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Evaluation of ventilators used during transport of critically ill patients – a bench study

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Conflict of interest

Salah Boussen and Marc Gainnier declare that they have no competing interests. Pierre Michelet has done consultancy for Air Liquide Medical System with no financial interest.

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Evaluation of new generation ventilators used during transport of critically ill patients – a bench study

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ABSTRACT

The aim of this study was to evaluate the most recent transport ventilators operational capacities regarding volume delivery in controlled mode, trigger function and the quality of pressurization in pressure support mode **Methods:** Eight recent transport ventilators were included in a bench study in order to evaluate: 1) Their accuracy to deliver a set tidal volume (VT) under normal resistance and compliance conditions (A), ARDS conditions (B) and obstructive conditions (C). 2) The performance of the triggering system assessed by the measure of the decrease in pressure (ΔP, cmH20) and the time delay (Δt, ms) required to open the inspiratory valve. 3) The quality of pressurization obtained by computing the integral of the pressure-time curve for the first 300 and 500 milliseconds after the onset of inspiration. **Results:** For the targeted tidal volumes of 300, 500 and 800 ml, the errors ranged from -3% to 48%, -7% to 18%, -5% to 25% respectively in condition A, -4 % to 27%, -2% to 36%, -3% to 35% in ARDS condition B and (-4% to 53%), (-6% to 35%), (-30% to 28%) in obstructive condition C ($p<0.01$). In PSV mode, pressure drop was (0.5 to 1.7 cmH20), trigger delay (68 ms to 198 ms), pressurization capabilities PTP300 ranged from -12 to 44% and PTP500 from 5.5% to 66% of ideal pressurization ($p<0.01$). **Conclusion:** Differences in performances were important between the ventilators tested. The most recent turbine ventilators outperformed the pneumatic transport ventilators. The best performers among turbine ventilators proved comparable to modern ICU ventilators.

Keywords: mechanical ventilation; transport ventilator; bench study; ICU patient transport; pressure support ventilation, Inspiratory trigger, ventilator performances

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INTRODUCTION

Transport ventilators are designed to transport critically ill patients from the ICU to the radiology department, the operating room, from the point of care by the emergency team to the ICU or from one hospital location to another[1]. The manufacturers regularly update and upgrade their machines with improvements in technologies in response to feedback from users and published data as well as for commercial reasons. To our knowledge, few studies have been published which specifically evaluate transport ventilators. One such study published in 2002, compared five transport ventilators [2]. Chipman et al performed the most recent and largest on in 2007 [3]. This study evaluated 15 transport ventilators, most of which are sold on the American market. Some other studies looked at the performances of transport ventilators during patient triggered ventilation [4] or volume controlled mode[5]. At present, there are mainly two categories of transport ventilators available on the market: pneumatic ventilators and turbine ventilators. The first have a pneumatic driving force generated by compressed oxygen that power the ventilator to create pressure. Their performance is highly depends on the pressure in the oxygen tank. The second category of transport ventilators, more recently available to clinicians, is based on a different technology inspired by home-care ventilators. They use an electrically powered turbine to generate pressure.. Their performance, particularly those of the last generation, seems to be very similar to those of intensive care ventilators but is highly dependent on the internal battery life. Other than these two main categories, the compressor driven ventilator is a less frequent solution.

The purpose of this bench study was to evaluate the performance of transport ventilators recently placed on the market by comparing their performances with that of older ones.

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MATERIALS AND METHODS

Ventilators tested

We tested eight portable ventilators *Osiris 3* and *Monnal T60* (Air Liquide Medical System, France); *Oxylog 3000+* and *Carina* (Dräger Medical, Germany), *Elisée 350,* (Resmed France), *Medumat Transport* with CO_2 measure WM 28400, (Weinmann, Germany), *Hamilton C1* and *Hamilton T1 (*Hamilton Medical, Switzerland). The ventilators were provided by the manufacturers or loaned from another ICU. The main characteristics of the eight ventilators are listed in **Table 1**. The Hamilton C1 is a compact mid-level ICU ventilator. T1 is its transportable version. The Monnal T60 was still under development at the time of the test.

Three of the tested ventilators are pneumatic (Oxylog 3000+, Medumat, and Osiris 3) while all the others are turbine ventilators.

Set-up of the experiment

The experimental set-up, very similar to the one used in previous works [2], (**Fig. 1-a**) included the following elements:

- A dual-chamber test lung (TTL 1600, Michigan Instruments, Grand Rapids, USA).
- A Fleish 2 pneumotachograph attached to a differential pressure transducer (TSD 160 A ± 2.5 cmH_2O –Biopac, Biopac systems inc, USA) for measurement of airflow ($\dot{V}$);
- A side-port connected to a pressure transducer (TSD104 -50 to 300 cmH_2O, Biopac) for pressure (P) measurement.
- An oxygen paramagnetic sensor with a response time of about 10 s (OHMEDA 5120).

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- The ventilator to be tested.

Before each experiment, the Fleisch pneumotachograph and the pressure transducer were calibrated with an ICU ventilator (PB 840 - Puritan Bennett USA) operating in ATPD (ambient temperature and pressure dry) conditions. The flow transducer was calibrated at 0 and 0.25 l/sec at constant flow in Volume Controlled mode (VC). The calibration of the pneumotachograph was then checked by measuring a known volume administered through the pneumotachograph via a one-liter super syringe. The pressure transducer was calibrated with the PB840 in ZEEP and a 10 cmH_20 PEEP level. The calibration accuracy of the pressure transducer was checked by measuring a known pressure of 10 cmH20 with a water column.

During the experiments, the flow ($\dot{V}$) and pressure (P) signals were acquired with an analog digital converter (MP100; Biopac Systems, USA). The volume was obtained by integrating the flow signal. The acquisition frequency of all the signals was set at 200 Hz. All data were stored in a computer for subsequent analysis (Acqknowledge software; Biopac Systems).

Protocol

We tested all the ventilators in both static and dynamic conditions. FiO_2 was monitored throughout the experiment.

Static conditions

This situation corresponds to a passively ventilated patient.

