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Reliability and limits of transport-ventilators to safely ventilate severe patients in special surge situations

Dominique Savary^{1,2*} , Arnaud Lesimple^{3,4}, François Beloncle⁵, François Morin¹, François Templier¹, Alexandre Broc⁶, Laurent Brochard^{7,8}, Jean-Christophe Richard^{5,9} and Alain Mercat⁵

Abstract

Background: Intensive Care Units (ICU) have sometimes been overwhelmed by the surge of COVID-19 patients. Extending ICU capacity can be limited by the lack of air and oxygen pressure sources available. Transport ventilators requiring only one O₂ source may be used in such places.

Objective: To evaluate the performances of four transport ventilators and an ICU ventilator in simulated severe respiratory conditions.

Materials and methods: Two pneumatic transport ventilators, (Oxylog 3000, Draeger; Osiris 3, Air Liquide Medical Systems), two turbine transport ventilators (Elisee 350, ResMed; Monnal T60, Air Liquide Medical Systems) and an ICU ventilator (Engström Carestation—GE Healthcare) were evaluated on a Michigan test lung. We tested each ventilator with different set volumes ($V_{t\text{set}} = 350, 450, 550$ ml) and compliances (20 or 50 ml/cmH₂O) and a resistance of 15 cmH₂O/l/s based on values described in COVID-19 Acute Respiratory Distress Syndrome. Volume error (percentage of $V_{t\text{set}}$) with $P_{0.1}$ of 4 cmH₂O and trigger delay during assist-control ventilation simulating spontaneous breathing activity with $P_{0.1}$ of 4 cmH₂O and 8 cmH₂O were measured.

Results: Grouping all conditions, the volume error was $2.9 \pm 2.2\%$ for Engström Carestation; $3.6 \pm 3.9\%$ for Osiris 3; $2.5 \pm 2.1\%$ for Oxylog 3000; $5.4 \pm 2.7\%$ for Monnal T60 and $8.8 \pm 4.8\%$ for Elisee 350. Grouping all conditions ($P_{0.1}$ of 4 cmH₂O and 8 cmH₂O), trigger delay was 50 ± 11 ms, 71 ± 8 ms, 132 ± 22 ms, 60 ± 12 and 67 ± 6 ms for Engström Carestation, Osiris 3, Oxylog 3000, Monnal T60 and Elisee 350, respectively.

Conclusions: In surge situations such as COVID-19 pandemic, transport ventilators may be used to accurately control delivered volumes in locations, where only oxygen pressure supply is available. Performances regarding triggering function are acceptable for three out of the four transport ventilators tested.

Keywords: COVID-19, Acute Respiratory Distress Syndrome, Respiratory failure, Mechanical ventilation, Respiratory mechanics

Introduction

During the COVID 19 pandemic, several hospitals experienced the greatest shortage of ventilators ever seen since the heroic times of the polio epidemic in the

1950s. In this context, alternative solutions including ventilator sharing, use of anesthesia ventilators and use of homecare ventilators have been considered to manage intubated patients with severe lung failure outside the walls of the ICU [1–3]. To be able to replace ICU ventilators in the early phase, ventilators must be relatively easy for the users, able to accurately control the delivered volume and provide assist control ventilation

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(ACV) in difficult mechanical conditions. Importantly, they must allow to vary FiO_2 without requiring two pressurized sources of gas (i.e., wall air and oxygen at 50 psi). Of note, this is one of the main limits of the homecare ventilators that makes them incompatible for very hypoxemic patients. Several transport ventilators are based on pneumatic systems and Venturi systems for gas mixing. Others use an internal turbine for pressurization; but need a pressurized gas source of oxygen to reach high FiO_2 values. Pneumatic transport ventilators have been used for decades both for in- and out-of-hospital transport. Their robustness and their relative technological simplicity could potentially facilitate massive industrial production. They represent interesting solutions in this context and could fulfill the mentioned requirements. The general view on these ventilators is, however, that their limitations make them acceptable only for a short period like transport but make them incompatible with the safe delivery of difficult ventilation for very sick patients over prolonged periods. Undoubtedly, they have limited capacities regarding ventilation modes and monitoring, but knowing whether their reliability is sufficient for delivering lung protective ventilation in patients with ARDS merited to be tested with these objectives in mind. Indeed, discarding their use in a context of surge could limit the extension of beds outside the walls of the ICU for mechanically ventilated patients. Performances of turbine ventilators are often excellent and have been well described [4, 5]. By contrast, limits of pneumatic ventilators have not been specifically tested with the appropriate settings in realistic conditions simulating

the respiratory mechanics of patients with COVID-19 induced ARDS [6–9].

The aim of the present study was to evaluate the reliability and the limitations of ventilation provided by these different technologies mimicking patients with COVID-19 induced ARDS in simulated bench conditions of passive and partially assisted situation.

Materials and methods

Performances during volume-controlled (VC) and ACV were evaluated with different conditions of simulated respiratory mechanics reproducing patients with COVID-19 induced ARDS. All experiments have been performed in the Ventilatory Laboratory of the Angers University Hospital, medical ICU.

Ventilators

Brands

Four transport ventilators necessitating only one O_2 pressurized gas source were included in the study. Two pneumatic transport ventilators using Venturi systems to mix air to oxygen were tested: the Oxylog 3000 (Draeger, Lubeck, Germany) and the Osiris 3 (Air Liquide Medical Systems, Antony, France). Two turbine transport ventilators, necessitating additional oxygen only to increase FiO_2 were also tested: the Elisee 350 (ResMed, Sydney, Australia) and the Monnal T60 (Air Liquide Medical Systems, Antony France). Performances of these ventilators were compared to a standard ICU ventilator: Engström Carestation (GE healthcare, Madison, USA). The characteristics of the five ventilators are given in Table 1.

