</th>
<th>Gas Source</th>
<th>Circuit</th>
<th>NIV Mode</th>
<th>ET Range</th>
<th>IT Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avea</td>
<td>CareFusion</td>
<td>ICU</td>
<td>Pressurized</td>
<td>Double</td>
<td>Manual</td>
<td>5%-45%</td>
<td>0.1-20 L/min</td>
</tr>
<tr>
<td>Engstrom</td>
<td>GE Healthcare</td>
<td>ICU</td>
<td>Pressurized</td>
<td>Double</td>
<td>Manual</td>
<td>5%-50%</td>
<td>1-9 L/min; ~1 to ~10 cm H₂O</td>
</tr>
<tr>
<td>Evita XL</td>
<td>Dräger</td>
<td>ICU</td>
<td>Pressurized</td>
<td>Double</td>
<td>Automatic</td>
<td>Automatic; 5%-70%</td>
<td>0.3-15 L/min</td>
</tr>
<tr>
<td>G5</td>
<td>Hamilton Co</td>
<td>ICU</td>
<td>Pressurized</td>
<td>Double</td>
<td>Manual</td>
<td>5%-70%</td>
<td>0.5-15 L/min</td>
</tr>
<tr>
<td>PB840+</td>
<td>Covidien</td>
<td>ICU</td>
<td>Pressurized</td>
<td>Double</td>
<td>Manual</td>
<td>1%-80%</td>
<td>0.2-20 L/min</td>
</tr>
<tr>
<td>Servo-i</td>
<td>MAQUET GmbH &amp; Co KG</td>
<td>ICU</td>
<td>Pressurized</td>
<td>Double</td>
<td>Manual</td>
<td>1%-40%</td>
<td>0%-100%; ~20 to 0 cm H₂O</td>
</tr>
<tr>
<td>V500</td>
<td>Dräger</td>
<td>ICU</td>
<td>Pressurized</td>
<td>Double</td>
<td>Automatic/manual</td>
<td>Automatic; 5%-70%</td>
<td>Automatic; 0.2-15 L/min</td>
</tr>
<tr>
<td>Vela</td>
<td>CareFusion</td>
<td>ICU</td>
<td>Turbine</td>
<td>Double</td>
<td>Manual</td>
<td>5%-40%</td>
<td>1-8 L/min</td>
</tr>
<tr>
<td>Elisee 250</td>
<td>ResMed</td>
<td>Transport</td>
<td>Turbine</td>
<td>Double</td>
<td>Automatic/manual</td>
<td>Automatic; 1%-6%</td>
<td>Automatic</td>
</tr>
<tr>
<td>Medumat</td>
<td>Weimann Medical Technology</td>
<td>ICU</td>
<td>Pneumatic</td>
<td>Single</td>
<td>Automatic</td>
<td>5%-50%</td>
<td>1-15 L/min</td>
</tr>
<tr>
<td>Onylag 3000</td>
<td>Dräger</td>
<td>Transport</td>
<td>Pneumatic</td>
<td>Single</td>
<td>Automatic</td>
<td>Automatic</td>
<td>Automatic</td>
</tr>
<tr>
<td>Supportair</td>
<td>Covidien</td>
<td>Transport</td>
<td>Turbine</td>
<td>Double</td>
<td>Manual</td>
<td>5%-95%</td>
<td>01-05</td>
</tr>
<tr>
<td>T1</td>
<td>Hamilton Co</td>
<td>Transport</td>
<td>Turbine</td>
<td>Double</td>
<td>Manual</td>
<td>5%-80%</td>
<td>1-20 L/min</td>
</tr>
<tr>
<td>BiPAP Vision</td>
<td>Philips Respironics</td>
<td>NIV</td>
<td>Turbine</td>
<td>Single</td>
<td>Automatic</td>
<td>Automatic</td>
<td>Automatic</td>
</tr>
<tr>
<td>Carina</td>
<td>Dräger</td>
<td>NIV</td>
<td>Turbine</td>
<td>Single</td>
<td>Automatic</td>
<td>Automatic</td>
<td>Analogical (sensible/normal)</td>
</tr>
<tr>
<td>Trilogy 100</td>
<td>Philips Respironics</td>
<td>NIV</td>
<td>Turbine</td>
<td>Single</td>
<td>Automatic</td>
<td>Automatic</td>
<td>Automatic</td>
</tr>
<tr>
<td>V60</td>
<td>Philips Respironics</td>
<td>NIV</td>
<td>Turbine</td>
<td>Single</td>
<td>Automatic</td>
<td>Automatic</td>
<td>Automatic</td>
</tr>
<tr>
<td>Vivo 40</td>
<td>Breas</td>
<td>NIV</td>
<td>Turbine</td>
<td>Single</td>
<td>Automatic</td>
<td>Automatic</td>
<td>Automatic</td>
</tr>
</tbody>
</table>