The performances while delivering a set volume were assessed with the test lung connected to the ventilator tested (**Figure 1 a**) under three different conditions:

- Condition A: normal resistance with normal compliance (R 5 cmH_2O/l/sec and C 100 ml/cmH_2O)

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- Condition B mimicking ARDS (Acute Respiratory Distress Syndrome) with a high resistance and low compliance (R=20 $cmH_2O/l/sec$, and C =30 ml/cmH_2O)
- Condition C: mimicking an acute obstruction of the airways with a very high resistance and normal compliance (R=50 $cmH_2O/l/sec$ and C=100 ml/cmH_2O).

Very high, high and normal resistances were achieved with resistors (PneufloRp50, Rp20 and Rp5, Michigan Instruments, USA). By changing the position of the spring connected to the test lung the compliance of the model can be easily modified (Fig 1a). All ventilators were operated according to the manufacturer's instructions taking into account the circuit compliance correction algorithm when it was available.

Gas consumption and Battery life testing

For both gas consumption and battery life testing, the ventilators were set to deliver a VT of 500 ml with a PEEP of 5 cm H_20 and a respiratory frequency of 12 breaths per minute under condition A.

Gas consumption was defined as the time during which ventilators could operate with a FiO2 of 100 % delivered by a 5-liter oxygen cylinder pressurized to 200 bars (2900 psig, 1000 l of oxygen). The VT was recorded when the pressure in the oxygen cylinder was near 200 then 100 then lower than 50 bars (batteries with full load).

The battery life was defined as the time during which the ventilator can function with a full battery at a minimal FiO_2 adjustable on each ventilator in order to limit oxygen consumption.

We reported gas consumption, battery life and VT variation during cylinder and battery life.

Tidal volume delivery

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For five of the ventilators tidal volume is delivered with a constant flow during volume-controlled mode (VC). For the other three, the Carina and the Hamilton C1 and T1, the "volume controlled mode" is actually similar to a pressure-controlled mode with a target tidal volume (dual mode). For all the ventilators tested, the respiratory rate (f) was set at 20 breaths/min, and the inspiratory time (TI) was one second. All ventilators were operated at ZEEP or their minimal PEEP.

VTs of 300 ml, 500 ml, and 800 ml were set for each test condition and for each ventilator. The measured VT values were averaged over 40 breaths. Breath to breath variability in delivered tidal volumes for each individual ventilator were computed as the difference between two consecutives breaths (VT(T+1)-VT(T))/V(T).

A plateau time of 10% was applied if the setting was available on the ventilator.

Dynamic conditions

Spontaneous ventilation is a major issue during transport of a conscious or moderately sedated, mechanically ventilated patient within and between hospitals[6]. Hence, we also tested these ventilators in an experimental situation simulating spontaneous ventilation. These experiments were done to assess the trigger sensitivity of the inspiratory valves of each the ventilators and their ability to pressurize the respiratory system.

The experimental set-up is shown in Figure 1 b. We used the two chambers of the test lung. One chamber (driving lung) was connected to a PB840 ventilator (PuritanBennet USA). To ventilate the driving lung, this ventilator was set in volume-controlled mode with constant flow. The respiratory frequency was set at 12 breaths/min with a fixed inspiration time ratio (TI) of 20% of the total respiratory cycle. The second chamber (experimental lung) was connected to the ventilator under evaluation. Compliance values of 30 ml/cmH_2O and of 80 ml/cmH_2O were adjusted to the driving and experimental lungs. The lung-coupling clip of

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the model connected the two chambers. A positive pressure created in the driving lung induced a negative relative pressure in the experimental lung that triggered the ventilator in evaluation. Since compliance of the two lungs were different, it was necessary to apply PEEP to the driving lung to obtain a perfect contact of the metal insert between the two chambers at the end of expiration. The triggering systems of the different ventilators were set at their maximal sensitivity and were not changed throughout the entire experiment even in case of auto triggering.

Each ventilator was tested during pressure support ventilation (PSV) at two levels of pressure-support (10 and 15 cmH_2O), with and without 5 cmH_2O positive end-expiratory pressure (PEEP). Rising time and triggering sensitivity were set to the fastest time and most sensitive respectively. They were also evaluated at two levels of simulated inspiratory effort (normal and strong). To simulate different magnitudes of inspiratory effort, the tidal volume of the driving ventilator was set at 220 and 440 ml with a fixed inspiratory time of 1s (corresponding flows 0.22 l/sec and 0.44 l/sec respectively). The corresponding effort intensity was evaluated by the pressure drop ($P_{0.1}$) within the first 100 msec at the exit of the tested chamber. This $P_{0.1}$ was equal to 2 (normal effort) and 4 (strong effort) cmH_2O. $P_{0.1}$ is about 2 cmH_2O during normal effort by healthy persons and during full assistance [7], whereas a very strong effort by a patient with acute respiratory failure can generate $P_{0.1}$ values greater than 10 cmH_2O [7].

We measured both the reduction in pressure (ΔP, cmH2O) and the time delay (Δt, ms) required to open the inspiratory valve (**Figure 2-a**). The measurements were made at FiO2 of 60% in all ventilators except for Osiris 3 (100%).

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To assess pressurization performance, we also computed the pressure-time product (PTP, $cmH_2O.sec$). The PTP represent the total area under or above the base line pressure (ZEEP or PEEP) on the pressure time curve during the first 300 and 500 msec (PTP300 and PTP500) after the beginning of the inspiratory effort (**Figure 2-b**). The triggering phase represents only a part of the total inspiratory effort and is shorter than the pressurization phase. The PTP was expressed as a percentage of the ideal pressure time product. The ideal PTP can be calculated by the product of time (t = 0.3 sec or 0.5 sec) by the PSV level [8]. PTP500 is better to evaluate pressurization performance than PTP300, which is more influenced, by trigger performance.

Comparison between Gas powered and Turbine ventilators

We computed the average error for each VT in each test condition for gas powered or turbine ventilators. We then performed a statistical comparison between the two groups. To evaluate trigger performance, we computed the average PTP product in each condition (minimal and 5 cmH2O PEEP, strong and weak inspiratory effort) for both gas powered and turbine ventilators. Finally, we computed the average PTP300 and the PTP500 of each inspiratory effort for gas powered and turbine ventilators.

