Tidal volume delivery from ICU ventilators in BTPS condition. A bench study.

Paul Duchateau, Claude Guérin, MD, PhD

Service de Réanimation médicale, Hôpital de la Croix Rousse, Hospices Civils de Lyon,

Lyon, France and Université de Lyon, Lyon, France

Paul Duchateau is a scholar of the Haute Etude d'Ingénieurs, Lille, France

Paul Duchateau has no conflict of interest to declare

Claude Guérin has no conflict of interest to declare

Address of corresponding author:

Claude GUERIN, Service de Réanimation Médicale, Hôpital de la Croix Rousse, 103 Grande

Rue de la Croix Rousse, 69004 Lyon, France

Phone 33(0)4 26 10 94 18

Fax 33(0)4 72 07 17 74

Email claude.guerin@chu-lyon.fr

Abstract

Background. We measured tidal volume (VT) delivered from ICU ventilators after adding an external filter to the expiratory limb of the breathing circuit. This latter may protect the expiratory valve from water saturation in case of nebulisation and the environnement in case of lung infection with multi-drug-resistant micro-organisms or H1N1 influenza, even though it is not a common practice.

Methods. Six ICU ventilators, two with built-in expiratory filter (Avea, PB 840) and 4 without (Engström, Evita XL, Evita V500, Servo-i) set in volume controlled mode, BTPS condition with a heated humidifier on, were connected to a lung model (compliance 16 ml.cmH₂O⁻¹ and resistance 20 cm H₂O.L⁻¹.s) placed inside a neonatal incubator. The temperature was targeted at 37°C for both heated humidifier and incubator. The set-up was run continuously for 24 hours. In the four last ICU ventilators, Hygrobac or Sterivent S external filter was placed upstream the expiratory valve for an additional 24-hour period for each. At the end of this period, VT was measured at four nominal VTs (300, 400, 500 and 800 ml) by using Fleish 4 pneumotachograph. The volume error computed from the ratio of set to measured VT (% set VT) was the primary end-point.

Results. In present warm and wet conditions, volume error averaged 96±3% for Avea, 100±7% for PB 840, 90±2% for Evita XL, 100±7% for Evita V500, 105±2% for Servo-i, and 108±4% for Engström (P<.0001). With Hygrobac, the values were 93±1% for Evita XL, 94±4% for Evita V500, 110±4% for Servo-i, and 99±2% for Engström, (P<.0001). With Sterivent, the corresponding values were 95±2%, 105±2%, 112±5%, and 98±2%, respectively (P<.0001).

Conclusions. In BTPS condition, volume error differed substantially across ICU ventilators for VT delivery with further significant changes occurring after adjunction of filter at the distal expiratory limb.

Introduction

During invasive mechanical ventilation in the ICU, a filter may be placed at the distal end of the expiratory limb of the ventilator circuit upstream the expiratory valve, whilst heated humidifier is working on, for two purposes. The first is to protect the expiratory valve from humidity in case of nebulisation of medication at the inspiratory limb¹⁻³. A recent survey in ICUs in France, Switzerland and Belgium has shown that 2/3 of the intensivists would use a filter at the expiratory limb of the circuit during nebulisation⁴. The second is to protect the environment and the healthcare providers from two risks: that of airborne contamination in case of lung infection due to multi-drug resistant micro-organism, like *Mycobacterium tuberculosis*^{5,6}, or of H1N1 influenza⁷, and that of toxicity of medication like Ribavirin or Pentamidin⁸ administered by using nebulizer. Under these circumstances, filter may become waterlogged while heated humidifier is running at the ventilator. However, in those ventilator circuits equipped with internal wire heating the expiratory limb, this risk should be minimized. Some ICU ventilators, as Avea™ (Carefusion, CA, USA) and PB 840™ Ventilator (Covidien, MA, USA), have such a built-in exhalation reusable filter encompassing expiratory valve designed to work for a long period of time without the risk for water saturation. Indeed, the filter, which is maintained at an elevated temperature, maximizes the vapor phase of the exhaled humidity and reduces the condensate from the gas.