ET = expiratory trigger, expressed as a percentage of peak inspiratory flow; IT = inspiratory trigger; NIV = noninvasive ventilation.

(1) Version comprising both an NIV mode and leak compensation.

(2) Use of an ICU ventilator whose NIV algorithm has been turned on (ICUniv+), and (3) use of a dedicated NIV ventilator (NIVv).

Results

Bench Study

Triggering Delay: The ICU and transport ventilators with their NIV algorithm turned off in the absence of leaks exhibited a total triggering delay (TD) of 117 milliseconds (99-131 milliseconds) and 143 milliseconds (114-174 milliseconds), respectively (P = .37) (Fig 2). The addition of inspiratory leaks did not significantly modify these values except for the Engstrom, G5, and T1, which had an increased TD, and the Medumat, which showed a reduced TD. Turning on the NIV algorithm while maintaining inspiratory leaks led to different behaviors among ICU and transport ventilators: TD significantly increased for five ventilators (Medumat, Evita XL, Servo-i, V500, Supportair), decreased for three (Engstrom, PB840, T1), and was not modified for the others. In this last condition, the TD of ICU, transport, and dedicated NIV ventilators were 107 (83-120), 126 (112-190), and 125 (102-145) milliseconds, respectively (P > .05 for every intergroup comparison). When NIV algorithms were used in the presence of inspiratory leaks, six ICU ventilators (Avea, Engstrom, PB840, Servo-i, V500, Vela), two transport ventilators (Elisee 250, Supportair), and two NIV ventilators (BiPAP Vision, V60) exhibited a TD < 117 milliseconds (ie, the median TD of ICU ventilators with the NIV algorithm turned off in absence of leaks). The additional assessment of the triggering pressure-time product is reported in e-Appendix 1 and e-Figure 1.

Auto-Triggering: Occurrence of auto-triggering was assessed during the presence of continuous leaks (Fig 3). Expiratory leaks induced an incidence of auto-triggering between 0% and 100% among ICU and transport ventilators when their NIV algorithm was
titators whose NIV algorithm can be turned off. The NIV algorithms generally minimized the insufflation time, which remained significantly higher than without leaks for only two ICU ventilators (Avea, G5) and three transport ventilators (Oxylog 3000, Supportair, T1). With NIV algorithm and inspiratory leaks, ICU, transport, and dedicated NIV ventilators exhibited a T\textsubscript{i}excess of 34% (29%-43%), 37% (25%-43%), and 37% (18%-49%), respectively. In this condition, the T\textsubscript{i}excess was <32% for four ICU ventilators (Engstrom, Evita XL, Servo-i, V500), two transport ventilators (Medumat, Supportair), and three dedicated NIV ventilators (BiPAP Vision, Trilogy 100, V60).

During inspiratory leaks when NIV algorithms were turned off, delayed cycling occurred with four ICU ventilators (Avea, G5, PB840, Vela) and three transport ventilators (Medumat, Oxylog 3000, T1). The activation of the NIV algorithm eliminated delayed cycling for all of these ventilators but one (G5). However, the NIV algorithm of the Servo-i overcorrected the T\textsubscript{i}excess (24%). Concerning dedicated NIV ventilators subjected to inspiratory leaks, one of them (VIVO 40) exhibited delayed cycling.