Statistical analysis

Each variable value represents the mean of values measured in a steady state. For VT measurements, we considered the mean of 40 consecutive breaths at the steady state. For dynamic measurements, each parameter represents the mean of 10 consecutives breaths at the steady state. All results were expressed as the mean with a 99% confidence interval. For comparative analysis we used a one-way analysis of variance on ranks (Kruskal Wallis test). A

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p value inferior to 0.05 was considered statistically significant. For our statistical analysis, we used SigmaStat software for Windows version 3.5 (SPSS, Chicago, Ill., USA).

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RESULTS

Gas Consumption and battery life

The results of gas consumption and battery life are summarized in table 2 for the eight ventilators tested.

Elisée 350 was tested with a single battery. It had an external battery with the same characteristics of the internal battery. For six ventilators we did not find any VT variation during the battery's or the oxygen tank's life. These ventilators seemed to stop before any malfunction occurred. The battery life of six of the ventilators lasted longer than the manufacturer's specification.

Gas consumption was homogenous and near the ideal gas consumption except for two pneumatic ventilators. The Medumat and OSIRIS III VT decreased with a low oxygen cylinder pressure.

Tidal volume delivery

The values of VT delivered by the ventilators in the three mechanical conditions for the three selected VTs are shown in **Figure 3**.

For target VTs of 300, 500, and 800 ml, the measured delivered VTs were:

- In condition A: VT ranged from 291 ml to 445 ml (relative error to targeted volume: -3% to 48%), 465 ml to 590ml (-7% to 18%), 762 ml to 1000 ml (-5 to 25%), respectively.
- In condition B: VT ranged from 287 ml to 382 ml (-4% to 27%), 491 ml to 673ml (-2% to 35%), 774 ml to 1080 ml (-3% to 35%) respectively.

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- In condition C: VT ranged from 289 ml to 460 ml (-4% to 53%), 469 ml to 650ml (-6% to 30%), 559 ml to 1021 ml (-30% to 28%) respectively.

In control condition A, five ventilators showed less than 10% error for each targeted volume (Oxylog 3000+, Carina, Elisée 350, Hamilton C1 and Monnal T60). Surprisingly, The Hamilton T1 was unable to deliver an accurate VT of 300 ml for the baseline condition A.

In ARDS condition B, only four ventilators showed a less than 10% average error in delivering the set VT (Carina, Osiris 3, Hamilton C1 and Monnal T60).

In obstructive condition C, five respirators showed a less than 10% average error in delivering the set VT (Oxylog 3000 +, Carina, Elisée 350, Hamilton C1 and T1 and Monnal T60). However, for 800 ml, the Carina and the Hamilton C1 failed to deliver the set VT due to the upper pressure limit.

The average breath to breath variability was less than 1% for all ventilators except MEDUMAT (**Figure 4**). However, it took approximately 10 breaths to obtain VT stabilization for the Carina, Hamilton T1 and C1

We did not find any significant FiO2 variation during these experiments even during high mechanical loads.

Dynamic measurements.

The Carina could not deliver ZEEP: It was operated at its minimal PEEP level for the first set of measurements. We measured a minimal PEEP level of $2.8 \pm 0.1 cmH_2O$ for a minimal PEEP setting of 3 cmH_2O.

We did not find any significant FiO2 variation during these experiments even during strong inspiratory efforts.

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The various indices of inspiratory effort required to open the demand valve of the portable ventilators are shown in **Figure 5**.

Inspiratory trigger

All turbine-based ventilators had a trigger delay of less than 120 ms (Carina, Elisée 350, Hamilton C1 and T1 and Monnal T60). For these ventilators we did not find significant variations in the trigger delay with different level of PEEP, regardless of the inspiratory effort.

Averaging all conditions, the mean trigger delay was between 68 and 198 msec, (median 111 msec).

Pressurization capacity

ΔP

The pressure drop ΔP required to open the inspiratory valve differed between the ventilators. The mean ΔP was 1.1 cmH_20 [0.4 to 1.7 cmH_20]. Five ventilators showed an average ΔP of less than 1.0 cmH_20 (Carina, Elisée 350, Hamilton C1 and T1, and Monnal T60).

PTP300 and PTP500

PTP300 and PTP500 values measured on both ZEEP or minimal (mPEEP) and PEEP for all studied ventilators according to a level of $P_{0.1}$ equal to 2 cmH_2O (normal effort) and to a 4 cmH_2O (strong effort) expressed as a percentage of the ideal time-pressure product is shown in **Figure 6**. At the two levels of PSV studied (10 and 15 cmH_2O), we found large differences in pressurization capacities between the ventilators tested.

The triggering phase represents only a part of the total inspiratory effort and is shorter than the pressurization phase. The PTP was expressed as a percentage of the ideal pressure time

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product. The ideal PTP (which can be calculated by the product of time(t equal to 0.3 sec or 0.5 sec) by the PSV level [8]. PTP500 is better to evaluate pressurization performance than PTP300 which is more influenced by trigger performance.

PTP300 ratio for normal effort ranged from -9 to 44 % and PTP500 ranged from 6 to 66 %.

PTP300 for strong effort ranged from -12 to 44 % and PTP500 ranged from 6 to 66 %.

Three ventilators failed to pressurize correctly in the first 0.3 s with a negative PTP300 in both conditions of effort (Oxylog 3000+, Medumat, and Osiris 3).

We noted that the PTP300 expressed as a percentage of ideal pressurization was always smaller than the PTP500. This was due to the initial triggering phase.

Comparison between Gas powered and Turbine ventilators

For each mechanical condition the turbine ventilators were significantly more accurate in delivering the set VT (**Figure 7**).

Considering trigger capabilities, turbine ventilators were significantly faster and more sensitive than gas powered ventilators. We reported in **Figure 8**, the PTP for the two groups.

We demonstrated a significant difference in PTP 300 and PTP 500 between the two groups.

We also found a significant difference between PTP 300 and PTP 500 in both groups of ventilators **(Figure 9).**

DISCUSSION

We used a lung model to test ventilators that can be used for transport. The main findings of this study are:

1-VT delivery was better achieved by turbine transport than pneumatic ventilators.

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2- The trigger system tests were comparable to ICU and home care ventilators for all turbine ventilators. All gas compressed ventilators trigger had poorer performance

3- We found heterogeneities among the ventilators tested. VT delivery, trigger function and quality of pressurization varied substantially during volume controlled and pressure support mode.

