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INFLUENCE OF AMBIENT AND VENTILATOR OUTPUT TEMPERATURES ON PERFORMANCE OF HEATED-WIRE HUMIDIFIERS

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ABSTRACT

Although heated humidifiers are considered the most efficient humidification devices for mechanical ventilation, endotracheal tube occlusion caused by dry secretions has been reported with heated wire humidifiers. We tested the hypothesis that inlet chamber temperature, influenced by ambient air and ventilator output temperatures, may affect humidifier performance as assessed by hygrometry. Hygrometry was measured with three different humidifiers under several conditions, varying ambient air temperatures (high, 28-30°C; and normal, 22-24°C), ventilators with different gas temperatures, two minute ventilation levels. Clinical measurements were performed to confirm bench measurements. Humidifier performance was strongly correlated with inlet chamber temperature in both the bench (P<0.0001, r^2=0.93) and the clinical study. With unfavorable conditions, absolute humidity of inspired gas was much lower than recommended (around 20 mgH_2O/L). Performance was improved by specific settings or new compensatory algorithms. Hygrometry could be evaluated from condensation on the wall chamber only when ambient air temperature was normal but not with high air temperature. Increase in inlet chamber temperature induced by high ambient temperature markedly reduces the performance of heated-wire humidifiers leading to a risk of endotracheal tube occlusion. Such systems should be avoided in these conditions unless automatic compensation algorithms are used .

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INTRODUCTION 593 words

During mechanical ventilation, humidification of delivered gases is frequently achieved with heated humidifiers (HH) (1). Inadequate humidification can lead to bronchial inflammation, cell damage, mucociliary clearance impairment, and endotracheal tube occlusion (2). Endotracheal tube occlusion is a potentially life threatening complication described mainly with hydrophobic heat and moisture exchangers (HMEs) characterized by poor humidification performance (3-7). In a recent large prospective study, Kapadia et al. noted 13 episodes of endotracheal tube occlusion over a 3-year period, of which 8 required cardiopulmonary resuscitation (7). HMEs used in this study were poor performing ones. With newer hygroscopic HMEs, endotracheal tube occlusion seems unusual (8-15), even with prolonged use (16-18).

HHs have been shown to provide better gas humidification performances than HMEs (19-23), although no data have demonstrated a better clinical outcome. However, we have also shown that partial undetected obstruction can markedly increase the patient's work of breathing and potentially impede weaning (24, 25). Anecdotal cases of endotracheal tube occlusion have been described with HHs, and may be more common when settings are suboptimal (3, 5, 8). Indeed, in these studies, temperature at the Y-piece was 31 to 32 °C, whereas recommended temperature settings for the most recent HHs are 37 °C for the outlet chamber and 40 °C at the Y-piece. In theory, these recommended settings ensure excellent performance with delivery to the patient of saturated gas at 37 °C (44 mg H_2O/L). Miayo et al. described the first cases of endotracheal tube occlusion with HHs based on heated wire circuits (26). In several recent studies involving the use of heated-wire humidifiers in large numbers of patients (11, 12), no cases of endotracheal tube occlusion were noted, although partial occlusions occurred in another study (27). Unexpectedly, a recent randomized controlled study comparing ventilator-associated pneumonia rates with an HME (Hygrobac DAR) and an HH found a substantial rate of endotracheal tube occlusion with the HH (5/169 patients compared with 1/172 patients in the HME group, P=0.12) (28). Using the recommended settings, we also observed several episodes of endotracheal tube occlusion with the new heated-wire humidifiers recently introduced in our intensive care unit (ICU). These episodes seemed to be associated with higher ambient air temperatures and with specific ventilator types.

The general working principles of the heated humidifiers are to heat water contained in the humidification chamber, and to humidify the gas passing through. A heated wire is present all along the inspiratory and expiratory circuits to avoid water condensation in the tubings. Consequently, new heated wire humidifiers need to regulate both the Y-piece and the outlet chamber temperatures. For the latter, the only regulated parameter is the temperature, and not the humidity by itself. Therefore, the principles underlying the regulation of these HHs (Figure 1) led us to hypothesize that their performances may be impaired by high inlet chamber temperature. Indeed, in such a case, the heater plate may stop to heat, leading to insufficient energy to humidify gases coming from the ventilator. Because of the potentially severe consequences of unrecognized underhumidification, the goal of this study was to determine whether factors such as ambient air temperature, type of ventilator and minute ventilation, may be important determinants of the HH performances. We designed a bench study to measure the hygrometry of inspiratory gases while varying ambient air temperature, ventilator type, minute ventilation, HH type, and HH settings (29). We then checked in patients that inlet chamber temperature predicted humidification efficiency *in vivo* (30). Some of the results of these studies have been previously reported in the form of abstracts (29, 30).

MATERIAL AND METHODS (additional details can be found in the repository) 499 words

Bench study

Protocol *(Figure 1, Table 1)*

The humidification performance of the heated humidifier MR 730 (Fisher&Paykel,® Auckland, New Zealand) was assessed using the following temperature settings for the outlet chamber/Y-piece, in °C: 37/40, 40/40.

The MR 850 model (Fisher&Paykel), which has a new automatic compensation system designed to automatically increase the set outlet chamber temperature in case of underheating was also tested.

Inspired gas hygrometry was measured with the ventilator and airway circuit connected to a test lung, under the following conditions:

- two ambient air temperatures: normal, 22-24 °C; and high, 28-30 °C;
- two ventilators with different gas output temperatures, low (close to 30°C, Evita 4, Dräger Medical®, Lübeck, Germany) and high (close to 40°C, T-Bird, Viasys Healthcare®, Conshohocken, PA, USA); these ventilators were selected among 16, on which measurements of gas output temperature has been performed (Table E1);
- two levels of minute ventilation (V_E): low V_E (10L/min) and high V_E (21L/min);
- several other conditions were tested (another humidifier Aerodyne Ultratherm [Kendall®, Tyco Healthcare, Mansfield, MA, USA], use of a long dry line, T-Bird with 21% FiO_2), all described in the online data supplement.
- Lastly, we measured HH performances in standard settings, modifying only the inlet chamber temperature to confirm the major influence of this factor.

Measurements

Hygrometric measurements: All hygrometric measurements were performed using the psychrometric method after 3 hours at the steady state (18). For each condition, three measurements were obtained on three different days and results are given as mean ± standard deviation.

Temperature measurements: temperatures of ambient air, ventilator output, and HH inlet chamber were measured at the end of each period. Outlet chamber, Y-piece and heater plate temperatures displayed by the HH were recorded.