Table 1 General characteristics of the ventilators

| | Engström Carestation | Osiris 3 | Oxylog 3000 | Monnal T60 | Elisee 350 |
|--|----------------------------|-----------------------------|--------------------|--|--------------------|
| Manufacturer | GE Healthcare | Air Liquide Medical Systems | Draeger | Air Liquide Medical Systems | Resmed |
| Weight [kg] | 31.0 | 5.0 | 5.4 | 3.7 | 4.0 |
| Working pressure | Pressurized oxygen and air | Pressurized oxygen | Pressurized oxygen | Pressurized oxygen | Pressurized oxygen |
| Expired volume monitoring | Yes | Yes | Yes | Yes | Yes |
| Tidal volume (V_t) [ml] | 20–2000 | 100–2000 | 50–2000 | 20–2000 | 50–2500 |
| Accuracy of Expiratory flow sensor | $\pm 10\%$ | $\pm 15\%$ | $\pm 15\%$ | $V_{Te} \geq 50 \text{ ml}; \pm (2.5 \text{ ml} \pm 15\%)$ | 10% or 10 ml |
| PEEP [cmH_2O] | 1–50 | 0–15 | 0–20 | 0–20 | 0–25 |
| Peak inspiratory pressure [cmH_2O] | 7–100 | 10–80 | PEEP + 3–PEEP + 55 | 0–80 | 0–100 |
| FiO_2 [%] | 21–100 | 70 or 100 | 40–100 | 21–100 | 21–100 |
| Battery duration [h] | 0.5–2 | 6–14 | 4 | 2.5–5 | 3–6 |

PEEP positive end expiratory pressure, FiO_2 fraction of inspired oxygen

Working principle and settings

In the two pneumatic transport ventilators tested (Oxylog 3000 and Osiris 3), the working pressure that generates ventilation comes from the high-pressure oxygen supply. These ventilators based on a “Venturi-distributor” technology work as flow generator.

With the Oxylog 3000, the air-O₂ mixing is regulated from 40 to 100% via a Venturi system coupled with a proportional inspiratory valve that also permits to directly set the volume ($V_{t_{\text{set}}}$). The inspiratory flow depends on both the respiratory rate (RR) and the Inspiratory:Expiratory (I:E) ratio. In other words, for a given set volume, changing RR and/or I:E ratio keep the set Vt but modifies inspiratory flow. The monitoring of the expired Vt is available via a specific flow sensor inserted between the endotracheal tube and the patient circuit.

With the Osiris 3, only two positions are available for FiO₂: 100% or 70%. A Venturi effect is used to obtain a FiO₂ of 70% by mixing ambient air and O₂ source. Inspiratory flow is delivered through a distributor. For a given combination of I:E ratio and respiratory rate, the Vt is set by directly adjusting a Vt knob that also regulates the inspiratory flow. The monitoring of the expired Vt is available via a specific flow sensor inserted between the endotracheal tube and the patient circuit.

The Elisee 350 and T60 are two turbine-based ventilators which need oxygen only to adjust FiO₂. On those ventilators, the Vt and the inspiratory flow are directly set on the screen. Changing the respiratory rate does not affect neither Vt nor inspiratory flow. The monitoring of the expired Vt is available via a flow sensor close to the expiratory valve.

The Engström Carestation is a classical high-quality ICU ventilator requiring two sources of pressurized gas for oxygen and air (usually wall pressure at 50–55 psi). The monitoring of the expired Vt is available via a flow sensor located close to the expiratory valve.

Volume delivered and PEEP with different respiratory mechanics

We assessed the volume effectively delivered ($V_{t_{\text{measured}}}$) by the ventilators in different conditions of respiratory mechanics simulated on a Michigan test lung (Michigan Instruments, Kentwood, MI, USA). A linear pneumotachograph (PNT 3700 series, Shawnee, USA) and a pressure transducer (SD160 series: Biopac systems, Goleta, CA, USA) were used to measure flow and airway pressure between the test lung and the patient circuit. Signals were converted with an analog digital converter (MP150; Biopac systems, Goleta, CA, USA) at a sample rate of 200 Hz, and stored in a laptop using a dedicated software

(Acknowledge, Biopac Systems). $V_{t_{\text{measured}}}$ was obtained from numerical integration of the flow signal. All the tests were done in ATPD conditions and not corrected for BTPS conditions.

Three set volumes ($V_{t_{\text{set}}}$) were tested: 350 ml, 450 ml and 550 ml, which approximately cover 6 ml/kg of Predicted Body Weight (PBW) for 161 to 199 cm height in male adult patients and 166 to 203 cm height in female adult patients. We also tested 300 mL on the Osiris 3. The different respiratory mechanics conditions tested were compliance of 50 ml/cmH₂O and 20 ml/cmH₂O, both combined with a resistance of 15 cmH₂O/L/s. The combinations of compliance and resistance tested were based on recently described COVID-19 respiratory mechanics [6–9].

Assist Control Ventilation (ACV) mode was selected and similar ventilator settings were applied for each ventilator (respiratory rate 30 cycles/min).

The pneumatic transport ventilators were set with an Inspiratory:Expiratory ratio of 1:3 (I:E), whereas a flow of 60 l/min was adjusted on the Engström Carestation, Elisee 350 and Monnal T60. For every condition tested, inspiratory flow was measured.