Tidal volume delivery

The VT was not perfectly delivered in baseline conditions for three ventilators (Hamilton T1, Medumat and Osiris 3). All the others showed less than 5 % average error in delivering the set VT. The case of the Hamilton T1 is different. This ventilator was unable to deliver an accurate VT of 300 ml in a low compliance and resistance although the manufacturer claims that it could be used for pediatric patients. The delivered VT was too high (430 ml instead of 300 ml). Pediatric patients have usually high compliance and need low VT (less than 300 ml).

With VT preset at 6 ml/kg of predicted body weight, 17% of volume error represents an error of 1 ml/kg [9]. Thus, errors may range from 1 to 3 ml/kg for VT in the ventilators tested. The clinical implication of this finding is unclear. In ARDS patients, for example, setting an accurate VT is crucial to avoid alveolar damage despite the data of the most recent studies on VT in ARDS did not find any difference between 7 and 10 ml/kg of VT in terms of mortality[10-12]. Clearly, transport ventilators are not designed or usually used to ventilate patients with ARDS for prolonged durations but rather for short transport times. However, delivered VT above 6 ml/kg could be deleterious in the acute phase of ARDS. Some of the ventilators tested in this study appear to be more accurate and could be used safely in patients where the control of VT is paramount. The turbine ventilator Elisée 350 did not

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deliver an accurate VT in the ARDS condition as tested in this study, with variations of VT > 10%. We do not have a clear explanation for this last finding. One reason could be the duration of the inspiratory pause, which could be too short. Consequently, the algorithm used the dynamic compliance to set the VT and not the static compliance. This finding is consistent with a previous study[9] which showed that when the user applied an inspiratory pause during the inspiratory phase, the VT was decreased in some ventilators.

In C (obstructive) pattern, only four ventilators (Elisée 350, Monnal T60, Hamilton T1 and Oxylog 3000+) could manage heavy mechanical load at VT equal to 800 ml and deliver an accurate VT. All the others showed errors (>10%) in VT delivery.

Two of the turbine ventilators showed dysfunctions for a specific range of test parameters (condition B for Elisée 350 and condition A at low volume for Hamilton T1). This suggests that there is some problem with the software. Apart from these specific dysfunctions, turbine ventilators are more accurate in VT delivery than pneumatic ventilators for each test condition.

Triggering system

The triggering performance was heterogeneous among the ventilators. The ventilators can be divided into two categories. The gas-powered ventilators had relatively long triggering time delay and poor pressure sensitivity. The turbine ventilators had a sensitive triggering system which is comparable in terms of performance with the ventilators designed for home care [8] and ICU use [13, 14]. The Monnal T60 showed autotriggering for the highest triggering sensitivity setting in a first study, but was corrected by the new software. A short triggering time (less than 100 ms) may be associated with a lower work of breathing[15], is below the conscious threshold of inspiratory effort [16]and may contribute to a

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better patient-ventilator synchrony[17-19]. We found that all turbine ventilators had a trigger time shorter than 100 ms, even with a weak effort.

Pressurization capacity

We found that airway pressure remained negative for more than 0.3 s for two ventilators (Medumat and Oxylog 3000+), during which the ventilator did not unload the patient's inspiratory effort. Such delay could increase patient work of breathing in a clinical situation.

If we consider the percentage of ideal pressurization, we did not show any dependence of the PTP300 and PTP500 on pressure support level, PEEP nor the inspiratory effort.

All turbine ventilators unloaded the simulated patient quite quickly and with an adequate level of pressure.

A previous study [20] showed that ICU turbine ventilators were no better than gas powered ones in PSV mode. Our evaluation of transport ventilators, did not reach the same conclusion. Clearly, for triggering and pressurization capabilities, the latest generation of turbine powered transport ventilators outperformed the gas-compressed powered models.

Synthesis

We can divide the ventilators tested in three categories. The first one includes the Carina, the Elisée 350, the Hamilton C1 and T1 and the Monnal T60. These ventilators have good performances both in static and dynamic tests. The second category includes the Osiris 3, and the Medumat. These ventilators have poorer test results both in static and dynamic tests. The third category which includes only the Oxylog 3000+ which has good

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performances in static tests but poor results in dynamic conditions. Oxylog 3000+, Osiris 3 and Medumat are gas powered ventilators.

Comparisons between powered gas and turbine ventilators with regard to VT accuracy, triggering and pressurization capabilities show a significant superiority of turbine ventilators.

These results suggest that turbine technology is a breakthrough in transport ventilators allowing for better performance.

Almost all of the turbine ventilators have improved their battery life. Advances in battery life and their miniaturization allow for the use of turbine ventilators for long-term transport.

Comparison with other studies

In comparison with ICU ventilators [2,9] some of the transport turbine ventilators and the Oxylog 3000 performed as well as modern ICU ventilators in VC mode. Monnal T60 has the same level of performance than the most efficient ICU ventilators as reported in other studies[9]. Many transport ventilators outperform the home care ventilators in VT accuracy[21]. However, the remaining ventilators did not perform as well (high airway resistance for almost all of them, ARDS with high airway resistance for Elisée 350). One should be aware of these limitations when using this category of ventilators. By comparison with older transport ventilators[2].[22], we note a substantial improvement in controlled volume modes in terms of accurcy.

In PSV mode, comparisons with ICU or anesthesia ventilators [2], [13], [23], [14], home care ventilators [8], [24] mid level ICU ventilators [25] and older generation transport ventilators[2] show that all the turbine ventilators tested in this study display comparable performances to ICU

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ventilators. In dynamic conditions, several ventilators are comparable to ICU or home care ventilators and display better performance than older generation ICU ventilators. On the other hand, the most recent pneumatic transport ventilators behave like prior generations, suggesting that we may have reached a limit in this technology.

Limitations

The limitations of such bench studies are discussed in other works. The main one is that the study is performed on a bench test rather than patients. Comfort of the patient and gas exchanges are particularly important and this is not tested by the bench study. The choice of transport ventilators depends on several other parameters such as the different modes available, the possibility of monitoring End tidal CO_2, ergonomics, and the quality of graphics [26]. However, bench studies are important to assess the mechanical performance of ventilators before clinical use on patients. Another limitation is that the durability of these ventilators is not tested in the long run. This problem is a particularly important issue for pre-hospital care where repeated mechanical shocks could damage all devices. Finally, our study does not describe well the auto-triggering phenomenon. Indeed, some ventilators show auto triggering in the triggered modes. We are not able to identify whether this unstable behavior is real or if it is an artifact due to the rebound of the tested lung on the small metallic coupling clip linking the two lungs.