We wanted to assess whether in BTPS condition, i.e. warmed to 37°C and fully saturated with water vapour by using a heated humidifier switched on, the adjunction of filter at the expiratory limb end would result in impairment in ventilator functioning. We raised three specific questions. First, does the filter resistance (Rf) increase after 24 hours of heated humidification working-up? Second, if present, was this increase, different between the two categories of filters, namely built-in or external? Third, could the delivery of tidal volume

(VT) be impaired from this situation? Impairment in VT delivery from the ventilator might occur if the ventilator algorithm that maintain VT constant irrespective of change in humidity, temperature and ventilatory circuit compliance, is challenged by the new physical environment. Our hypothesis for the first two questions was that Rf would increase with humidification and that the magnitude of this would be higher with external than with built-in filters. Our hypothesis for the third question was that VT delivery was impaired to a greater extent with external than with built-in filters. Therefore, we investigated these questions on the bench.

Material and methods

Experimental set-up

We implemented the following set-up to replicate the hygrometric conditions of clinical practice as close as possible. Six ICU ventilators were tested: Avea™ (Carefusion), PB 840™ Ventilator (Covidien), Engström Carestation™ (GE Healthcare), Servo-i™ (Maquet), Evita XL™ (Dräger) and V500™ (Dräger). They were provided with and fully checked by the manufacturers before present investigation.

The following external filters were used: hydrophobic Sterivent S® filter and hygroscopic/hydrophobic Hygrobac® filter/HME (Mallinckrodt DAR, Mirandola, Italy and released by Tyco Health care). With both filters, the bacterial/viral filtration efficiency is greater than 99.999%. The filtration is mechanical with the former and electrostatic with the latter. The pressure drop at 1 L.s⁻¹ flow (V') given by the manufacturer for each filter is 1.9 and 2.1 cmH₂O, respectively. For the disposable filters designed for use with PB840 and Avea, the bacterial/viral filtration efficiency is greater than 99.999% and the pressure drop less than 2.5 cm H₂O and of 4 cm H₂O at 1.7 L.s⁻¹ V', respectively.

Specifications regarding ICU ventilators and filters provided by the manufacturers are shown in table 1.

The present ICU ventilators were equipped with a double heater-wire hot water circuit (RT 200 dual heated circuit with MR290, Fisher and Paykel Auckland, New Zealand) and a heated humidifier (MR 850, Fisher Peyckell, Auckland, New Zealand). ICU ventilator was attached to a lung model (Test Lung 190, Maquet, Solna, Sweden) whose compliance was $16 \text{ ml.cmH}_2\text{O}^{-1}$ and resistance $20 \text{ cm H}_2\text{O.L}^{-1}.\text{s}$. The lung model was placed vertically in a neonatal incubator (ISIS MP4, Mediprema, Tours, France) (figure 1) during some parts of the experiment (see below). Both lung model and incubator were tightly linked to avoid any leak (figure 1).

V' was measured by using a pneumotachograph (Fleish 4, Lausanne, Switzerland) which was linear over $\pm 10 \text{ L.s}^{-1}$ V' range. V' ports were connected to piezoresistive transducers (BD Gabarith™, Vogt Medical Vertrieb GmbH, Karlsruhe, Germany). Pressure at the airway opening (P_{ao}) was measured by using a straight connector (VBM Medizintechnik GmbH, Sulz a. N., Germany). The signals were amplified, sent to analog-digital hardware (Biopac MP150, BIOPAC Systems, Inc., Goleta, USA), and recorded at 400 Hz (Acqknowledge®, BIOPAC Systems, Inc., Goleta, USA).