Semi-quantitative visual evaluation of condensation was performed and results are described in the online data supplement.

Clinical study

This part of the study was approved by the ethics committee of the French Society for Critical Care Medicine (Société de Réanimation de Langue Française), which waived the need for consent. Patient or family was informed of the measurements.

We used the psychometric method to measure delivered gas humidity in 20 consecutive patients ventilated in our ICU with the HH MR 850. The aim of this clinical study was to assess in patients the impact of the inlet chamber temperature on the HH performance and to evaluate the efficacy of a new algorithm, developped to avoid low humidifications performances. After 2 hours at the steady state, hygrometry was determined during three successive periods: with the new automatic compensation system on, after this system was switched off (with the outlet chamber temperature at 37 °C and the Y-piece at 40 °C), and with the compensation system switched back on.

Statistical analysis

Friedman test and pairwise comparisons using the Mann-Whitney test were performed to compare the different conditions. Spearman correlation tests were performed between visual evaluation of humidification and absolute humidity of inspired gas, and linear regression was performed between inlet temperature and absolute humidity of inspired gas. *P* values smaller than 0.05 were considered significant.

RESULTS

Hygrometric results (bench study)

Fully saturated air at 37°C has an absolute humidity of 44 mg H_2O/L. This would be the value observed with HHs capable of fully humidifying the inspired gas. In the first part of the study, with the settings recommended by the manufacturers (37°C at the outlet chamber and 40°C at the Y-piece), absolute humidity was 35.8±1.9 mg H_2O/L in the best condition (Table E2) and 19.0±0.8 mg H_2O/L in the worst condition (Table E2).

Hygrometric data expressed as absolute (mg H_2O/L) and relative (%) humidities are shown in Table 2 and Figure 2 To simplify the presentation, absolute humidity data are displayed in the tables as means±SD obtained by pooling the values obtained at 10 and 20 L/min. The results for each individual condition are reported in the online data supplement.

Main hygrometric results

Humidification performance of HH was markedly decreased by several factors.

· high ambient air temperature decreased HH performance in comparison with normal temperature (P<0.0001) (Tables 2, E2 and Figure 2): ambient air temperature was the factor with the greatest influence on HH performance.

· use of the T-Bird was associated with lower performance of HH in comparison with the Evita 4 (P<0.0001);

· high (20 L/min) minute ventilation decreased HH performance in comparison with low (10 L/min) minute ventilation (P<0.0001).

These differences were found for humidification performance expressed as both absolute humidity (mg H_2O/L) (Tables 2, E2) and relative humidity (%) (Figure 2).

Inlet chamber temperature

There was a strong inverse correlation between inlet chamber temperature and HH performance (P<0.0001, r^2=0.93) (Figure 3). There was also a strong inverse correlation between inlet chamber temperature and heater plate temperature (P<0.0001, r^2=0.93).

Inlet chamber temperature varied from 27.4±0.8°C (with normal ambient air temperature, EVITA 4, and low minute ventilation) to 37.9±1.3°C (with high ambient air temperature, T-Bird, and high minute ventilation). Ambient air temperature had the largest effect on the inlet chamber temperature.

Output ventilator temperature ranged from 29.8±1.0°C (with normal ambient air temperature, EVITA 4, and high minute ventilation) to 45.1±2.2°C (with high ambient air temperature, T-Bird, and high minute ventilation) and was influenced by the ventilator and the settings. With the turbine ventilator, output gas temperature was influenced by the level of minute ventilation. These results are presented in Table 3.

The combination of high ambient air temperature and high outlet ventilator temperature (with T-Bird and high minute ventilation) led to the highest inlet chamber temperatures (Table 3) and was associated with the worst HH performances. In these conditions, HH performance was extremely poor, with an absolute humidity of less than 20 mg H_2O/L (Table 2, Table E2).

Optimized settings

When inlet chamber gas temperature was high, settings with no temperature gradient between the outlet chamber and Y-piece temperatures (40/40 with MR 730) prevented poor performance (Table 2, Figure 2, Table E4). The automatic compensation system (MR 850) partially prevented poor humidification (Table 2, Figure 2, Table E4).

Hygrometric results (clinical study)

The results of the clinical study were consistent with the bench study. The clinical study was performed between September and November 2002. Ambient air temperature in the rooms varied between 24.1 and 29.1°C (mean, 26.6°C). Mean patients temperature was 37.2±1.9°C Absolute humidity ranged from 23.4 mg H_2O/L (without compensation) to 41.9 mg H_2O/L (with compensation). In six patients, absolute humidity was lower than 30 mg H_2O/L without compensation. With compensation, absolute humidity was consistently greater than 30 mg H_2O/L (Figure 4). Performance was poorest with the highest inlet chamber temperature. A good correlation was found between inlet chamber temperature and absolute inspired gas humidity, in keeping with the bench study (r^2=0.69, P<0.0001). A good correlation was also found between heater plate temperature and absolute humidity of inspired gas (r^2=0.60, P<0.0001).

DISCUSSION

This study is the first to highlight the major negative effect of ambient air and ventilator output temperatures on HH performance. The most striking finding is that the performance of a recent-generation HH was greatly influenced by inlet chamber temperature, becoming extremely poor when this temperature was high (Tables 2, E2, Figures 2, 3). Absolute humidity of inspired gas was strongly and inversely correlated to inlet chamber temperature in the bench (Figure 3) and in the clinical study. Inlet chamber temperature was influenced by ambient air temperature and ventilator output temperature (Table 3).

The weakness point of these new-generation heated-wire humidifiers lies in the mechanism that regulates outlet chamber temperature (Figure 1). When inlet chamber temperature is high, the heater plate stops heating, supposedly maintaining the set outlet chamber temperature. The water contained in the chamber remains too cold for evaporation to occur, leading to extremely low levels of relative and absolute humidity.

Inlet chamber temperature is influenced both by ambient air temperature and by ventilator output temperature (Table 3). High ambient air temperature prevents the gas from cooling in the circuitry between the ventilator output and the humidification chamber. Ventilator output gas temperature is also influenced by minute ventilation, and all these parameters influence HH performance.

Under unfavorable conditions (high ambient air temperature, high ventilator output gas temperature), performance was extremely poor, with absolute humidities of less than 20 mg H_2O/L. This is lower than measured with the HMEs reported to be responsible for endotracheal tube occlusion (3-6, 19). These results are consistent with the specific mechanism that regulates HH function (Figure 1) but are nevertheless troublesome given their potential for inducing adverse clinical effects.