CONCLUSION

In conclusion, the performance of transport ventilators is heterogeneous in VT delivery and during spontaneous ventilation. Some of the transport ventilators tested, particularly turbine ventilators, show good performance comparable to those of ICU ventilators

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suggesting that they could improve the safety of the critically ill patients during transport. These results suggest that turbine powered transport ventilators allow for better performance. Other studies should be performed in order to show the real clinical benefits in patients and to assess the ergonomics of these devices.

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TABLE TITLES

Table 1*:* Characteristics of the tested ventilators (NA not available, weight between brackets the weight with the second battery, for the Carina the trolley).

Table 2*:* Battery life for the ventilator tested (* Elisée 350 was tested with a single internal battery). We also report the relative volume change during the life of a 200 bar oxygen tank and during the battery life.

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FIGURE TITLES

Figure 1: The experimental apparatus: **a** the static experiment, **b** the dynamic experiment. Note the coupling between the two lungs with a small metallic insert.

Figure 2: Schematic drawing of the assessment of the performance of the ventilator triggering systems. ΔP (cm H2O) and ΔT (ms) are the changes in pressure and time delay, respectively, required to open the inspiratory valve. b) PTP300 and PTP500 signals are the net area under the pressure curve for the first 300 ms and 500 ms respectively. The measured PEEP is subtracted before integration of the pressure-time curve.

Figure 3: Mean values of tidal volumes (VT) delivered from the ventilators during three mechanical conditions: A (*black rectangles*), B (*white rectangles*), and C (*hatched rectangles*). The set VTs were 300 ml, 500 ml and 800 ml as indicated by the horizontal lines. * P <0.05 versus control mechanical condition A. *Horizontal bars* are errors when greater than *rectangles.*

Figure 4: VT breath to breath variability after averaging all mechanical conditions. *Horizontal bars* are error when greater than *rectangles.*

Figure 5: Performance of the triggering systems of the seven ventilators assessed with normal inspiratory effort with the minimal PEEP or ZEEP (*black rectangles*) and PEEP 5 (*white*

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rectangles) in a normal inspiratory effort and with a strong inspiratory effort with minimal PEEP or ZEEP (*grey rectangles*) and PEEP 5 (*hatched rectangles*).. *Horizontal bars* are errors.

Figure 6: Pressure–time products at 300 and 500 ms expressed as a percentage of the ideal pressurization for each respiratory cycle (PTP300 and PTP500), computed as the area under the time–pressure curve 300 ms and 500 ms after the onset of inspiratory effort, with normal inspiratory effort ($P_{0.1}$ = 2 cmH2O) with the minimal positive end-expiratory pressure and positive end-expiratory pressure 5 cmH2O for the two pressure support ventilation (PSV) levels: 10 and 15 cmH2O, (*black rectangle*: PTP300 for normal inspiratory effort, *grey*: PTP300 for strong inspiratory effort, *white rectangle*: PTP500 for normal inspiratory effort, *hatched*: PTP500 for strong inspiratory effort) , *Comparison pairwise for all ventilators are significant with P* < 0.05, *Horizontal bars* are errors.

Figure 7: Comparison of relative errors averaged for all VT in the three mechanical conditions (C, B, A) between gas powered and turbine ventilators. The line represents the median and boxes the 25th ('and' or 'to') 95th percentile. * P<0.05 gas powered vs turbine ventilators. ° p <0.05 vs mechanical condition A. *Horizontal bars are errors*.

Figure 8: Comparison between averaged PTP products in gas powered and turbine ventilators. The line is the median and boxes the 25th-95th percentile. * P<0.05 gas powered vs turbine ventilators. *Horizontal bars are errors*.

Figure 9: Comparison between pressurization capabilities. W averaged PTP 300 and PTP 500 for gas powered and turbine ventilators. Line is median and boxes 25th-95th percentile. *

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P<0.05 gas powered vs turbine ventilators. ° P<0.05, PTP 300 vs PTP 500 *Horizontal bars are errors*.

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	OXYLOG 3000+	MEDUMAT	OSIRIS 3	CARINA	ELISEE 350	HAMILTON C1	HAMILTON T1	MONNAL T60
Weight (kg)	5.8	4,4 (4,6)	5	5.5 (11.5)	4,5	4,9	6.5	3,7 (4,0)
Dimension (cmxcmxcm)	29 x 18.4 x 17.5	34.5 x 16.3 x 14.9	25x 21 x 17	17.5 x 27.5 x 38.5	26 x 24 x 13	24 x 31 x 24	21 x 30 x 26.5	29 x 25 x 11
VT (ml)	50-2000	50-2000	100-2000	100-2000	20-2500	20-2000	20-2000	100-2000
Rate (breaths/min)	2-60	0-60	6-40	5-50	2-50	4-80	5-80	5-40
PEEP (cm H_20)	0-20	0-30	0-15	3-20	0-25	0-35	0-35	0-20
Peak inspiratory pressure limit (cmH2O)	PEEP +3 to +55	60	80	5-50	3-60	60	60	70
FiO2 (%)	40-100	40-100	60 or 100	21-100	21-100	21-100	21-100	21-100
Battery Life (hour)	4	4,5	6 to 14	1 (internal) 9(external)	>3 (internal) >3 (external)	2	5,5	5=2,5+2,5
Pressure generating devices	Compressed Gas	Compressed Gas	Compressed Gas	Turbine	Turbine	Turbine	Turbine	Turbine
Graphics	YES	YES	NA	YES	YES	YES	YES	YES
Pressure Support Ventilation	YES	YES	YES	YES	YES	YES	YES	YES
Capnogramme	YES	YES	NA	NA	NA	YES	YES	YES

Table 1*:* Characteristics of the tested ventilators (NA not available, weight between brackets the weight with the second battery, for the Carina the trolley).