Protocol

The piezoresistive transducers were calibrated before the measurements were taken, using rotameter flow meter (Martin Médical, Lyon, France) for V' and manometer (717 1G pressure calibrator, Fluke Biomedical, WA, USA) for P_{ao} . The protocol was deciphered as follows (table 2).

First step: assessment of filter airflow resistance in ATPD condition (dry gas at ambient temperature and pressure). Each built-in or external filter was attached at the Y piece of a ventilatory circuit (Breathing circuit, Mallinckrodt DAR, Mirandola, Italy and Tyco Health care) connected to a ventilator (Xtend™, Taema, France). V' was varied from 0.2 to 2 L.s^{-1} by steps of 0.2 L.s^{-1} while V' and P_{ao} signals were recorded.

Second step: measurement of delivered VT and comparison with set VT in

ATPD condition with ventilator set in BTPS. After complete check-up, the ICU ventilator under investigation was set in BTPS. Four nominal values of set VT were defined as 300, 400, 500 and 800 ml. Each nominal VT was applied for 1 minute while V' and Pao signals were recorded.

Third step: measurement of delivered VT and comparison with set VT in BTPS

condition (gas at 37°C and fully saturated with water vapor) maintained during 24 hours without external filter. The ICU ventilator set in BTPS was connected to the incubator, with both heated humidifier and incubator switched on, and 37°C temperature targeted. Heated humidifier was filled by 500 ml sterile water vial, after we had verified that this amount supplied the chamber for 24 hours. Once the targeted temperature was reached, the set-up was run for 24 consecutive hours. A probe was inserted every six hours into the incubator to check for temperature allowing to maintain it at the desired level. At the end of this period, the measurement set-up was attached. VT was changed to 300, 400, 500 and 800 ml for 1 minute each with heated humidifier working on while V' and Pao signals were recorded.

Fourth step: measurement of delivered VT and comparison with set VT in BTPS

condition maintained during 24 hours with external filter added. For the four ventilators with no built-in expiratory filter (Engström Carestation, Evita XL, Evita V500 and Servo-i), external filters were inserted at ventilatory circuit expiratory end, upstream expiratory valve. Each filter was applied in a random order and the set-up ran for 24 hours. At the end of each 24-hour period, VT was changed to 300, 400, 500 and 800 ml for 1 minute each with heated humidifier working on while V' and Pao signals were recorded.

Fifth step: measurement of Rf in BTPS condition. At the end of each 24-hour running out period, built-in reusable filters and external filters were removed from the set-up and attached at the Y piece of a ventilatory circuit (Breathing circuit, Mallinckrodt DAR,

Mirandola, Italy and Tyco Health care) connected to a ventilator (Xtend™, Taema, France).

$\dot{V}'$ was varied from 0.2 to 2 L.s⁻¹ by steps of 0.2 L.s⁻¹ while $\dot{V}'$ and Pao signals were recorded.

Data analysis

Pao and $\dot{V}'$ were fitted to the following equation:

$$\Delta P = K_1 \dot{V}' + K_2 \dot{V}'^2 \quad (1)$$

where ΔP was the pressure difference across the filter. Rf was obtained as:

$$Rf = \Delta P / \dot{V}' = K_1 + K_2 \dot{V}' \quad (2)$$

Inspiratory VT was obtained by numerical integration of the $\dot{V}'$ signal. VT was measured in the three last consecutive breaths.

Statistical analysis

The primary end-point was the ratio of set to measured VT (expressed as % set VT) and named volume error. For the statistical analysis, we used ANOVA to compare the volume error between ventilators in BTPS condition without external filter at each level of nominal VT. We also compared the difference in volume error between absence and presence of external filter across the ventilators at each level of nominal VT and kind of external filter. When the overall effect was statistically significant we performed post-hoc pairwise comparisons to Avea or PB 840 ventilator as taken as control by using Dunnett test where an overall statistically significant effect of ventilator was found. The difference in volume error between absence and presence of external filter was negative if volume error was greater with than without external filter for Evita XL, Evita V500, Engström and Servo-i. This difference was equal to zero for Avea and PB 840. Therefore, comparing volume error for Evita XL, Evita V500, Engström and Servo-i to Avea or PB 840 as control pertained to comparing volume error to zero.