We also assessed the ability of the ventilators to pressurize the airway in the first 300 milliseconds with or without leaks. For the sake of simplicity, these data are only shown in e-Appendix 1 and e-Figure 2.

Clinical Study

Fifteen patients of median age 68 years old (61-76 years) were included, 13 men and two women, with a median BMI of 24 kg/m\textsuperscript{2} (20-27 kg/m\textsuperscript{2}). At inclusion, Simplified Acute Physiology Score II was 47 (32-62) and arterial blood gas levels were as follows: pH = 7.36 (7.29-7.42), Paco\textsubscript{2} = 48 mm Hg.

Cycling and Insufflation Time: ICU and transport ventilators without their NIV algorithm in the absence of leaks exhibited a T\textsubscript{i}excess of 32% (30%-34%) and 49% (24%-75%), respectively (P = .93) (Fig 4). Inspiratory leaks led to a significant increase in insufflation time for six ICU ventilators (Avea, Engstrom, G5, PB840, Servo-i, Vela) and all four transport ventilators whose NIV algorithm can be turned off. The NIV algorithms generally minimized the insufflation time, which remained significantly higher than without leaks for only two ICU ventilators (Avea, G5) and three transport ventilators (Oxylog 3000, Supportair, T1). With NIV algorithm and inspiratory leaks, ICU, transport, and dedicated NIV ventilators exhibited a T\textsubscript{i}excess of 34% (29%-43%), 37% (25%-43%), and 37% (18%-49%), respectively. In this condition, the T\textsubscript{i}excess was <32% for four ICU ventilators (Engstrom, Evita XL, Servo-i, V500), two transport ventilators (Medumat, Supportair), and three dedicated NIV ventilators (BiPAP Vision, Trilogy 100, V60).

During inspiratory leaks when NIV algorithms were turned off, delayed cycling occurred with four ICU ventilators (Avea, G5, PB840, Vela) and three transport ventilators (Medumat, Oxylog 3000, T1). The activation of the NIV algorithm eliminated delayed cycling for all of these ventilators but one (G5). However, the NIV algorithm of the Servo-i overcorrected the T\textsubscript{i}excess (24%). Concerning dedicated NIV ventilators subjected to inspiratory leaks, one of them (VIVO 40) exhibited delayed cycling.

We also assessed the ability of the ventilators to pressurize the airway in the first 300 milliseconds with or without leaks. For the sake of simplicity, these data are only shown in e-Appendix 1 and e-Figure 2.
for both comparisons) (Fig 5). The incidence of each asynchrony during the three NIV sessions is represented in Figure 6. Auto-triggering had the highest incidence. The incidence of auto-triggering, however, was significantly lower with NIVv than with ICUniv2 and ICUniv1, 0.1/min (0.1-0.1/min) vs 0.5/min (0.1-1.1/min) and 0.3/min (0.1-1.2/min), P < .001, and the proportion of patients who exhibited a high incidence of auto-triggering (> 1/min) was significantly lower with NIVv than with ICUniv2 and ICUniv1 (Table 3). Four patients (27%) had an AI > 10% with ICUniv+, two (13%) with ICUniv+, and none with NIVv (P = .091). The level of leaks throughout the clinical study was noticeably high in these two last patients (14 and 16 L/min, respectively). The proportion of patients who exhibited at least one asynchrony with a high incidence (> 1/min) was significantly higher with ICUniv— and ICUniv+ than with NIVv (Table 3).

**Discussion**

To our knowledge, this study is the first to compare patient-ventilator synchronization during NIV between ICU, transport, and dedicated NIV ventilators, with both a bench and a clinical evaluation. The observations made with these two approaches were consistent, offering a strong validation of the bench model, a logical explanation for the clinical data, and