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	BATTERY LIFE	GAS CONSUMPTION	VT CHANGE DURING BATTERY LIFE	VT CHANGE DURING GAS TANK DURATION
OXYLOG 3000	7h25	3h00	<1%	<1%
MEDUMAT	6h15	1h30	5%	20%
OSIRIS III	6h35	2h15	<10%	25%
CARINA	1h20	2h45	<1%	<1%
ELYSEE 350	5h45 (*)	2h45	<1%	<1%
HAMILTON T1	6h10	2h20	<1%	<1%
HAMILTON C1	2h30	2h25	<1%	<1%
MONNAL T60	6h	2h20	<1%	<1%

Table 2*:* Battery life for the ventilator tested (* Elisée 350 was tested with a single internal battery). We also report the relative volume change during the life of a 200 bar (1900 psig) oxygen tank and during the battery life.

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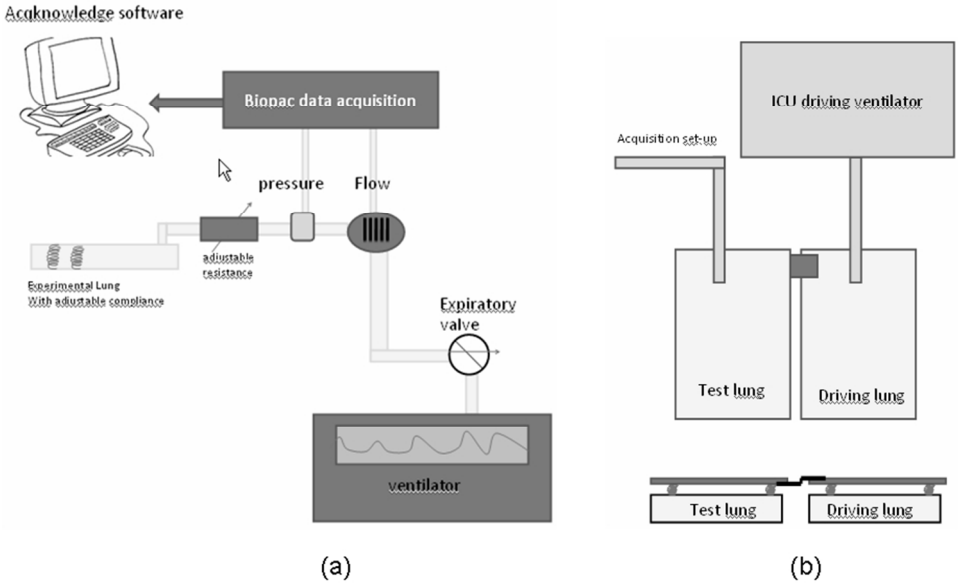

Figure 1: The experimental apparatus: a the static experiment, b the dynamic experiment. Note the coupling between the two lungs with a small metallic insert.

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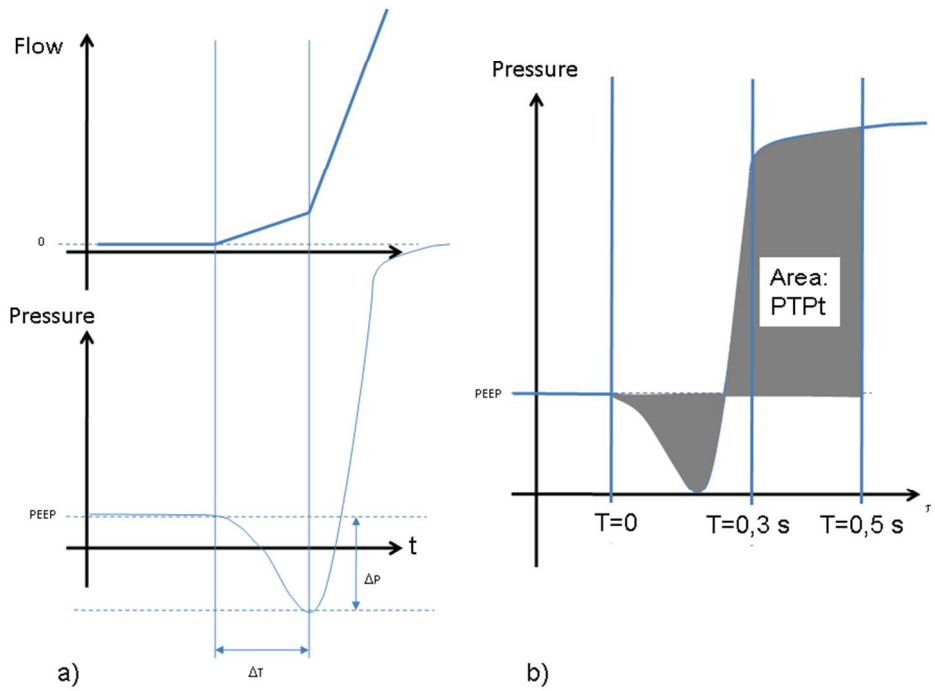