The difference in volume error between ATPD and BTPS conditions for each ventilator set in BTPS was tested by using paired t tests at each nominal VT. Bonferroni correction was applied.

The constants K_1 and K_2 were obtained by using linear regression.

The values were expressed as mean $\pm$ 1 SD unless otherwise stated. The statistical analysis was carried out using SPSS software version 17.0. $P<.05$ was set as the threshold for statistical significance.

Results

Resistance of filters

Under ATPD condition both external filters exhibited similar ΔP -V' relationships and higher R_f than built-in filters (figure 2). The coefficient of determination was greater than 0.98 in all instances ($P<.001$). Under BTPS condition, R_f became greater for Sterivent[®] than Hygrobac[®]. In BTPS condition, R_f increased for PB 840 and did not change for Avea so that R_f of both built-in filters were similar and markedly lower than R_f of external filters (figure 2). R_f computed at 1 L.s⁻¹ from constants K_1 and K_2 (figure 2) were 0.56 and 0.66 for Avea, 0.43 and 0.77 for PB 840, 1.57 and 1.71 for Hygrobac[®] and 1.64 and 2.53 cmH₂O.L⁻¹.s for Sterivent[®] in ATPD and BTPS conditions, respectively.

Volume error under BTPS condition without external filter

After 24 hours working at 37°C, there was a significant effect of the ventilator, the set VT and their interaction on volume error (figure 3). Volume error was within 10% limits of set VT in all instances but the following exceptions: Evita XL at VT 300 and 400 ml, PB 840 at VT 800 ml, and Servo-i at VT 300 ml. Volume error ranged from 86 to 113% across all VT for all ventilators. It averaged 96 $\pm$ 3% for Avea, 100 $\pm$ 7% for PB 840, 90 $\pm$ 2% for Evita XL, 100 $\pm$ 7% for Evita V500, 108 $\pm$ 4% for Engström, 105 $\pm$ 2% and for Servo-i ($P<.0001$). At each

nominal VT, volume error was statistically significantly different from each control (figure 3). In all ventilators but Evita XL, volume error decreased with increased nominal set VT.

Effect of external filter on volume error

With external filter, volume error further changed from the baseline (without external filter) (figure 4). Except for Evita XL at 800 ml, all differences were significantly different from zero, and henceforth from Avea or PB 840 (figure 4). There was a negative difference in volume error, ie volume error increased between without and with external filter conditions, with Evita XL and Evita V500 while the difference was positive with the two others. Adding external filter shifted volume error with Evita XL towards 100% (figures 3 and 4) and largely above 100% (above 120% at VT 300 ml) with Evita V500 (figures 3 and 4). Volume error was close to 100% for Engström and between 100% and 108% with Servo-i (figures 3 and 4).

The magnitude of change in volume error was significantly greater with Hygrobac than Sterivent for Servo-i at the four nominal set VTs, for Engström at VT 800 ml and for Evita V500 at VT 500 ml. The volume error range in the four ICU ventilators was 90-117% with Hygrobac and 92-122% with Sterivent. With Hygrobac, the volume error averaged $93\pm1\%$ for Evita XL, $94\pm4\%$ for Evita V500, $99\pm2\%$ for Engström, and $110\pm4\%$ for Servo-i ($P<.0001$). With Sterivent, the corresponding values were $95\pm2\%$, $105\pm2\%$, $98\pm2\%$ and $112\pm5\%$ ($P<.0001$).