The three set volumes were tested with FiO₂ 100% and 70% as follows: FiO₂ was selected, $V_{t_{\text{set}}}$ was adjusted on the ventilator and $V_{t_{\text{measured}}}$ was recorded and averaged over 5 cycles after stabilization. As Osiris 3 does not have an oxygen sensor to monitor oxygen content, FiO₂ was measured on this ventilator when air-O₂ mix was selected with a PF300 gas analyzer (IMT Medical, Buchs, Switzerland) in different conditions ($V_t = 350\text{--}450\text{--}550$ ml and Compliance = 20–50 ml/cmH₂O).

The performances of Venturi-based ventilation in terms of volume delivery could be altered by set inspiratory flow values [10]. To assess in the Osiris 3 the impact of the inspiratory flow on $V_{t_{\text{error}}}$, we tested a $V_{t_{\text{set}}}$ of 450 ml obtained with different inspiratory flows achieved by changing respiratory rate (RR). ACV mode with air-O₂ mix was selected, a resistance of 15 cmH₂O/l/s and a compliance of 20 ml/cmH₂O were applied and we set a I:E ratio of 1:3. The lowest RR (6 cycles/min) was chosen and was progressively increased by 4 cycles/min until reaching the maximum RR of 40 cycles/min. $V_{t_{\text{set}}}$ had to be adjusted in consequence at each RR increment to keep its value at 450 ml. $V_{t_{\text{error}}}$ was estimated at each step.

Two levels of PEEP were applied (10 cmH₂O and 15 cmH₂O) and the accuracy of the effective PEEP ($PEEP_{\text{measured}}$) was assessed.

Volume error and PEEP end-points

The relative volume error ($V_{t_{\text{error}}}$), which is the difference between the effective expired volume ($V_{t_{\text{measured}}}$) and the set volume ($V_{t_{\text{set}}}$) was calculated and averaged as

previously described over the four different conditions [4, 11]:

$$\begin{aligned}\text{Resistance} &= 15 \text{ cmH}_2\text{O/l/s, Compliance} \\ &= 20 \text{ or } 50 \text{ ml/cmH}_2\text{O, PEEP} \\ &= 10 \text{ or } 15 \text{ cmH}_2\text{O}\end{aligned}$$

The relative volume error was expressed in percentage and defined as follows:

$$Vt_{\text{error}} = \frac{|Vt_{\text{measured}} - Vt_{\text{set}}|}{Vt_{\text{set}}} \times 100$$

End-point for Vt_{error} The three tidal volumes tested were chosen to cover theoretical “6 ml/kg PBW” in adult male or female patients (350, 450 and 550 ml correspond to 6 ml/kg PBW for, respectively 58, 75 and 92 kg PBW).

Ventilation was considered safe and acceptable when Vt_{measured} was within ± 0.5 ml/kg PBW, which covers a volume between 5.5 and 6.5 ml/kg PBW. This corresponds to an 8% difference between set and measured Vt .

End-point for PEEP A difference between measured PEEP and set PEEP was acceptable when less than 2 cmH₂O.

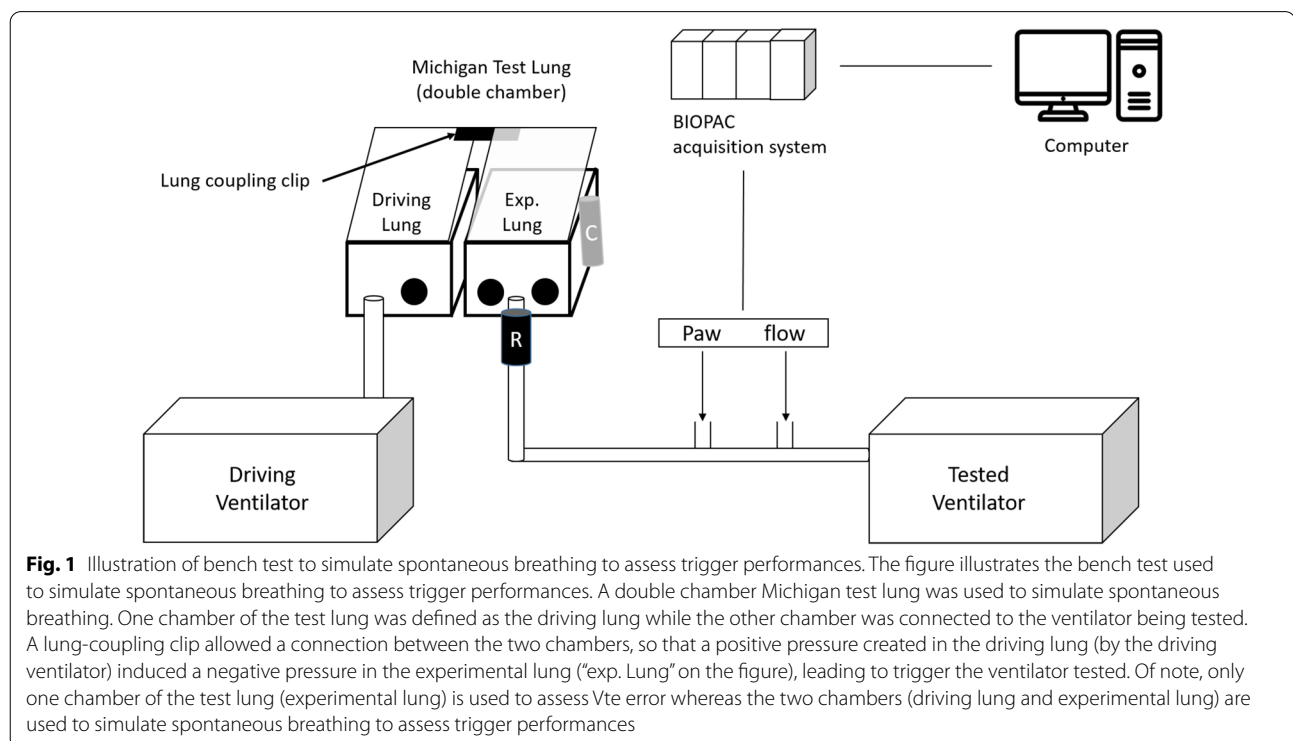
Trigger performances

Assist control ventilation (ACV) with the inspiratory trigger function “on” was tested by connecting ventilators to the double chamber Michigan test lung to

simulate spontaneous breathing (see Fig. 1). One chamber of the test lung was defined as the driving lung, while the other chamber was connected to the ventilator being tested. A lung-coupling clip allowed a connection between the two chambers, so that a positive pressure created in the driving lung induced a negative pressure in the experimental lung, leading to trigger the ventilator tested.