Figure 2: Schematic drawing of the assessment of the performance of the ventilator triggering systems. ΔP (cm H2O) and ΔT (ms) are the changes in pressure and time delay, respectively, required to open the inspiratory valve. b) PTP300 and PTP500 signals are the net area under the pressure curve for the first 300 ms and 500 ms respectively. The measured PEEP is subtracted before integration of the pressure-time curve.
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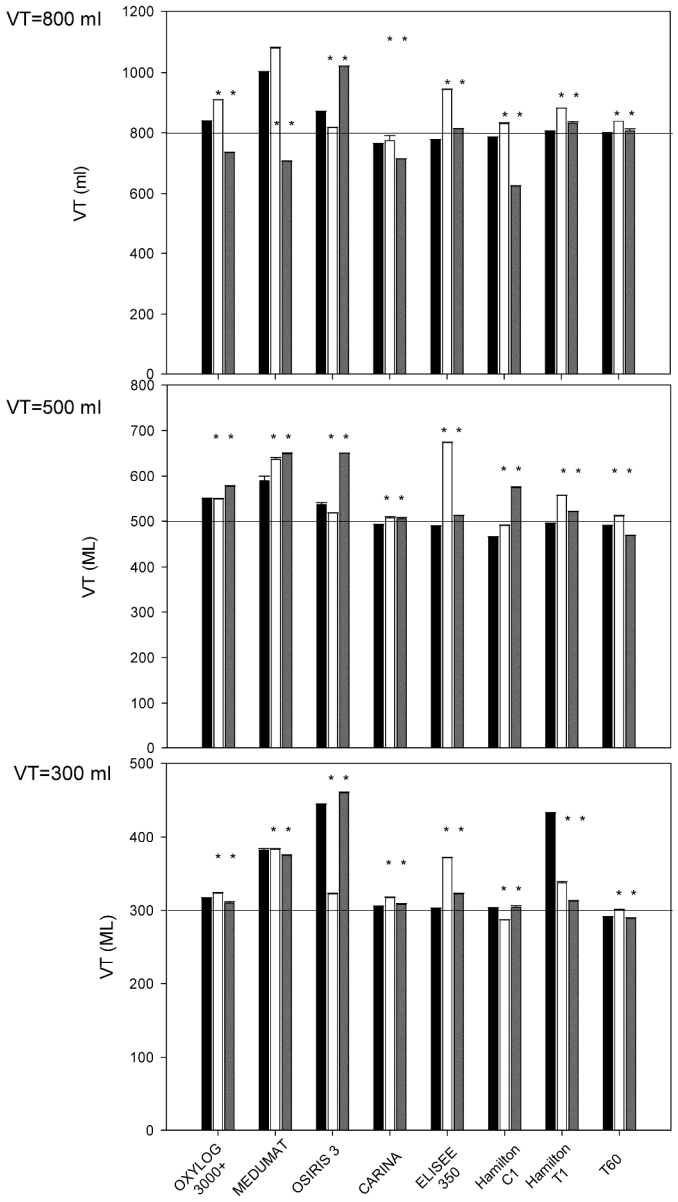

Figure 3: Mean values of tidal volumes (VT) delivered from the ventilators during three mechanical conditions: A (black rectangles), B (white rectangles), and C (hatched rectangles). The set VTs were 300 ml , 500 ml and 800 ml as indicated by the horizontal lines. * P <0.05 versus control mechanical condition A. . Horizontal bars are errors when greater than rectangles.
297x422mm (300 x 300 DPI)

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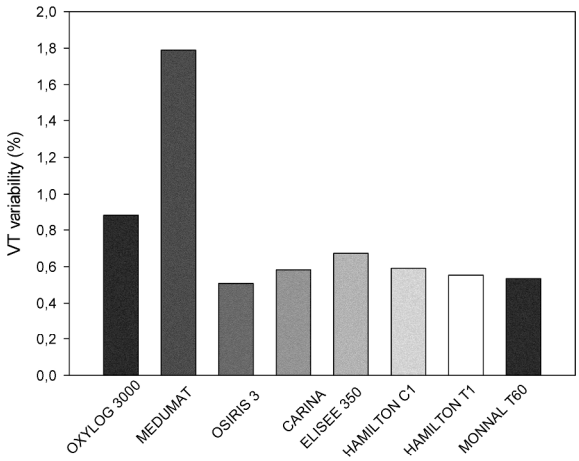

Figure 4: VT breath to breath variabilty after averaging all mechanical conditions.Horizontal bars are error when greater than rectangles.
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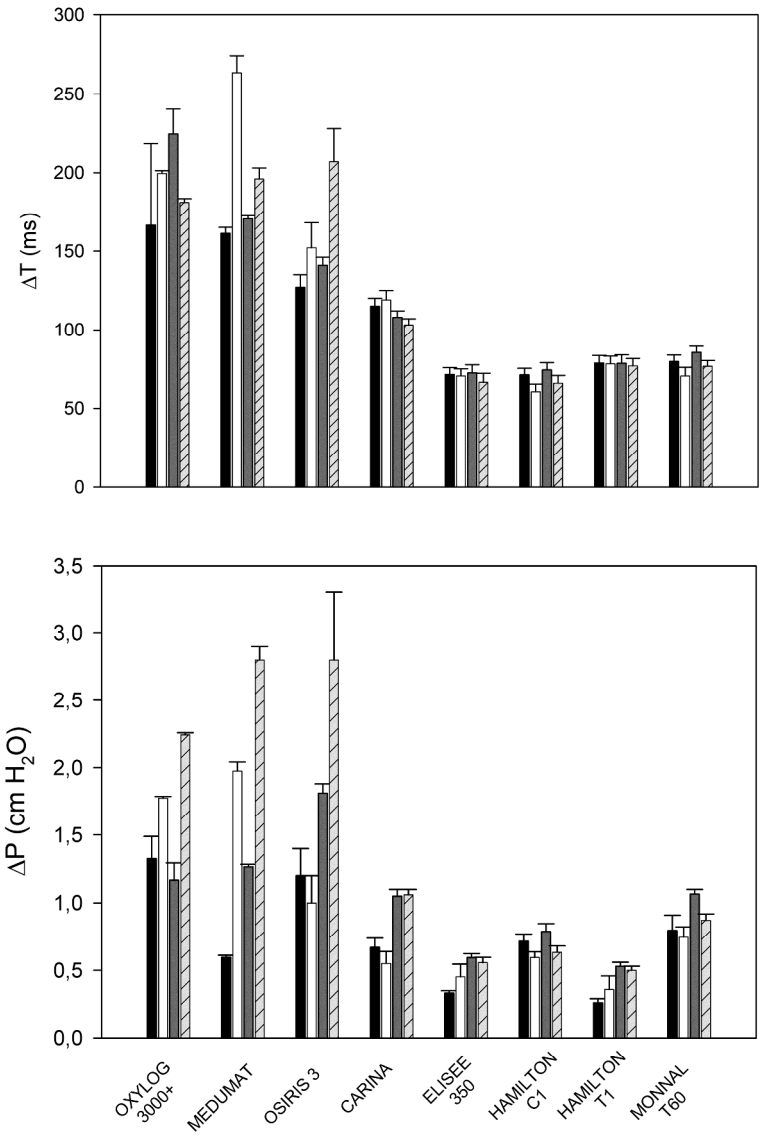

Figure 5: Performance of the triggering systems of the seven ventilators assessed with normal inspiratory effort with the minimal PEEP or ZEEP (black rectangles) and PEEP 5 (white rectangles) in a normal insipiratory effort and with a strong inspiratory effort with minimal PEEP or ZEEP(grey rectangles) and PEEP 5 (hatched rectangles).. Horizontal bars are errors.
296x420mm (300 x 300 DPI)