ATPD versus BTPS condition while the ventilator is set in BTPS

Volume error was systematically greater, except for Evita XL at VT 300 ml (figure 5), in BTPS condition without external filter than in ATPD condition with the ventilators set in BTPS in both instances. The level of statistical significance was reached in some instances (figure 5).

Discussion

In this bench study performed in BTPS condition, we found: 1) significant differences in volume error across ventilators, 2) further significant changes in volume error by adding external filters in four ICU ventilators, 3) lower Rf for built-in than for external filters.

One strength of present study was to investigate the volume error in VT from ICU ventilators while temperature and humidity conditions were maintained close to those in the clinical setting for 24 hours. It should be stressed that in present study the term BTPS refers to both a setting on the ventilator and a condition with which the ventilator is being tested. Bench studies are commonly done by using ICU ventilators fed by cold and dry air and set in ATPD. Such design may not reflect in vivo hygrometric conditions. When correction for BTPS condition is applied, the VT measured in ATPD condition has unexpectedly been found markedly different across ICU ventilators⁹. This may be due to the fact that the algorithms that work for the ICU ventilators to deliver VT as close as possible to set VT differ across the ventilators once BTPS conditions are present. Facing heated inspired air the algorithm should decrease the amount of gas that gets out from the ventilator because heating dilates the gas. In the same time, the algorithms should increase the amount of gas expelled from the ventilator to compensate for the gas compression into the inspiratory limb in relation with the compliance of the latter and the inspiratory pressure. In the bench study quoted above⁹, the measurements were performed under ATPD conditions and VT was derived to BTPS conditions from computation. Present study was done in actual BTPS conditions with algorithms activated. Let's compare the values of volume error BTPS computed (figure 2 in ⁹) or BTPS measured (figure 3 in present work) in those five ICU ventilators investigated in both studies. In Lyazidi et al. ⁹ study, at nominal set VT 300, 500 and 800 ml, the volume error was in the range 100-105% for PB 840 and Evita XL and in the range 105-115% for Avea, Servo-i and Engström. Present findings do not confirm these results except for Servo-i. As an example the volume error under BTPS condition in present study was largely < 100%, as

for PB 840 and Engström at VT 800 ml. Several reasons may explain these discrepant results. First of all, the measurements in the study by Lyazidi et al.⁹ were done in ATPD and extrapolated to BTPS by using a computation. Present results were obtained with ICU ventilators were set in BTPS, algorithms working on and heated humidifiers switched on. The comparison of volume error between ATPD condition and BTPD condition without filter with ICU ventilator set in BTPS in both instances can shed light on this apparent discrepancy (figure 5). The actual BTPS condition was systematically, with one exception, associated with greater volume error than the ATPD condition, whereas the BTPS algorithm was activated in the ventilator. This would suggest that the actual condition plays a major role and may even impair the algorithm functioning. Second, the ICU ventilators presently tested may be equipped with more recent algorithms than those tested by Lyazidi et al.⁹. Indeed, manufacturers take into account the results of bench testing to regularly improve the algorithms.

Some findings in present study were not clearly explained. It was a unique feature for Evita XL that volume error increased with increasing nominal set VT. The other ventilator from the same manufacturer did not exhibit this behaviour. Volume error was greater without than with filters in two ventilators and the opposite was true for the other two ventilators (Figure 4). Both ICU ventilators of the same manufacturer behaved similarly with each filter. These results suggest that the delivery of VT was different across the ventilators facing this additional filter.

Others measured Rf, as we did, over time on the bench. Pelosi et al.¹⁰ measured Hygrobac's Rf after 24 and 48 hours of mechanical ventilation with heated humidifier. They found baseline Rf values very close to present ones. They also found, as in present study, a slight increase of Rf over time. Lucato et al.¹¹ investigated, among other filters, Hygrobac S, which has both hygroscopic and hydrophobic properties. They found greater Rf values than in

present study and a significant increase from 2 to 3.8 cm H₂O.L⁻¹.s after water saturation . It should be noted that Rf was measured in the bench set in spontaneous or in pressure support ventilation. Furthermore, the saturation was induced by manual saline instillation inside the external filter, which is clearly not the same process as heating and humidifying. High Rf value has been also reported for Hygrobac S by others¹². Lellouche et al.¹³ found that pressure drop measured at 1 L.s⁻¹ was 2 cmH₂O for Hygrobac and 1.9 cm H₂O for Sterivent after a 3-hour exposure to wet environment. This latter value was lower than that presently found, a discrepancy that can be explained by difference in time frame.