The driving lung was connected to an Evita XL ventilator (Draeger, Lubeck, Germany), which was set in volume-controlled mode with constant flow. The respiratory rate was set at 25 breaths/min. The ventilatory settings were chosen to achieve a moderate effort, with a decrease in airway pressure 100 ms after occlusion ($P_{0.1}$) of 4 cmH₂O (consistent with $P_{0.1}$ value recently described in COVID patients [12] measured at the airway opening of the lung model [13, 14]. A level of PEEP was applied to the driving lung to obtain a perfect contact of the lung-coupling clip between the two chambers at the end of expiration.

For each ventilator tested, volume assist-control ventilation (ACV) mode was selected, with a tidal volume of 450 ml, a respiratory rate of 20 cycles/min and a PEEP of 10 cmH₂O. I:E ratio was set at 1:3 for Osiris 3 and Oxylog 3000, while a flow of 60 l/min was set on Elisee 350, Monnal T60 and the Engström Carestation ICU ventilator. Inspiratory triggers were set at their most responsive position while avoiding auto-triggering. The trigger of the Osiris 3 was set at -0.5 cmH₂O.



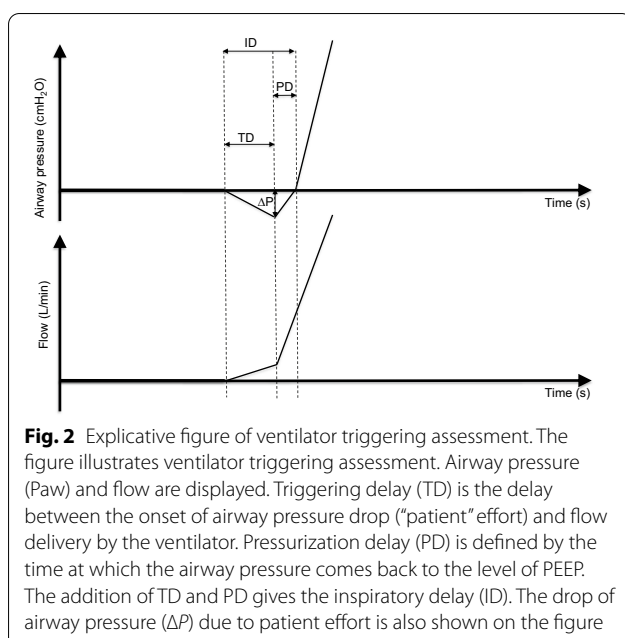


Fig. 2 Explicative figure of ventilator triggering assessment. The figure illustrates ventilator triggering assessment. Airway pressure (Paw) and flow are displayed. Triggering delay (TD) is the delay between the onset of airway pressure drop (“patient” effort) and flow delivery by the ventilator. Pressurization delay (PD) is defined by the time at which the airway pressure comes back to the level of PEEP. The addition of TD and PD gives the inspiratory delay (ID). The drop of airway pressure (ΔP) due to patient effort is also shown on the figure

Flow-triggered ventilators were set at 1 l/min for Engström Carestation and Oxylog 3000 and 2 l/min for Monnal T60 and Elisee 350. Two respiratory mechanics were tested: $C = 20$ ml/cmH₂O and 50 ml/cmH₂O with $R = 15$ cmH₂O/l/s.

For each configuration, trigger performance was assessed by measuring the airway pressure changes using the flow trace to determine the start of inspiration [11, 15]. Negative pressure drop (ΔP , cmH₂O), Triggering Delay (TD, ms) and Pressurization Delay (PD, ms) as defined in Fig. 2 were measured. The overall Inspiratory Delay (ID) corresponds to the addition of TD and PD.

We repeated the tests for all the ventilators at a strong effort corresponding to a $P_{0.1}$ of 8 cmH₂O; we tested the effect of set volume ($V_{t\text{set}} = 350\text{--}450\text{--}550$ ml), compliance ($C = 20\text{--}50$ ml/cmH₂O) and Positive End Expiratory Pressure (PEEP = 5–10–15 cmH₂O) on triggering delay performances (see Additional file 1).

End-point Triggering function was considered as “safe and acceptable” when TD was less than 100 ms [16].

Statistical analysis

Continuous variables were expressed as mean \pm SD values averaged from 5 consecutive breaths. These variables were compared using an ANOVA test. The type I significance level was set at 0.05. When the global F was significant, post hoc tests were computed using a student *t* test with Bonferroni correction, which sets the level of significance for pairwise differences between the five ventilators at 0.005.