(41-63 mm Hg), PaO2/FIO2 = 206 mm Hg (183-252 mm Hg). Patients had spent one median day (0.3-1.0 days) under NIV before inclusion. Indications for NIV were the following: to avert respiratory failure after extubation (n = 5), exacerbation of COPD (n = 4), cardiogenic pulmonary edema (n = 3), community-acquired pneumonia (n = 2), and post thoracic surgery (n = 1). Eight patients (53%) had COPD. Ventilator settings were pressure support level = 10 cm H2O (8-11 cm H2O), PEEP = 4 cm H2O (4-5 cm H2O), inspiratory trigger = 1 L/min (1-2 L/min), pressurization slope = 100 milliseconds (100-100 milliseconds), and FIO2 = 40% (30%-50%). There was no significant difference between the three NIV sessions regarding ventilator settings, respiratory parameters, and the measured level of leaks (Table 2). ICU ventilators used in the clinical study had a similar response to leaks as during the bench study in terms of asynchrony: a propensity to auto-triggering with expiratory leaks, partially corrected by the NIV algorithm, but no delayed cycling with the NIV algorithm and inspiratory leaks (Figs 3, 4).

**Patient-Ventilator Synchrony:** The asynchrony index (AI) did not significantly differ when using ICU ventilators without (ICUniv−) or with (ICUniv+) their NIV algorithm engaged, 3.7% (1.4%-10.3%) vs 2.0% (1.5%-6.6%), respectively, P = .118. By contrast, AI was significantly lower with NIVv (0.5% [0.4%-1.2%]) than with both ICUniv− and ICUniv+ (P = .001 for both comparisons) (Fig 5). The incidence of each asynchrony during the three NIV sessions is represented in Figure 6. Auto-triggering had the highest incidence. The incidence of auto-triggering, however, was significantly lower with NIVv than with ICUniv− and ICUniv+, 0.1/min (0.1-0.1/min) vs 0.5/min (0.1-1.1/min) and 0.3/min (0.1-1.2/min), P < .001, and the proportion of patients who exhibited a high incidence of auto-triggering (> 1/min) was significantly lower with NIVv than with ICUniv− and ICUniv+ (Table 3). Four patients (27%) had an AI > 10% with ICUniv−, two (13%) with ICUniv+, and none with NIVv (P = .091). The level of leaks throughout the clinical study was noticeably high in these two last patients (14 and 16 L/min, respectively). The proportion of patients who exhibited at least one asynchrony with a high incidence (> 1/min) was significantly higher with ICUniv− and ICUniv+ than with NIVv (Table 3).
In NIV conditions, most dedicated NIV ventilators allowed better patient-ventilator synchronization than ICU and transport ventilators, even when the NIV algorithm was engaged, especially regarding the risk of auto-triggering.

Most of the dedicated NIV ventilators exhibited a synchronization performance in the presence of leaks equivalent to that of the ICU ventilators in absence of leaks.

Synchronization performance in the presence of leaks remains heterogeneous among ICU as well as transport ventilators, and each machine should be considered individually.

The NIV algorithm usually improved, at least slightly, the triggering and/or cycling synchronization of ICU and transport ventilators in the presence of leaks.

### Table 2—Clinical Study: Main Respiratory Parameters

<table>
<thead>
<tr>
<th>Respiratory Parameters</th>
<th>ICUuniv−</th>
<th>ICUuniv+</th>
<th>NIV</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRp, per min</td>
<td>29 (22-31)</td>
<td>27 (22-31)</td>
<td>26 (24-30)</td>
<td>.982</td>
</tr>
<tr>
<td>Ttp, ms</td>
<td>780 (599-914)</td>
<td>674 (559-957)</td>
<td>749 (629-923)</td>
<td>.057</td>
</tr>
<tr>
<td>Tiexcess, %</td>
<td>14 (4-24)</td>
<td>12 (6-23)</td>
<td>13 (11-21)</td>
<td>.344</td>
</tr>
<tr>
<td>Vte, mL</td>
<td>467 (269-633)</td>
<td>465 (322-548)</td>
<td>487 (278-539)</td>
<td>.931</td>
</tr>
<tr>
<td>Vte, mL/kg</td>
<td>6.5 (4.3-9.4)</td>
<td>6.9 (4.6-8.3)</td>
<td>7.0 (4.6-9.0)</td>
<td>.797</td>
</tr>
<tr>
<td>Ve, L/min</td>
<td>11.5 (8.7-15.5)</td>
<td>10.3 (9.2-16.7)</td>
<td>10.6 (8.6-14.0)</td>
<td>.683</td>
</tr>
<tr>
<td>Leaks, L/min</td>
<td>6.3 (4.3-10.8)</td>
<td>6.2 (2.6-12.1)</td>
<td>7.3 (3.0-11.7)</td>
<td>.947</td>
</tr>
<tr>
<td>Leaks, % Ve</td>
<td>55 (39-101)</td>
<td>47 (26-113)</td>
<td>81 (16-121)</td>
<td>.612</td>
</tr>
</tbody>
</table>