Clinical implications. According to present results, for preset VT of 6 ml.kg⁻¹ predicted body weight, delivered VT would be in the range of 5.2-6.8 ml.kg⁻¹ in BTPS condition without external filter and of 5.4-7.3 ml.kg⁻¹ in BTPS condition + external filter. Therefore, errors are in the range of 1 to 2 ml.kg⁻¹. The addition of external filter at the expiratory limb to protect expiratory valve or environment had a significant effect on the delivery of VT, which was different across ICU ventilators. This effect was not related to Rf but rather to its structure.

Limitations. First of all, we added filters at the expiratory limb of the ventilator circuit, and of notice HME. HMEs are not to be used as a filtering device on the expiratory limb as they are not designed for. Even though this statement is sound, in the most recent AARC Clinical Practice Guideline Humidification During Invasive and Non-Invasive mechanical Ventilation, no specific contra-indication to locate HME at the expiratory limb of the ventilator circuit was mentioned¹⁴. It could be argued that heating the expiratory limb, as done by the kind of ventilator circuit we used, may prevent the filter from water saturation.

By study design we had to use a lung model that imposed on ventilators severe respiratory mechanics impairment. Different results might have been obtained with other mechanical conditions. A longer period than the 24-hour presently used might have disclosed

findings of different amplitude. Few ICU ventilators were tested. Finally, we did not assess the reproducibility of measurements across external filter.

Conclusions

In actual BTPS condition volume error in VT delivery differed substantially across ICU ventilators with further significant changes occurring after adjunction of external filter at the expiratory limb.

Table 1. Features regarding ICU ventilators and filters relevant for present study.

	VT delivery adjustment and accuracy	Feed-back or algorithm from expiratory VT value	Switch for BTPS or ATPD settings	Filter or HME at the expiratory line in case of nebulisation or risk to environment when heated humidifier is on
PB 840	VT compensated for BTPS and circuit compliance. $\pm(10+10\%)$ ml	All expiratory volumes are compliance-compensated. Both inspiratory and expiratory VT are reported in BTPS units. Changes to VT are phased in during exhalation based on a five-breath average or at the start of inspiration.	Yes depending on the information about type of humidification (heated humidifier or HME at the Y piece) and type of circuit (wire-heated or not)	No. Filter is incorporated in the expiratory valve block
Avea	If circuit compliance compensation is active the VT is corrected for the measured compliance $\pm(20+10\%)$ ml	No, because leaks in the system could change VT.	No. It is important to select the correct setting (BTPS and either active or passive humidification). This feature adjusts BTPS correction factor for the exhaled VT.	No. 1) Filter is incorporated in the expiratory valve block. 2) This would add unnecessary resistance.
Evita XL	VT is compensated for BTPS setting through an algorithm that depends on pre-set humidification and kind of ventilator circuit (standard or one limb-heated or two limbs-heated) $10 \pm 10\%$ or 10 ± 10 ml (the best of them)	no	no	Hydrophobic bacterial/viral filter acceptable HME contra-indicated
V500	VT is compensated for BTPS setting through an algorithm that depends on pre-set humidification and e kind of ventilator circuit (standard or one limb-heated or two limbs-heated) $10 \pm 10\%$ or 10 ± 10 ml (the best of them)	no	no	Hydrophobic bacterial/viral filter acceptable HME contra-indicated
Carestation	VT delivery is generated via 2 proportionnal valves according to the value of insufflated flow measured by 3 internal flow sensors, the compliance of the circuit and the BTPS setting if set. $\pm 10 \%$ or ± 5 ml	Expiratory VT value is only used if the leak compensation algorithm is activated. Apart from this, expired VT is not used in any control algorithm.	No. BTPS setting has to be used as soon as the ventilator is connected to a patient and either HME or heated-humidifier is on. ATPD setting is only used in bench studies.	Not contra-indicated provided properly used (avoiding water condensation)
Servo-I	Delivered VT in ATPD setting Compensation for circuit compliance must be activated	No. Only insufflated VT is used	no	Recommended provided it does not increase expiratory resistance