Very few data in the literature can be directly compared with this study. One recent publication concluded that inlet gas temperature had little influence on HH performance (31). This study was performed using pediatric ventilators with very low flows and provided few hygrometric data. On the contrary, we found a marked influence of external conditions with a major effect of ambient air temperature.

The HH never provided the theoretical ideal value of 44 mg H_2O/L when the outlet chamber temperature was set at 37 °C. With this setting, normal ambient air temperature and low ventilator output temperature, the highest measured humidity value was 35.8 mg H_2O/L (Table E2). In a recent publication (32), with the same settings and using a dew point mirror hygrometer, a similar result of 36.2 mg H_2O/L was obtained. These results emphasize the need for independent assessment of humidification devices (33).

Gas humidity values measured using psychrometry have been obtained over the last 10 years in several clinical and bench studies, with a good reproducibility across research groups (18, 19, 21, 23, 26, 34-39). The hygrometry values of inspired gas in the present study (from less than 20 mg H_2O/L of absolute humidity under the worst conditions to more than 40 mg H_2O/L under the best conditions with best settings: 40/40) are comparable to previously reported psychrometric values obtained using various humidification devices. Ricard et al. measured the absolute humidity produced by the BB2215 (19), an HME used in several studies and associated with endotracheal tube occlusion (3-6), and found a mean value of 21.8±1.5 mg H_2O/L. Under the worst conditions of the present study, the HH provided equivalent or even lower humidification values than the BB2215. This may explain the clinical occurrence of endotracheal tube occlusion, since this event is closely related to insufficient performance of humidification devices (3-6). The American Association for Respiratory Care recommends a minimum of 30 mg H_2O/L of absolute humidity provided by humidification devices for prolonged mechanical ventilation (40). Absolute inspired gas humidity values obtained with the most efficient hygroscopic and hydrophobic HMEs were 29.1±1.8 mg H_2O/L (21) and 30.8±1.5 mg H_20/L (18), respectively, as measured using the psychrometric method. We are aware of only three reported cases of endotracheal tube occlusion with these HMEs, including one in a patient who experienced massive tracheal bleeding before the occlusion (9, 13). This suggests that an absolute humidity of 30 mg H_2O/L (with the psychrometric method) or even a bit less may be sufficient to prevent most cases of endotracheal tube occlusion. In the present study, absolute inspired gas humidity was well below this threshold under many conditions (Tables 2, E2).

Endotracheal tube occlusion is a very late and insensitive index of inadequate humidification during mechanical ventilation. Most studies evaluating the effects of inadequate humidification on the bronchial mucosa were performed during anesthesia, and few data on patients receiving prolonged mechanical ventilation have been reported. Chalon et al. showed that, after less than 4 hours of mechanical ventilation, anesthetized patients who received inadequately humidified gas (23 °C and 60% of relative humidity, i.e., 12.5 mg H_2O/L of absolute humidity) had significantly more postoperative complications and cytologic tracheobronchial tree damage than did patients who received saturated gas at 32°C (33.9 mg H_2O/L of absolute humidity) (41). Thus, the low levels of humidification measured in our study (around 20 mg H_2O/L) may lead to mucosal damage, especially in the event of prolonged mechanical ventilation.

Williams et al. suggested that airway mucosal dysfunction may be related to the time spent by the mucosa at a given level of humidity (2). In their model, mucosal dysfunction arose after about 1 hour of exposure to inspired gas humidity values lower than 25 mg H_2O/L. When exposure was about 24 hours, mucosal damage occurred with humidity levels below 30 mg H_2O/L. After exposure for 5 days, Hurni found moderate airway epithelial damage in patients ventilated with a heated humidifier (Fisher&Paykel) set at 31°C at Y-piece or a high-performance HME (Hydroster-DAR), both devices delivering about 30 mg H_2O/L (8). Using a heated-wire humidifier, we found a wide range of inspired gas humidity values (from 19.0±0.8 to 41.5±1.2 mg H_2O/L). Performances of earlier-generation HHs, which do not share the same regulation mechanism, have been reported to vary between 29.2±1.4 and 34.3±1.3 mg H_2O/L absolute humidity measured using the psychrometric method (19, 21, 23). The main drawback of these earlier HHs is that the water traps must be emptied repeatedly, which increases the nurse workload and carries a risk of cross-contamination (42, 43). Heated-wire humidifiers heat both the inspiratory and the expiratory line, thereby avoiding condensation in the circuitry and obviating or minimizing the need for water traps. Condensation remains a problem, however related to some compensating systems (30, 44). We did not compare new-generation to earlier-generation HHs. We used two, very similar, recent HHs, Aerodyne Kendall and MR 730 Fisher&Paykell. We found that humidification performance was slightly but significantly better with the Aerodyne Kendall under several conditions (Table E1), but both the humidification chamber and the circuits used were different, which may have influenced the inlet chamber temperature. The most important finding was that a high inlet chamber temperature was associated with poor performance for both HHs. This suggests that the mechanism for regulating outlet chamber temperature, which is the same for both HHs, was the relevant characteristic. Thus, the influence of external conditions demonstrated in our study does not seem to be specific to one manufacturer but may apply to HH with heated wire circuits having the same mechanism for regulating outlet chamber temperature. Therefore, the use of these heated humidifiers should be avoided in case of high ICU room air temperature, unless equipped with automatic compensation.

Air-conditioning of the room is obviously important to avoid high inlet temperatures, but even with normal temperatures (22-24°C in present study), unfavorable conditions (e.g., turbine ventilator at high minute ventilation) may result in poor HH performance, and the type of ventilator may influence the inlet chamber temperature (Table 3). In the present study, we used two ventilators with very different output temperatures (30 to 35°C with the EVITA 4, 36 to 47°C with the T-Bird (Table 3)), but in a preliminary step we noted that temperatures varied widely among ventilators (from 26 °C to 60 °C) (Table E1).

We tested the automatic compensating system of the MR 850, which is based on a theoretical calculation of the energy needed to warm and humidify a given volume of gas. This system requires that the HH measures the flow delivered by the ventilator. When the heater plate is not sufficiently warm (i.e., when the energy delivered by the HH is insufficient), the outlet chamber temperature is automatically increased until the heater delivers the level of energy determined by the theoretical calculation. The system can automatically increase the set temperature of the outlet chamber by 3 °C (from 37 to 40 °C, for intubated patients). Under unfavorable conditions, it avoided very low humidification levels in our study. Values obtained with this system were generally greater than 30 mg H_2O/L with high ambient air temperatures, except under the worst conditions (Table 2, Table E4).