Results

Volume delivered and PEEP measured with different respiratory mechanics

Results obtained with a $P_{0.1}$ of 4 cmH₂O (moderate effort) are displayed in Fig. 3 and mean volume errors ($V_{t\text{error}}$) for each ventilator are shown in Table 2. When all conditions and set volumes were included, the Engström Carestation was the most accurate ventilator, and the Oxylog 3000 was comparable. The performance was considered as acceptable ($\Delta V_t \pm 0.5$ ml/kg PBW) except for one turbine ventilator (Elisee 350). The impact of FiO_2 selection (FiO_2 100% or 70%) on volume error was significant considering all ventilators ($p < 0.05$, see Table 2). There was no impact of compliance on volume error ($p > 0.05$, Table 2). FiO_2 measured on Osiris 3 was $72.3 \pm 1.7\%$ across all the conditions tested. Differences between measured PEEP and set PEEP were less than 2 cmH₂O as shown in Table 2 (all conditions together).

Volume delivered at a $V_{t\text{set}}$ of 300 ml for the Osiris 3 is shown in Additional file 1: Figure S1. Additional file 1: Table S1 summarizes measured inspiratory flow for each ventilator in the different experimental conditions.

Impact of inspiratory flow on pneumatic ventilators

The effect of inspiratory flow rates on $V_{t\text{error}}$ for Osiris 3 is shown in Fig. 4. Considering a $V_{t\text{set}}$ of 450 ml, the lowest values of inspiratory flow were associated with a $V_{t\text{error}}$ higher than 8% ($\Delta V_t \pm 0.5$ ml/kg PBW). Performances were acceptable when inspiratory flow (resulting from the combination of V_t , I:E ratio and respiratory rate) was strictly above 30 l/min, which corresponds to a respiratory rate higher than 18 cycles/min.

Trigger performances during ACV

Inspiratory trigger was evaluated for each ventilator and results corresponding to a moderate effort ($P_{0.1} = 4$ cmH₂O) are displayed in Fig. 5. All simulated efforts triggered a ventilatory cycle. The Triggering Delay was 42 ± 4 ms, 65 ± 5 ms, 151 ± 14 ms, 51 ± 6 ms and 64 ± 5 ms for Engström Carestation, Osiris 3, Oxylog 3000, Monnal T60 and Elisee 350, respectively (all conditions grouped, $p < 0.05$; pairwise differences between ventilators were all significant with a p -value < 0.005). The Inspiratory Delay (ID) was measured at 54 ± 5 ms for Engström Carestation, 95 ± 5 ms for Osiris 3, 217 ± 21 ms for Oxylog 3000, 72 ± 6 ms for Monnal T60 and 85 ± 7 ms for Elisee 350 and ($p < 0.05$; pairwise differences between ventilators were all significant with a p -value < 0.005).

The airway pressure drop was much larger for Oxylog 3000 (-4.2 ± 0.3 cmH₂O), than for the others:

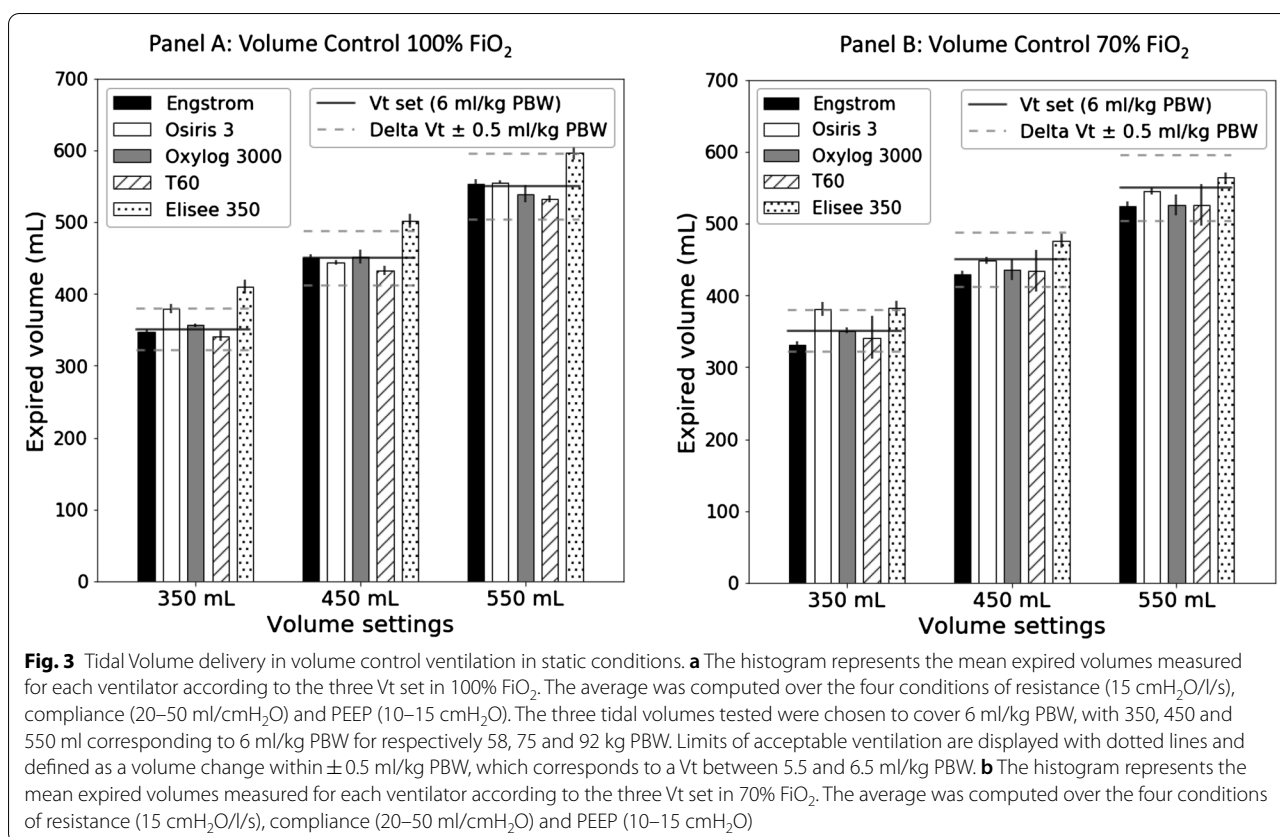


Table 2 Mean volume errors and Positive End Expiratory Pressure 1 (PEEP) measured for each ventilator