Main respiratory parameters recorded throughout the three NIV sessions during the clinical study. ICUuniv− = NIV session using an ICU ventilator whose NIV algorithm has been turned off; ICUuniv+ = NIV session using an ICU ventilator whose NIV algorithm has been turned on; NIVv = NIV session using a dedicated NIV ventilator; RRp = patient’s respiratory rate measured with the use of the electromyogram signal; Tiexcess = percentage of insufflation time that exceeds the neural inspiratory time; Ttp = patient’s neural inspiratory time; Ve = minute ventilation; Vte = expired tidal volume. See Table 1 legend for expansion of other abbreviation.
Patient-Ventilator Interactions During NIV

Patient-ventilator asynchrony is frequent during both invasive\(^6,17\) and noninvasive\(^7,14\) mechanical ventilation. However, the respective proportion of each type of major asynchrony markedly differs between these two techniques. During invasive mechanical ventilation, ineffective effort represents the most prevalent asynchrony.\(^6,18\) Its occurrence is largely favored by overassistance and can frequently be avoided by reducing the amount of support both in terms of tidal volume and inspiratory time.\(^19,20\) By contrast, during NIV, additional asynchronies, especially auto-triggering and delayed cycling, are induced by the presence of leaks around the mask\(^4,7\) and reflect more the ventilator’s ability to manage leaks than the settings chosen by the clinician. Our bench study showed a wide variation in this ability among ICU ventilators and their NIV algorithms, which is consistent with previous bench studies.\(^12,13\) More interestingly, our bench results were also well reproduced during our clinical study. In fact, auto-triggering represented the most frequent asynchrony with ICU ventilators used in the clinical study, as predicted during their bench evaluation. Furthermore, there was a trend toward less asynchrony with the NIV algorithm, which usually minimized asynchronies during the bench study. Vignaux et al\(^14\) assessed the impact of the NIV algorithm on the incidence of patient-ventilator asynchronies during NIV in a clinical study involving 65 patients and five ICU ventilators. Without the NIV algorithm engaged, 46% of the patients had an AI > 10%. The NIV algorithm permitted a decrease in the incidence of asynchronies due to leaks but without a decrease in the overall incidence of patient-ventilator asynchronies (38% vs 46%, \(P = .69\)), due to a high incidence of asynchronies not directly related to leaks. We report a lower proportion of patients exhibiting an AI > 10% due to a lower incidence of some major asynchronies. Several reasons explain this discrepancy. First, the level of assistance in our study was lower than the one observed in the study by Vignaux et al, leading to a lower tidal volume, which might explain our low incidence of ineffective efforts.\(^20\) Second, we have modified the definition of premature cycling, considering that the previous one was too sensitive in terms of clinical relevance and what can be considered as a “major” patient-ventilator asynchrony. This definition modification has automatically led to less recorded premature cycling, so to a lower AI. Third, the ICU ventilators used in our clinical assessment had the same behavior during our bench evaluation: a propensity to auto-triggering with expiratory leaks, but no delayed cycling in the presence of inspiratory leaks. Although the strength of our bench model was to assess separately the impact of expiratory and inspiratory leaks on triggering and cycling synchronizations, respectively, the originality of our clinical study was to use ICU ventilators that had the same behavior during their bench evaluation. This led to intelligible results and gave a mutual validation to the two assessments. In the meantime, as a part of this behavior was to avoid delayed cycling, this logically led to a decrease in the overall AI during the clinical study as compared with previous studies conducted with other ventilators. Finally, an AI > 10% in our clinical study was mainly related to a high incidence of auto-triggering, which reflects the ventilator’s ability to manage leaks rather than the relevance of the settings chosen by the clinician.