A simple way to avoid low humidification was to set the temperatures at 40/40 with the MR 730 (Table 2 and Figure 2), but this setting cannot be recommended under all environmental conditions: indeed, when the air temperature decreases (at night for example), it may lead to considerable condensation in the circuitry. We also found that with turbine ventilators and an FiO_2 set at 21%, the absolute humidity of inspired gas was significantly higher than when dry gases were used (100% FiO_2) (Table E4). Turbine ventilators predominantly use ambient air, whose hygrometry level is greater than that of wall medical gases.

Another important finding from this study is that condensation is not a reliable clinical marker for adequate humidification when the ambient air temperature is high. When the ambient air temperature was normal, between 22 and 24°C, we found a good correlation (Rho=0.85) between inspired gas hygrometry and condensation on the HH chamber wall. In contrast, the correlation did not exist at high ambient air temperature (Figures E1 and E2). In this situation, the gas cannot cool and therefore cannot condense on the wall of the HH chamber. Unfortunately, this corresponds to impaired HH function. There is no other means of checking the humidification level. A correlation between inspired gas hygrometry and condensation has been found (19, 45) in studies performed in air-conditioned ICUs or under favorable climatic conditions. Our results confirm that visual evaluation is useful only when the ambient air temperature is not too high.

In conclusion, the performance of the new heated-wire humidifiers is greatly influenced by inlet gas temperature. Under unfavorable conditions, especially in case of high ambient air temperature (which is common in ICUs without air conditioning), inspired gas humidification is extremely poor, suggesting a high risk of endotracheal tube occlusion, and the heated-wire humidifiers should then be avoided in these situations. This risk may be lowered using specific settings or automatic compensation systems that partially correct the dysfunction. For the present time, a simple alternative in these special conditions is to use a heat and moisture exchanger. Other types of heated humidifiers, despite presenting other drawbacks, or “active” heat and moisture exchangers, both of which are not influenced to the same amount by external conditions, could also be an alternative.

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FIGURE LEGENDS

Figure 1: **Diagram of the temperature regulation system of a heated humidifier (HH) with a heated circuit, and of the bench study methodology**. The HH outlet temperature is regulated through the heater plate. When the inlet temperature is low, the heater plate heats the water and evaporation occurs, ensuring sufficient humidification. When the inlet temperature is high, the water may not be warmed and, consequently, the gas may remain dry. We demonstrated this in the present study by measurements of hygrometry of inspired gas in different situation leading to varied inlet chamber temperature. Framed parameters are those measured (hygrometry of inspired gas, ambient air, ouput ventilator and inlet chamber temperatures) or recorded from the heated humidifier (heater plate, outlet chamber, Y-piece temperatures).

Figure 2: Decrease in the relative humidity (%) of inspired gas observed with high ambient air temperature: normal ambient air temperature (dark) versus high ambient air temperature (white). Standard settings for intubated patients.. Comparison with two optimized settings for high ambient air temperature (white) : 40/40 with MR 730, Fisher&Paykel, and with the automatic compensating system (MR 850 Fisher & Paykel).

Relative and absolute humidity follow the same variations for all conditions.

Figure from data obtained with T-Bird ventilator.

Figure 3: Correlation between heated wire humidifier performance and inlet chamber temperature in the bench study. A very close correlation was found between humidifier performance (absolute humidity (mg H_2O/L) of inspiratory gas) and inlet chamber temperature (°C). A good correlation was also found between humidifier performance and heater plate temperature.

Figure 4: Clinical study. Hygrometry of inspired gas during three successive periods: with the automatic compensation on, with standard settings (37 °C outlet chamber temperature/40 °C Y-piece temperature) under the same conditions of ambient air and ventilator output temperature, and with the automatic compensation switched back on

TABLES

Table 1. Conditions tested in the bench study. All the conditions were combined. In each combination, inspiratory hygrometry and temperatures (ambient air, output ventilator and inlet chamber) were measured and semi-quantitative visual evaluation of condensation was performed.

Variables	**Conditions tested**	
Ambient air temperature	Normal: 22-24°C	High: 28-30°C
Ventilator with different output temperature	Low: 30°C (Evita 4)	High: 40°C (T-Bird)
Minute ventilation	Low: 10L/min	High: 21L/min
Heated Humidifiers	F&P MR 730, MR 850, Aerodyne Ultratherm (Kendall)*	
Heated Humidifiers settings *Chamber/Y-piece temperatures (°C)*	- Standard: 37/40 (MR 730), 37/39 (Aerodyne Ultratherm)* - No gradient: 40/40 (MR 730), 39/39 (Aerodyne Ultratherm)* - Automatic compensation (MR 850)	
Other	Long dry line*, T-Bird with 21% FiO_2*	

* Results shown in the repository

Table 2. Bench study. Absolute humidity (mg H_2O/L) of inspired gas under various conditions with standard settings (37/40), optimized settings (40/40) with the MR 730 humidifier and with the automatic compensation system with the MR 850 humidifier.

	Standard settings (40/37) (MR 730) *		No gradient (40/40) (MR 730)		Automatic compensation (MR 850)	
Ambient air temperature	**Normal**	**High**	**Normal**	**High**	**Normal**	**High**
Ventilator with low output temperature	35.2±1.8	23.4±2.4	38.6±2.1 †	32.3±3.5 †	35.3±1.8 †	32.0±2.3 †
Ventilator with high output temperature	31.2±0.7	22.7±4.3	36.5±1.7 †	30.1±3.8 †	36.4±1.6 †	27.7±4.3 †

Means±SD of pooled data for 10 and 20 L/min set minute ventilation.

Normal ambient air temperature=22 to 24 °C / High ambient air temperature=28 to 30 °C

Ventilator with low output temperature: EVITA 4 / Ventilator with high output temperature: T-Bird (with FiO_2 100%)

* Standard settings : all statistical comparisons for normal vs. high ambient air temperature and for low vs. high ventilator output temperature are significant with *P* values < 0.0001 (Mann-Whitney tests)

† *P*<0.05 versus standard settings (displayed in Table 1) for the same condition. (Mann-Whitney tests)

Table 3. Effect of ambient air temperature, type of ventilator and minute ventilation on ventilator output and inlet chamber temperature (expressed in °C). Means±SD.