| | Engström Carestation | Osiris 3 | Oxylog 3000 | Monnal T60 | Elisee 350 |
|---|----------------------|----------------|----------------|----------------|----------------|
| Vt _{error} global [%] | 2.9 ± 2.2 | 3.6 ± 3.9 | 2.5 ± 2.1 | 5.4 ± 2.7 (*) | 8.8 ± 4.8 (*) |
| Vt _{error} 100% FiO ₂ [%] | 1.0 ± 0.7 | 3.7 ± 3.7 (*) | 2.0 ± 1.2 (*) | 3.3 ± 1.4 (*) | 11.9 ± 4.1 (*) |
| Vt _{error} 70% FiO ₂ [%] | 4.9 ± 1.3 | 3.5 ± 4.2 | 2.9 ± 2.7 (*) | 7.5 ± 2.0 (*) | 5.9 ± 3.5 |
| Vt _{error} C50 [%] | 3.3 ± 2.7 | 3.4 ± 4.0 | 1.6 ± 1.1 (*) | 5.1 ± 3.1 (*) | 10.4 ± 5.3 (*) |
| Vt _{error} C20 [%] | 2.6 ± 1.6 | 3.8 ± 3.8 | 3.4 ± 2.6 | 5.7 ± 2.2 (*) | 7.0 ± 3.7 (*) |
| Mean PEEP 10 [cmH ₂ O] | 9.9 ± 0.2 | 10.6 ± 0.6 (*) | 11.5 ± 0.3 (*) | 9.5 ± 0.5 (*) | 10.3 ± 0.1 (*) |
| Mean PEEP 15 [cmH ₂ O] | 15.1 ± 0.2 | 14.9 ± 0.6 (*) | 15.4 ± 2.2 | 14.7 ± 0.1 (*) | 15.4 ± 0.2 (*) |

Vt_{error} global = mean volume error including all conditions of resistance (15 cmH₂O/l/s), compliance (20–50 ml/cmH₂O) and PEEP (10–15 cmH₂O) for both 100% FiO₂ and 70% FiO₂. Vt_{error} 100% FiO₂ = mean volume error including all conditions of resistance (15 cmH₂O/l/s), compliance (20–50 ml/cmH₂O) and PEEP (10–15 cmH₂O) for 100% FiO₂. Vt_{error} 70% FiO₂ = mean volume error including all conditions of resistance (15–12 cmH₂O/l/s), compliance (20–50 ml/cmH₂O) and PEEP (10–15 cmH₂O) for 70% FiO₂. Vt_{error} C50 = mean volume error including all conditions of 1 resistance (15 cmH₂O/l/s), FiO₂ (100–70%) and PEEP (10–15 cmH₂O) for a compliance of 50 ml/cmH₂O. Vt_{error} C20 = mean volume error including all conditions of resistance (15 cmH₂O/l/s), FiO₂ (100–70%) and PEEP (10–15 cmH₂O) for a compliance of 20 ml/cmH₂O. Mean PEEP 10 = mean PEEP measured when PEEP was set at 10 cmH₂O including all conditions of resistance (15 cmH₂O/l/s) and compliance (20–50 ml/cmH₂O) for both 100% FiO₂ and 70% FiO₂. Mean PEEP 15 = mean PEEP measured when PEEP was set at 15 cmH₂O including all conditions of resistance (15 cmH₂O/l/s) and compliance (20–50 ml/cmH₂O) for both 100% FiO₂ and 70% FiO₂.

**p* < 0.005 when comparing each transport ventilator with the Engström ICU ventilator (ANOVA test: global F was significant)

– 0.9 ± 0.3 cmH₂O for Engström Carestation, – 1.9 ± 0.1 cmH₂O for Osiris 3, – 0.6 ± 0.1 cmH₂O for Monnal T60 and – 0.8 ± 0.1 for Elisee 350 (*p* < 0.05; pairwise differences between ventilators were all significant with a *p*-value < 0.005, except between Engström Carestation-Elisee 350 and Engström Carestation-Monnal T60).

Ventilator performances were considered acceptable (TD < 100 ms) except for one pneumatic ventilator (Oxylog 3000).

Triggering Delays obtained with a strong effort (P_{0.1} = 8 cmH₂O) are available in Additional file 1: Figure S2. Grouping all conditions (P_{0.1} of 4 cmH₂O and 8 cmH₂O),