As with ICU ventilators, our bench evaluation also showed very uneven performances of transport ventilators and their NIV algorithms in the presence of leaks. Such heterogeneity has also been previously reported with transport ventilators assessed in invasive conditions.\(^21,22\)

On the whole, our results suggest that rather than being considered as belonging to a group of ventilators, each ICU and transport ventilator should be examined individually regarding its ability to manage NIV conditions. By 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

![Graph showing clinical study asynchrony index during the three NIV sessions.](Image)
indication for NIV in ICU. Second, only one level of both inspiratory and expiratory leaks was designed. These experimental conditions may not reproduce what happens in clinical conditions. However, our clinical study showed that our bench model succeeded in capturing the kind of asynchronies that may occur in the presence of leaks with each ventilator in the clinical setting.

Clinical Relevance

It is currently unknown if patient-ventilator asynchronies, especially those due to leaks, can affect the clinical outcome of NIV and therefore influence ventilator choice by clinicians. However, several arguments favor the best possible synchronization during NIV. First, it seems reasonable to assume that auto-triggering and delayed cycling will reduce the tolerance of the procedure, an important key to NIV success. Second, the occurrence of delayed cycling

 Limitations

Several limitations of this study should be underlined. First, during the bench study, only mild obstructive respiratory mechanics were simulated, as respiratory mechanics are known to affect the cycling delay. Our aim was to uncover delayed cycling in the presence of inspiratory leaks, which could be minimized in the case of restrictive respiratory mechanics. In addition, COPD represents the most recognized

Table 3—Clinical Study Patients Presenting Each Type of Asynchrony With a High Incidence (> 1/min) or an Asynchrony Index > 10%

<table>
<thead>
<tr>
<th>Type of Asynchrony</th>
<th>ICUUniv−</th>
<th>ICUUniv+</th>
<th>NIVv</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auto-triggering</td>
<td>5 (33)</td>
<td>5 (33)</td>
<td>0</td>
<td>.016</td>
</tr>
<tr>
<td>Double-triggering</td>
<td>0</td>
<td>1 (7)</td>
<td>0</td>
<td>...</td>
</tr>
<tr>
<td>Ineffective effort</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>...</td>
</tr>
<tr>
<td>Delayed cycling</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>...</td>
</tr>
<tr>
<td>Premature cycling</td>
<td>3 (20)</td>
<td>1 (7)</td>
<td>0</td>
<td>.097</td>
</tr>
<tr>
<td>At least one asynchrony</td>
<td>6 (40)</td>
<td>5 (33)</td>
<td>0</td>
<td>.012</td>
</tr>
<tr>
<td>Asynchrony index &gt; 10%</td>
<td>4 (27)</td>
<td>2 (13)</td>
<td>0</td>
<td>.091</td>
</tr>
</tbody>
</table>

Data are presented as No. (%). See Table 1 and 2 legends for expansion of abbreviations.
can lead to dynamic hyperinflation and contribute to the development of ineffective efforts, which are associated with a prolongation of the ventilation during invasive mechanical ventilation. Given the benefits of NIV when avoiding intubation, each factor potentially involved in its success should logically be promoted. However, if no patient exhibited a high incidence of asynchrony with the NIV ventilator in our study, just a few had an AI > 10% with ICU ventilators. We cannot know to what extent this difference may be clinically relevant and further clinical studies addressing the impact of different devices on the outcome of different groups of patients under NIV are needed to formulate some recommendations.

CONCLUSION

In conclusion, our study shows that dedicated NIV ventilators allow a better patient-ventilator synchrony in the presence of leaks than ICU and transport ventilators, even if their NIV algorithm is engaged, especially for what concerns auto-triggering. When using an ICU or transport ventilator to perform NIV, the NIV algorithm usually improves, at least slightly and with variations among ventilators, triggering and/or cycling synchronization.

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Additional information: The e-Appendix and e-Figures can be found in the “Supplemental Materials” area of the online article.

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