Set minute ventilation	*10 L/min*		*20 L/min*	
Ambient air temperature	**Normal** (23.0±0.2)	**High** (29.0±0.2)	**Normal** (22.9±0.2)	**High** (29.0±0.2)
Ventilator with low output temperature				
Vent. output T°	30.2±0.9	35.2±1.0	29.8±1.0	35.8±1.5
Inlet chamber T°	27.4±0.8	32.7±0.8	27.7±1.1	33.4±0.7
Ventilator with high output temperature				
Vent. output T°	36.0±0.6	41.7±2.2	40.7±1.5	45.1±2.2
Inlet chamber T°	29.8±0.9	35.9±1.3	33.1±0.9	37.9±1.3

Ventilator output temperature: $P<0.0001$: high vs. normal AAT, Evita 4 vs. T-Bird and 10 vs. 20 L/min (only for T-Bird)

Inlet chamber temperature: $P<0.0001$: high vs. normal AAT, Evita 4 vs. T-Bird and 10 vs. 20 L/min (only for T-Bird)

Ventilator with low output temperature: EVITA 4 / Ventilator with high output temperature: T-Bird (with FiO_2 100%)

Figure 1:

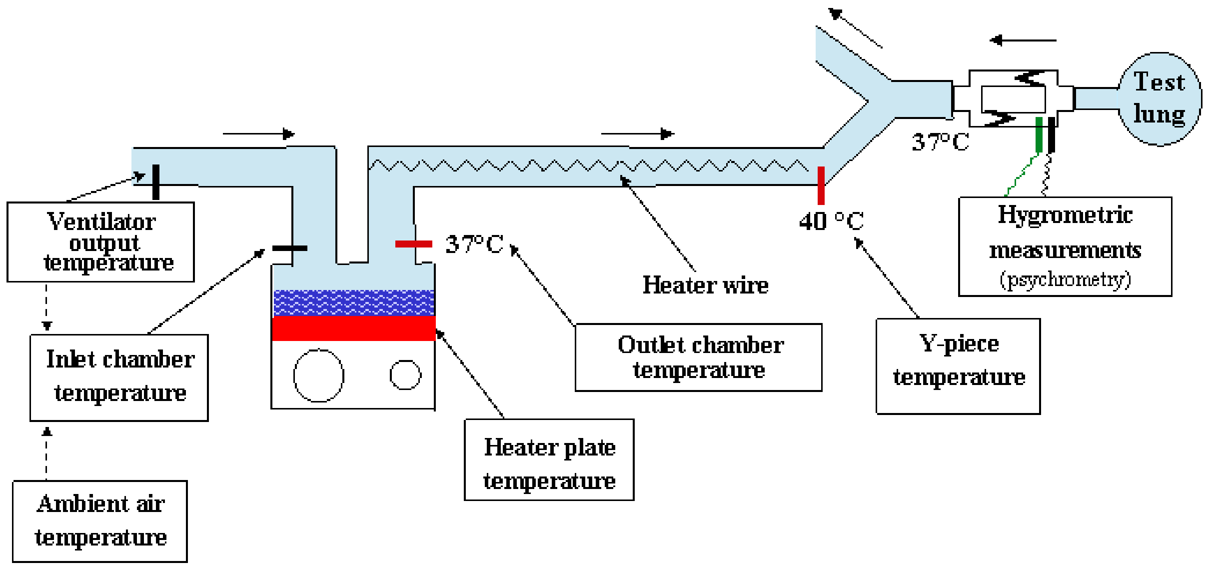
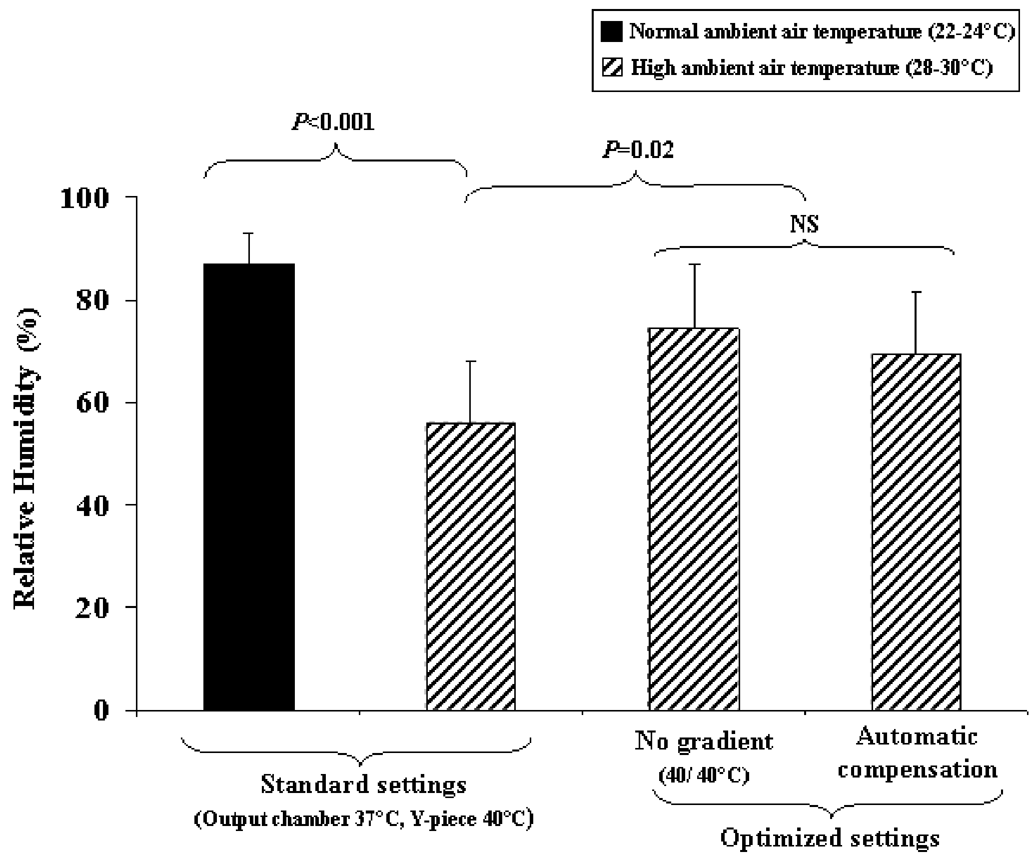
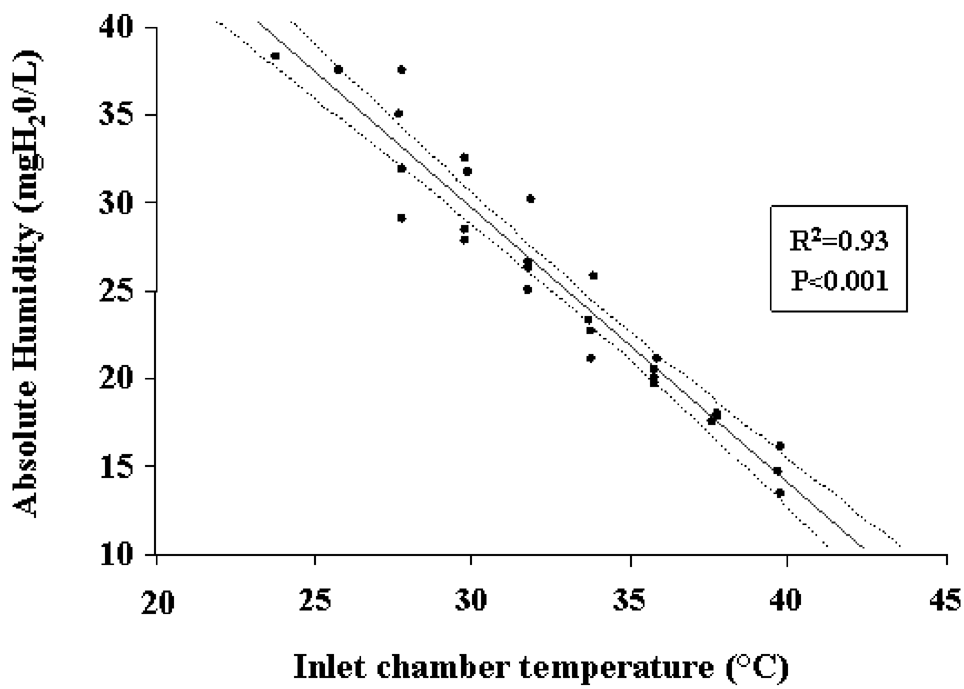