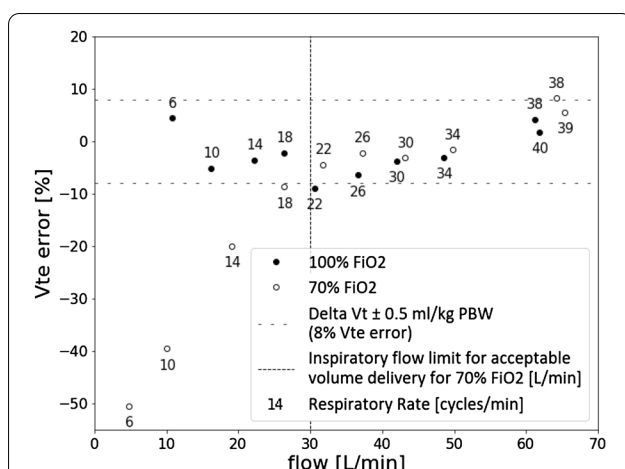


Fig. 4 Impact of flow on effective volume with Osiris 3 ventilator. This figure shows the volume error of the Osiris 3 expressed in percentage of V_t set according to different inspiratory flows obtained at a constant 450 ml V_t set. Compliance, resistance and PEEP were set at 20 ml/cmH₂O, 15 cmH₂O/l/s and 10 cmH₂O respectively. Black circles were obtained with 100% FiO_2 while the white circles were obtained with 70% FiO_2 . Respiratory rate associated with each point is also displayed. This figure illustrates that for an inspiratory flow below 30 l/min, the V_t error is substantial with 70% FiO_2 . The V_t error is within ± 0.5 ml/kg PBW (which corresponds to an 8% difference between set and measured V_t) whatever the inspiratory flow when 100% FiO_2 is selected

trigger delay was 50 ± 11 ms, 71 ± 8 ms, 132 ± 22 ms, 60 ± 12 and 67 ± 6 ms for Engström Carestation, Osiris 3, Oxylog 3000, Monnal T60 and Elisee 350, respectively. The effect of set volume, compliance and PEEP on triggering delay performances (at $P_{0.1} = 8$ cmH₂O) are shown in Additional file 1: Tables S2, S3 and S4, respectively.

Discussion

The results of the present bench test study comparing turbine and pneumatic transport ventilators to an ICU ventilator, can be summarized as follows: 1. Turbine ventilators' performances in VC and ACV are very close to those of the ICU ventilator tested for most of the settings including volume delivery and reliability of PEEP. 2. For most of the severe respiratory mechanics conditions tested, the volume error does not exceed 0.5 ml/kg PBW except for one turbine ventilator (two conditions) and one pneumatic ventilator (one condition). Volume error delivered by the simplest pneumatic ventilator significantly increased at FiO_2 70%, when inspiratory flow was less than 30 l/min indicating a technological limit of the Venturi system. 3. Inspiratory trigger reactivity was less than 100 ms except for one pneumatic transport ventilator.

The increasing number of patients requiring mechanical ventilation in the context of the COVID-19 worldwide crisis, and the ventilators shortage reported in some

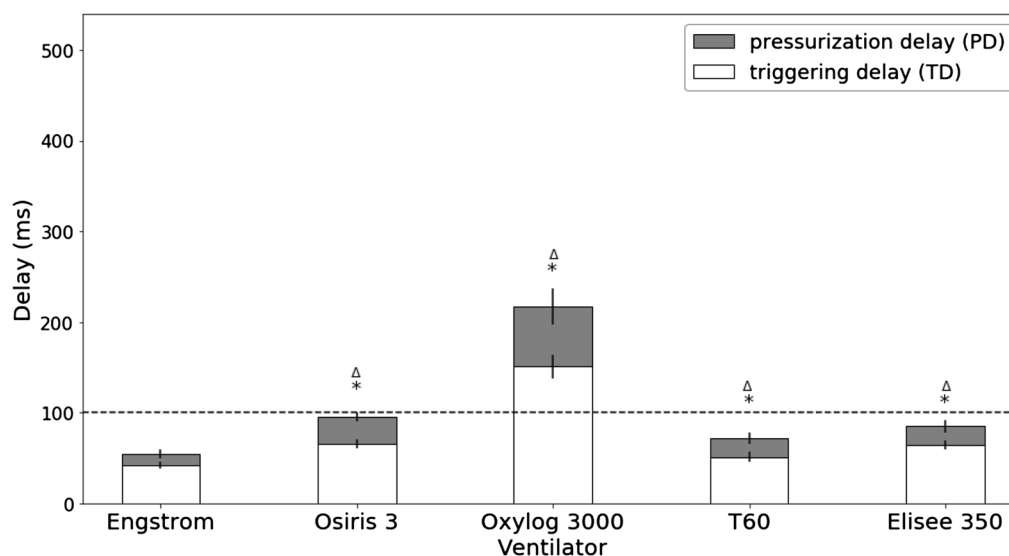


Fig. 5 Triggering characteristics in volume assist-control ventilation for a $P_{0.1}$ of 4 cmH₂O. The figure illustrates the triggering efficiency for each ventilator tested during assist-control ventilation using the Michigan test lung to simulate spontaneous breathing. A moderate effort was achieved, corresponding to a decrease in airway pressure 100 ms after occlusion ($P_{0.1}$) of 4 cmH₂O was achieved. A PEEP of 10 cmH₂O, a compliance of 20 and 50 ml/cmH₂O and a resistance of 15 cmH₂O/l/s were selected. Triggering Delay (TD, ms) and Pressurization Delay (PD, ms) were computed. A definition of TD and PD is available on Fig. 1. Triggering function was considered safe and acceptable when TD was less than 100 ms. * $p < 0.005$ for TD when comparing each transport ventilator with the Engstrom ICU ventilator (ANOVA test: global F was significant). $\Delta p < 0.005$ for PD when comparing each transport ventilator with the Engstrom ICU ventilator (ANOVA test: global F was significant)

severely affected countries, has led to discuss the possibilities to manage intubated patients outside the walls of the ICU [2]. According to this dire scenario, simple and easy to set ventilators that only require one oxygen pressure source to function and able to reliably deliver lung protective ventilation could be considered. In addition, an assisted mode that controls the V_t with PEEP up to 15 cmH₂O and FiO₂ up to 100% is required to manage patients with high elastic load and severe shunt that characterize potentially severe COVID-19 ARDS [1, 2].