	± 6 %			
--	-------	--	--	--

VT=tidal volume; TI=inspiratory time; HME= Heat and Moisture Exchanger.

Table 2. Investigation steps summary.

Step number	Step goal	Measurement set-up used	Ventilator settings
1	Filter airflow resistance in dry condition	Pneumotachograph and port of Pao between the Y piece and filter	Volume-controlled mode Constant Flow inflation Positive end-expiratory pressure 0 mH ₂ O F _I O ₂ 21% Respiratory rate 20 breaths.min ⁻¹ Inspiratory time 1 sec
2	Delivered VT in ATPD condition with ventilator set in BTPS	Pneumotachograph and port for Pao between Y piece and lung test Heated humidifier off No external filter	Volume-controlled mode Constant flow inflation Positive end-expiratory pressure 0 cmH ₂ O F _I O ₂ 21% VT 400 ml Respiratory rate 20 breaths.min ⁻¹ Inspiratory time 1 sec Set in BTPS
3	Delivered VT in BTPS condition for 24 hours without external filter	Pneumotachograph and port for Pao between Y piece and lung test. Heated humidifier on No external filter 24 hours	Volume-controlled mode Constant flow inflation Positive end-expiratory pressure 0 cmH ₂ O F _I O ₂ 21% VT 400 ml Respiratory rate 20 breaths.min ⁻¹ Inspiratory time 1 sec Set in BTPS
4	Delivered VT in BTPS condition for 24 hours with external filter.	Pneumotachograph and port for Pao were inserted between Y piece and lung test Heated humidifier on external filter upstream expiratory valve 24 hours	Volume-controlled mode Constant flow inflation Positive end-expiratory pressure 0 cmH ₂ O F _I O ₂ 21% VT 400 ml Respiratory rate 20 breaths.min ⁻¹ Inspiratory time 1 sec Set in BTPS
5	Filter airflow resistance in BTPS condition for 24 hours	Pneumotachograph and port of Pao between the Y piece and filter 24 hours	Volume-controlled mode Constant Flow inflation Positive end-expiratory pressure 0 mH ₂ O F _I O ₂ 21%

			Respiratory rate 20 breaths.min ⁻¹ Inspiratory time 1 sec
--	--	--	---

F_IO₂=inspired oxygen fraction in air, V_T=tidal volume.

Legends for figures

Figure 1. In vitro experimental set-up.

Figure 2. Plots of pressure drop (ΔP) to airflow for built-in expiratory filters and external filters in ATPS and BTPS conditions.

Figure 3. Mean values of volume error (% set tidal volume) in six ventilators during BTPS conditions without external filter. Bars are for the four nominal set tidal volumes at each ventilator which were defined as: 300 (Black), 400 (Grey), 500 (White) and 800 ml (hatched). Errors bars are SD. * $P < .05$ vs Avea. ** $P < .05$ vs PB 840. The asterisks above each horizontal bar indicate the statistical significance between paired ventilators for all the nominal tidal volumes.