Test lung
37°C
40 °C
37°C
Ventilator output temperature
Inlet chamber temperature
Ambient air temperature
Heater wire
Outlet chamber temperature
Heater plate temperature
Y-piece temperature
Hygrometric measurements (psychrometry)

Figure 2:



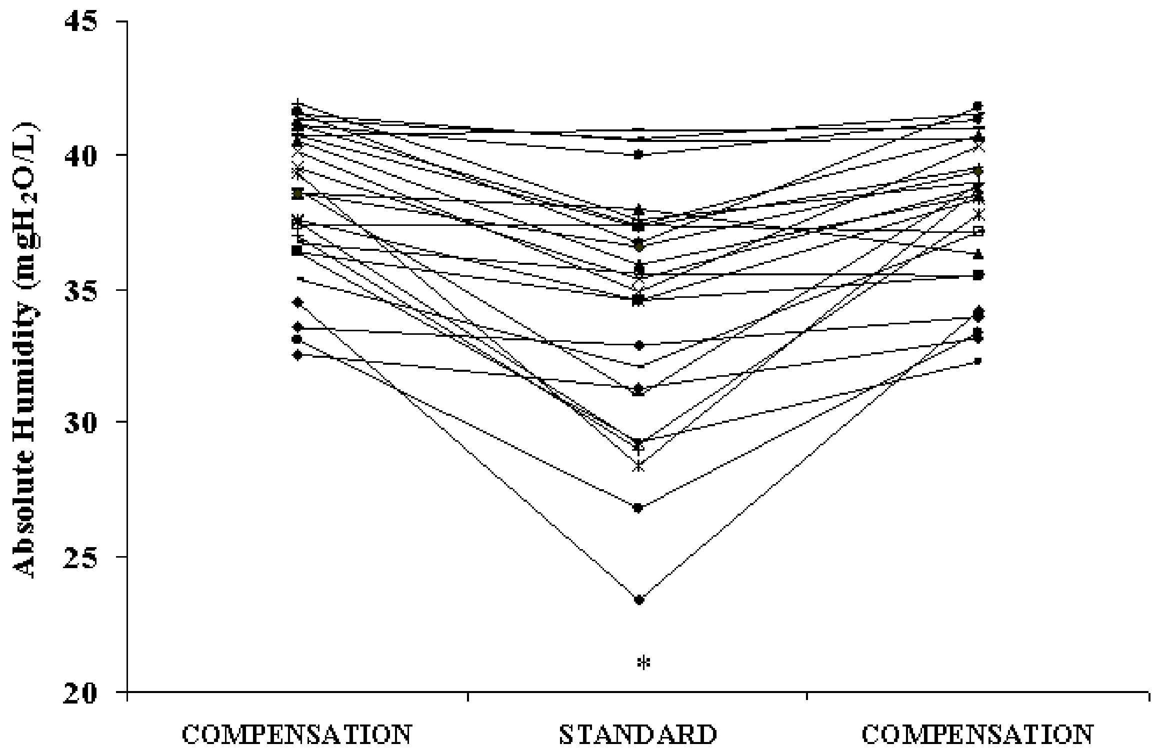
Normal ambient air temperature (22-24°C)
High ambient air temperature (28-30°C)
P<0.001
P=0.02
NS
100
80
60
40
20
0
Relative Humidity (%)
Standard settings
(Output chamber 37°C, Y-piece 40°C)
No gradient
(40/ 40°C)
Automatic compensation
Optimized settings

Figure 3:



40
35
30
25
20
15
10
20
25
30
35
40
45
Absolute Humidity (mgH20/L)
Inlet chamber temperature (°C)
R²=0.93
P<0.001

Figure 4:


45
40
35
30
25
20
Absolute Humidity (mgH$_2$O/L)
*
COMPENSATION
STANDARD
COMPENSATION

INFLUENCE OF AMBIENT AND VENTILATOR OUTPUT TEMPERATURES ON PERFORMANCE OF HEATED-WIRE HUMIDIFIERS

François Lellouche, Solenne Taillé, Salvatore Maurizzio Maggiore, Siham Qader, Erwan L'Her, Nicolas Deye, Laurent Brochard

Online Data Supplement

DETAILED MATERIAL AND METHODS

Bench study

Protocol (Figure E1)

The performance of the heated-wire humidifier (HH) MR 730 (Fisher&Paykel, Auckland, New Zealand) was assessed at various settings for outlet chamber temperature/Y-piece temperature, in °C: 37/40 and 40/40 (both recommended for intubated patients);

Inspired gas hygrometry was measured using the psychrometric method, under various conditions of room air temperature, minute ventilation, FiO_2, and ventilator type:

- two ambient air temperatures: normal, 22-24 °C; and high, 28-30 °C;
- two ventilators with different gas output temperatures, low (close to 30°C, Evita 4, Dräger Medical®, Lübeck, Germany) and high (close to 40°C, T-Bird, Viasys Healthcare®, Conshohocken, PA, USA), connected to a test lung; these ventilators were selected to explore the hypothesis that ventilator type may affect heated humidifier (HH) performance; because different ventilator types use different mechanisms to generate gas flow, we first measured gas output temperature of 16 ventilator models (Evita 4, Evita 2, Savina, Dräger Medical (Lübeck, Germany), T-Bird, Vela, 8400STi, Viasys Healthcare (Conshohocken, PA, USA), LTV 1000, Pulmonetic Systems (Minneapolis, Minnesota, USA), Bipap vision, Respironics, (Murrysville, PA, USA), Puritan Benett 840, Puritan Benett 760, Puritan Benett 7200, Tyco Healthcare (Mansfield, MA, USA), Servo i, Siemens Elema (Solna, Sweden), Galiléo, Hamilton Medical (Rhäzüns, Switzerland), Horus, Taema (Antony, France), Inspiration, eVent Medical Limited (Carlsbad, CA, USA), Elisée, Saime (Savigny le Temple, France); the two ventilators used for the study were selected based on the results shown in Table E1.

- two levels of minute ventilation (V_E) during controlled ventilation with a constant flow of 60 L/min: low V_E (10 L/min, respiratory rate 25/min, tidal volume 400 ml, and external positive end-expiratory pressure 5 cm H_2O); and high V_E (21 L/min, respiratory rate 35/min, tidal volume 600 ml, and external positive end-expiratory pressure 10 cm H_2O).
- Because ambient air and dry wall oxygen are used with turbine ventilators, we tested two FiO_2 levels (21 and 100%) with the T-Bird. With the Evita 4, FiO_2 was 21%. We previously checked that FiO_2 differences did not affect hygrometric values as measured by the psychrometric method when dry wall gases were used (with heated humidifier set at 40/37, with normal ambient air temperature, with the EVITA 4 set at 10L/min, absolute humidity of inspired gas at 21% FiO_2 was 34.6±1.7 mgH_2O/L, and 34.8±1.5 mgH_2O/L at FiO_2 100%, NS).
- We also measured inspired gas hygrometry with another HH, the MR 850 (Fisher&Paykel) in the standard setting for invasive mechanical ventilation, 37/40 °C. For this device, a new automatic compensation system was available and was activated for all measurements. This system automatically increases the set chamber outlet temperature if underheating occurs.
- Another heated-wire humidifier, Aerodyne Ultratherm (Kendall, Tyco healthcare), was tested at the following temperature settings (outlet chamber temperature/Y-piece temperature): 37/39, and 39/39. This HH works on the same principle as the MR 730, with the same regulation mechanism.
- Inspiratory gas hygrometry was also measured with no humidification device, with both ventilators and at both ambient air temperatures (normal and high), to replicate possible conditions during noninvasive ventilation.
- HH performance was evaluated also using a long dry line between ventilator output and the inlet chamber, as recommended by HH manufacturers in order to improve the peformances.

The inspiratory line of a standard circuit (170 cm) was used (Breathing System, Intersurgical, Wokingham, United Kingdom).

The humidification chamber was an MR 290 and the circuits were RT 100 inspiratory and expiratory heated-wire circuits (Fisher&Paykel).

Lastly, we measured HH performance with standard settings, modifying only the inlet chamber temperature to confirm the major influence of this factor. We performed additional measurements with the MR 730 with standard settings (Outlet chamber temperature: 37°C, Y-piece temperature: 40°C): in the worst conditions (high ambient air temperature, high outlet ventilator temperature, high minute ventilation), after three hours of stabilization, the inlet chamber temperature being measured at 40°C. We then decreased gradually the inlet temperature from 40 to 24°C by two degrees steps and hygrometric measurements were performed after steady state at each step in the standard setting (outlet chamber / Y-piece temperatures stable at 37 / 40°C), and heater plate temperature steady, the others conditions (ambient air temperature, ventilator and ventilator settings) remaining stable. The decrease of the inlet temperature was realised by covering the dry line (between the ventilator outlet and the inlet humidification chamber) with some pieces of wet paper.

Measurements

Hygrometric measurements: the psychrometric method has been described previously (20) and used to measure gas humidity (absolute humidity expressed in mg H_2O/L and relative humidity expressed in %) in many clinical and bench studies (20, 21, 23, 25, 26, 28-33). We calibrated the psychrometer and we compared the temperatures using a high-precision thermometer (Duotemp, Fisher&Paykel) before each measurement. Hygrometry and temperature of ambient air were also measured on each test day, after stabilization of ambient air temperature. All hygrometry values were obtained after 3 hours at the steady state. For each test condition, three measurements were obtained in all, on 3 different days.

Temperature measurements: temperatures of ambient air, ventilator output, and the heated humidifier inlet were measured at the end of each period, using a high-precision thermometer (Duotemp, Fisher & Paykell). The outlet chamber and Y-piece temperatures displayed by the HHs were recorded. During the clinical study, heater plate temperatures displayed by the HHs (in the submenu) were recorded.

Visual evaluation of condensation: the level of condensation on the humidification chamber wall was assessed by visual inspection and recorded as follows (1: dry; 2: vapor; 3: vapor with a few small droplets; 4: numerous droplets not covering the entire wall; 5: numerous droplets covering the wall almost completely). This evaluation was performed to assess a simple marker of humidification.This scale was used in an earlier study (21) and adapted slightly for the current study. We used the condensation observed on the chamber wall because it is specific of inspired gas humidification and not influenced by the expiratory gas (as at the Y-piece).

We tested 126 conditions (120 combinations with HHs and 6 combinations without humidification), obtaining at least three psychrometric determinations of inspiratory gas humidity in each condition, for a total of 420 hygrometry measurements. In addition, 1140 temperature measurements (ambient air, ventilator output, and inlet chamber) were obtained.

Clinical data

The bench conditions were designed to simulate clinical conditions as closely as possible. To check that the bench study data predicted humidifcation efficiency in clinical settings, we measured delivered humidity in 20 consecutive ICU patients receiving invasive ventilation with a heated-wire humidifier. All parameters shown to influence humidity were recorded and compared to the values predicted from the bench study data. Heater plate temperatures displayed by the HH were recorded.

In the patients, hygrometry measurements were obtained during three successive periods after 2 hours at the steady state: with the new compensation system powered on, then powered off (with 37 °C at the outlet chamber and 40 °C at the Y-piece) and, finally, powered on again. Standard ventilators were used, and air temperature was measured. This part of the study was approved by the Ethics Committee of the French Society for Critical Care Medicine.