Performances during controlled ventilation

Recent turbine transport and emergency ventilators display performances which are very close to conventional ICU ventilators [5, 17]. In the context of “mass casualty”, as experienced with the COVID-19 crisis, pneumatic transport ventilators could be used to extend the possibility to manage intubated patients in case of ICU beds shortage. The working principle of these pneumatic ventilators is based on a “Venturi system” which is a simple technological solution that permits to manage ventilation generated by the oxygen pressurized source when a position called air-O₂ mix is selected. Interestingly, the simplicity of such pneumatic systems permits to consider massive industrialization faster and at a lower cost. On the opposite, the Venturi system explains the limits observed with low inspiratory flow previously described with this technology [10].

For pneumatic ventilators, in case of high impedance, a low inspiratory flow may increase significantly volume error when the air-O₂ mix position is selected “on”. In turn, manipulating I:E ratio, respiratory rate and increasing inspiratory flow above 30 l/min permits to reverse the V_t error that is directly explained by the working principle of this ventilator (see Fig. 4). The technological adaptations available on Oxylog 3000 (Venturi coupled with proportional inspiratory valve) solve this problem, while expired V_t monitoring available on Osiris 3 simplifies settings adaptation if required. Previous bench test studies have reported a V_t error with pneumatic basic transport ventilators that reached 20% of set V_t with resistive load [10, 18]. These experiments were performed with very low set inspiratory flow thus explaining the V_t reduction observed. For clinical practice, when FiO₂ 70% is used on the Osiris 3, an essential recommendation is to follow these steps: first adjust the I:E ratio at 1:3 (i.e., the minimal available value) and the respiratory rate at 18/min or above. Secondly, the V_t knob that also controls the inspiratory flow must be adjusted to reach the desired V_t based on V_t expired monitoring. With these recommendations, volume error measured on pneumatic transport ventilators at low compliance is close from turbine performances and acceptable.

Of note, only the ICU and turbine ventilators tested compensate for the loss in V_t due to the compression of gas inside the circuit. Nevertheless, this effect previously quantified in ICU ventilators with inspiratory–expiratory circuits is significantly less in basic transport ventilators, since they are equipped with a single limb circuit [4]. Of note, an HEPA filter can be easily adjusted on the expiratory limb to limit risks of viral contamination.

Performances during assisted ventilation

Recent experience with COVID-19 induced ARDS reports that these patients often exhibit high respiratory drive and asynchrony that may require deep sedation and sometimes paralysis [7]. We, therefore, evaluated the behavior of the four transport ventilators during triggered breaths, especially pneumatic ones, since performances of their trigger have been questioned [5, 18]. The triggering performances were acceptable except for the Oxylog 3000 exhibiting the poorest triggering performances. The triggering delay was consistently longer in pneumatic ventilators but acceptable except on the Oxylog 3000, compared to the ICU ventilator [5].

Limitations

The results obtained in vitro necessitate some caution to be translated to the clinical practice, but previous studies showed that this type of simulation predicts the results observed in clinical situations with a high fidelity [4, 19, 20]. The lung model gives the unique opportunity to compare ventilator performances according to several simulated but standardized clinical conditions. Bench experiment also permits to accurately depict and understand advantages and limits of the different ventilator’s technologies as previously done [10]. The Michigan test lung (Michigan Instruments, Kentwood, MI, USA) used in the present study is a simple model that presents obvious limitations, but its reliability for V_t and trigger performances evaluation has been well demonstrated. Of note, the results have not been corrected in BTPS conditions, which may have slightly underestimated actual expired volumes [17]. Our experiment reported performances of only two pneumatic and two turbine ventilators, while several other ventilators with similar technology are available worldwide. We did not evaluate pressure support ventilation, while this approach can be useful to manage weaning of COVID-19 patients. Previous studies already showed that turbine-based ventilator significantly outperform pneumatic transport ventilators during pressure mode ventilation [5, 17].

Performances of pneumatic ventilators can be viewed as “acceptable” during the initial phase of respiratory failure. For patients with difficulties to be separated from

the ventilator, better performances may be expected for assisted ventilation.

Conclusion

The present bench study suggests that turbine technologies may acceptably replace ICU ventilators, at least transiently, to extend ICU beds, where only oxygen pressure supply is available, in special surge situations such as COVID-19 crisis. Pneumatic transport ventilators are limited in terms of FiO_2 settings, but provide acceptable volume accuracy in severe simulated conditions. For this purpose, the respiratory rate should be set at or above 18/min (to maintain sufficient inspiratory flow) in the Osi-ris 3 with a FiO_2 of 70% [21]. A monitoring of expired Vt available on the two pneumatic transport ventilators tested greatly facilitates adequate settings. Performances regarding triggering function are non-acceptable in one of the pneumatic transport ventilators.

Supplementary information

Supplementary information accompanies this paper at <https://doi.org/10.1186/s13613-020-00782-5>.

Additional file 1. Additional tables and figures.

Abbreviations

ACV: Assist-Control Ventilation; ARDS: Acute Respiratory Distress Syndrome; COVID-19: Coronavirus Disease 2019; C_{RS} : Compliance of the respiratory system; FiO_2 : Fraction of inspired oxygen; ICU: Intensive Care Unit; PEEP: Set Positive End-Expiratory Pressure; SARS-CoV-2: Severe Acute Respiratory Syndrome Coronavirus-2; VC: Volume control; Vt : Tidal volume.

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Authors' contributions

AL, JCR and AM contributed to the study conception and design. AL, JCR performed the experiments, the data collection and the initial data analysis. JCR, LB and AM prepared the first draft of the manuscript. All authors contributed to the data analysis and to the critical revision of the final manuscript. All authors read and approved the final manuscript.

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Competing interests

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