Figure 4. Mean values of differences in volume error (% set tidal volume) between absence and presence of external filter. A negative difference means greater volume error with than without external filter and the opposite is true for a positive difference. For Avea and PB 840 ventilators, the difference is equal to zero, as without was the same as with external filter. Bars are for the four nominal set tidal volumes at each ventilator: 300 (Black), 400 (Grey), 500 (White) and 800 ml (hatched). Errors bars are SD. * $P < .05$ vs 0.

Figure 5. Mean values of volume error (% set tidal volume) at four nominal set VT in BTPS (black bars) and ATPD (white bars) conditions in six ICU ventilators on which BTPS was set. * $P < .05$ vs dry.

Acknowledgements. The authors wish to thank Daniel Gouzou, bioengineering technician and Jean-Loup Carraz-Billat, medical bioengineering, both at Croix Rousse Hospital, Lyon, France, for their help in fixing the experimental set-up and Jérôme Girard, Sebac, France, for feed-back and support.

References

1. Dixon B, Schultz MJ, Smith R, Fink JB, Santamaria JD, Campbell DJ. Nebulized heparin is associated with fewer days of mechanical ventilation in critically ill patients: a randomized controlled trial. *Critical Care* 2010;14(R180):1-10.
2. Varma PK. Mechanical Ventilation & Nutrition In Critically Ill Patients. New Dehli Elsevier; 1999:81.
3. Dhand R, Mercier E. Effective inhaled drug administration to mechanically ventilated patients. *Expert Opin Drug Deliv* 2007;4(1):47-61.
4. Ehrmann S, Roche Campo F, Sferrazza F, Brochard L, Apiou G. Pratique de la nébulisation au cours de la ventilation mécanique : enquête internationale. *Réanimation* 2011;21(S1):S283-S286.
5. World Health Organization. WHO policy on TB infection control. In: Press W, editor. WHO policy on TB infection control in health-care facilities, congregate settings and households. Geneva, 2009:1-40.
6. Demers RR. Bacterial/viral filtration: let the breather beware! *Chest* 2001;120(4):1377-1389.
7. O' Sullavan I. H1N1 Influenza Management in the Critical Care Areas. 12/01/2011. Available from: <http://handbook.muh.ie/Infections/H1N1%20Influenza%20Management%20in%20the%20ICU%20Jan%202011.pdf>.
8. Kacmarek R. Ribavirin and Pentamidine Aerosols: Caregiver Beware! . *Respir Care* 1990;35(11):1033.
9. Lyazidi A, Thille AW, Carteaux G, Galia F, Brochard L, Richard JC. Bench test evaluation of volume delivered by modern ICU ventilators during volume-controlled ventilation. *Intensive Care Med* 2010;36(12):2074-2080.
10. Pelosi P, Severgnini S, Selmo G, Corradini MD, Chiaranda M, Novario R, et al. In Vitro Evaluation of an Active Heat-and-Moisture Exchanger: The Hygrovent Gold. *Respir Care* 2010;55(4):460-466.
11. Lucato JJ, Tucci MR, Schettino GP, Adams AB, Fu C, Forti G, Jr., et al. Evaluation of resistance in 8 different heat-and-moisture exchangers: effects of saturation and flow rate/profile. *Respir Care* 2005;50(5):636-643.
12. Morgan-Hughes NJ, Mills GH, Norwood D. Air flow resistance for 3 heat and moisture exchanging filter designs under wet conditions: implications for patient safety. *Br J Anaesth* 2001;87(2):289-291.
13. Lellouche F, Taillé S, Lefrançois F, Deye N, Maggiore SM, Jouvét P, et al. Humidification Performance of 48 Passive Airway Humidifiers. *Chest* 2009;135(2):276-286.

14. Restrepo RD, Walsh BK. AARC Clinical Practice Guideline: Humidification During Invasive and Noninvasive Mechanical Ventilation: 2012. *Respir Care* 2012;57(5):782-788.

Figure 1

Figure 3

Volume error without filter minus volume error with filter
(% set VT)

Figure 4

Figure 5