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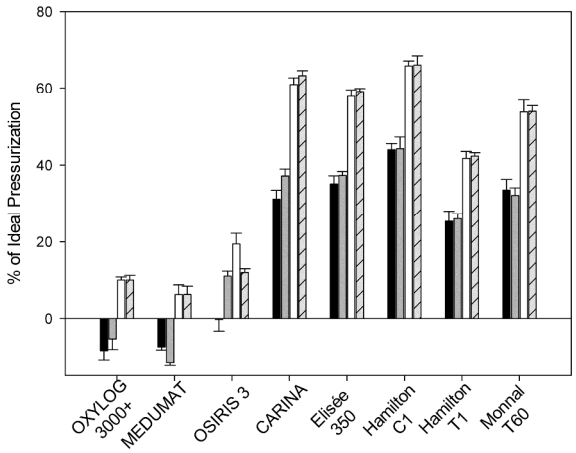

Figure 6: Pressure–time products at 300 and 500 ms expressed as a percentage of the ideal pressurization for each respiratory cycle (PTP300 and PTP500), computed as the area under the time–pressure curve 300 ms and 500 ms after the onset of inspiratory effort, with normal inspiratory effort (P0.1 = 2 cmH2O) with the minimal positive end-expiratory pressure and positive end-expiratory pressure 5 cmH2O for the two pressure support ventilation (PSV) levels: 10 and 15,cmH2O, (black rectangle: PTP300 for normal inspiratory effort, grey: PTP300 for strong inspiratory effort, white rectangle: PTP500 for normal inspiratory effort, hatched: PTP500 for strong inspiratory effort) , Comparison pairwise for all ventilators are significant with P < 0.05, Horizontal bars are errors.
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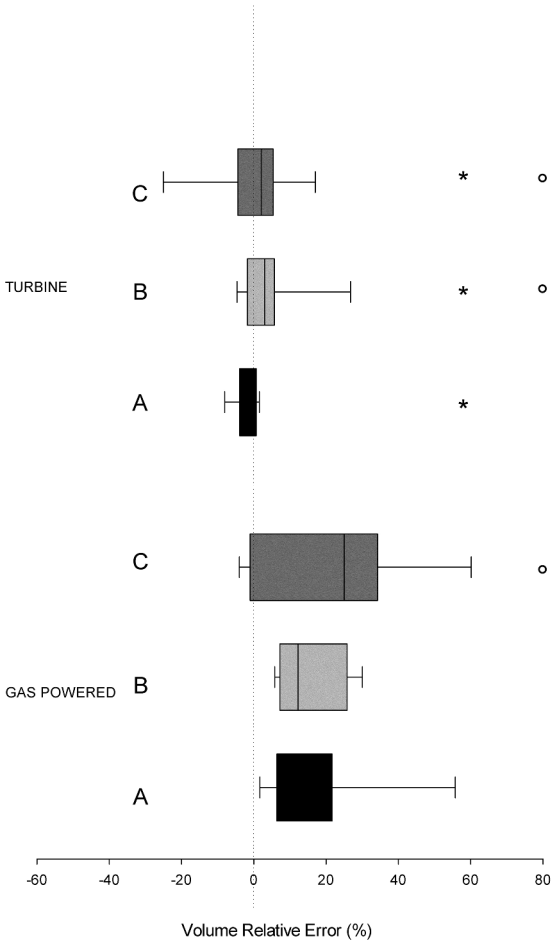

Figure 7: Comparison of relative errors averaged for all VT in the three mechanical conditions (A, B, C) between gas powered and turbine ventilators. The line represents the median and boxes the 25th ('and' or 'to')95th percentile. * P<0.05 gas powered vs turbine ventilators. ° p<0.05 vs mechanical condition A. Horizontal bars are errors.
296x420mm (300 x 300 DPI)

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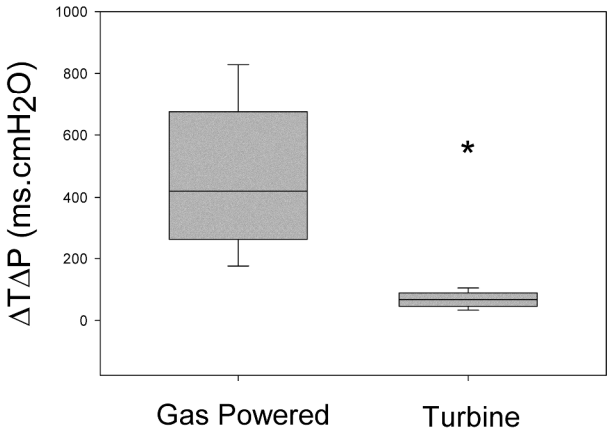

Figure 8: Comparison between averaged PTP products in gas powered and turbine ventilators. The line is the median and boxes the 25th-95th percentile. * P<0.05 gas powered vs turbine ventilators. Horizontal bars are errors.
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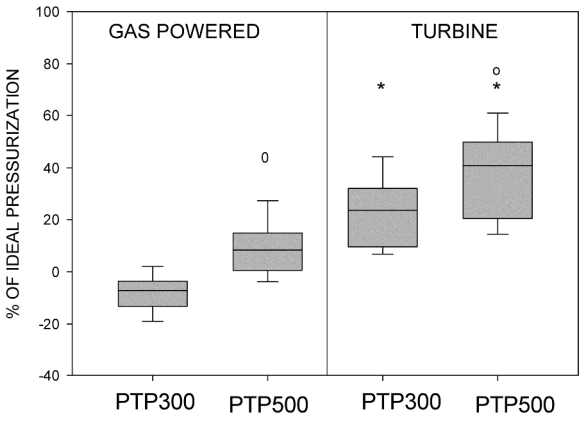

Figure 9: Comparison between pressurization capabilites. W averaged PTP 300 and PTP 500 for gas powered and turbine ventilators. Line is median and boxes 25th-95th percentile. * P<0.05 gas powered vs turbine ventilators. ° P<0.05, PTP 300 vs PTP 500 Horizontal bars are errors.
296x420mm (300 x 300 DPI)