Statistical analysis

To assess the influence of each condition, measurements were compared between normal and high ambient air temperature, among the ventilator types and settings, between the FiO_2 values used with the T-Bird ventilator, and among the HHs. Comparisons between the EVITA 4 and T-Bird ventilators were done with 100% FiO_2 for the T-Bird to ensure that dry gases were used in both cases. Friedman test and pairwise comparisons using the Man-Withney test. Spearman correlation coefficients were calculated between visual evaluation of humidification and absolute humidity of inspired gas, and simple regression was performed between inlet temperature and absolute humidity of inspired gas. *P* values smaller than 0.05 were considered significant.

ADDITIONAL RESULTS

- There was a very high inverse correlation between inlet chamber temperature and HH performances was found (P<0.0001, r^2=0.93) (Figure 3). There was also a very high inverse correlation between inlet chamber temperature and heater plate temperature (P<0.0001, r^2=0.93). And we found also a very close correlation between heater plate temperature and HH performances (P<0.0001, r^2=0.96).

- Impact of FiO_2 on humidification performances (with turbines ventilators). With the turbine ventilator, absolute humidity of inspired gas was higher when FiO_2 was set at 21% than at 100% (P<0.001) (table E3).

- Impact of long dry line on humidification performances. Placing a long dry line between the ventilator output and the HH did not improve humidification performance (table E3).

- Performances of an other heated-wire heated humidifier. Performance of the Aerodyne was similar to that of the MR 730, with the same decrease in hygrometric performance when high ambient air and ventilator output temperatures were used (tables E1-E4).

- Visual evaluation of humidification. Condensation on the HH wall was closely correlated with absolute humidity of inspired gas when ambient air temperature was normal (P<0.0001, Rho=0.85) (Figure E1) but no correlation existed when ambient air temperature was high (Figure E2).

FIGURE LEGENDS

Figures E1 and E2: Visual evaluation of humidification. A close correlation was found between visual evaluation of humidification (condensation scale) and heated wire humidifier performance (absolute humidity (mg H_2O/L) of inspiratory gas) when ambient air was normal (22 to 24°C) (E1). No correlation existed when ambient air was high (28 to 30°C) (E2).

Table E1. Ventilator output temperatures (VOT) (expressed in °C, mean±SD).

Ventilator	VOT
TBird	39.0±2.1
Vela	39.3±1.6
LTV1000	51.0±4.0
Savina	32.4±3.5
Elisée	50.3±5.1
Bipap vision	40.7±5.2
PB760	32.3±4.7
Evita 4	30.1±2.7
PB 840	35.0±2.4
Servo i	29.2±1.9
Inspiration (event)	26.2±2.1
Galileo	27.8±3.8
Horus	26.8±3.3
Evita 2	35.0±2.2
PB7200	31.4±1.8
Bird 8400	35.1±2.1

Ventilator categories:

T-Bird to Bipap vision: turbine ventilators; PB 760 : piston ventilator; Evita 4 to Bird 8400: ICU ventilators

AAT: Ambient air temperature (expressed in °C. mean±SD)

The following ventilators were tested : Evita 4, Evita 2, Savina, Dräger Medical (Lübeck, Germany), TBird, Vela, 8400STi, Viasys Healthcare (Conshohocken, PA, USA), LTV 1000, Pulmonetic Systems (Minneapolis, Minnesota, USA), Bipap vision, Respironics, (Murrysville, PA, USA), Puritan Benett 840, Puritan Benett 760, Puritan Benett 7200, Tyco Healthcare (Mansfield, MA, USA), Servo i, Siemens Elema (Solna, Sweden), Galiléo, Hamilton Medical (Rhäzüns, Switzerland), Horus, Taema (Antony, France), Inspiration, eVent Medical Limited (Carlsbad, CA, USA), Elisée, Saime (Savigny le Temple, France)

Table E2. Hygrometry results under various conditions, with standard heated humidifier settings (for intubated patients). Absolute humidity (expressed in mg H_2O/L). Means±SD. In bold, values lower than 25 mg H_2O/L (increased risk of endotracheal tube occlusion)

AAT: Ambient air temperature

P<0.0001: high vs. normal AAT, Evita 4 vs. T-Bird, 10 vs. 20 L/min

		10 L/min		*20 L/min*	
AAT		**Normal**	**High**	**Normal**	**High**
EVITA 4					
Aerodyne	37/39	37.2±1.4	33.1±2.0	35.2±0.8	27.5±1.4
MR 730	37/40	34.6±1.7	25.2±0.1	35.8±1.9	**21.6±2.1**
T-BIRD 100% FiO_2					
Aerodyne	37/39	36.8±1.0	25.7±0.3	28.4±0.6	**21.4±1.7**
MR 730	37/40	31.8±0.4	26.4±2.1	30.7±0.4	**19.0±0.8**

Table E3. Hygrometry results under various conditions, with standard heated humidifier settings.

Relative humidity (expressed in %). Means±SD.

AAT: Ambient air temperature

P<0.0001: high vs. normal AAT, Evita 4 vs. T-Bird, 10 vs. 20 L/min

		10 L/min		*20 L/min*	
AAT		**Normal**	**High**	**Normal**	**High**
EVITA 4					
Aerodyne	37/39	90.6±4.1	80.0±3.4	81.0±0.6	63.8±1.8
MR 730	37/40	91.4±1.1	65.6±2.4	87.7±4.6	51.8±7.8
T-BIRD 100% FiO_2					
Aerodyne	37/39	91.7±4.7	60.5±2.1	67.2±0.6	48.4±4.4
MR 730	37/40	92.0±1.9	65.7±9.6	81.3±2.2	46.6±2.2

Table E4. Hygrometry results under the conditions associated with better performance: with the automatic compensation system (MR 850), with specific settings (no temperature gradient between outlet chamber temperature and Y-Piece), and with low FiO_2 and a turbine ventilator. Absolute humidity (expressed in mg H_2O/L). In bold, values lower than 25 mg H_2O/L (increased risk of endotracheal tube occlusion).

Means±SD

AAT: Ambient air temperature

MR 850		*10 L/min*		*20 L/min*	
Compensation		**Normal AAT**	**High AAT**	**Normal AAT**	**High AAT**
EVITA 4	*37/40*	35.4±0.4	32.9±1.9	35.1±2.8	31.0±2.6
T-Bird 100%	*37/40*	35.6±0.1	31.5±1.6	37.1±2.1	**23.8±0.2**

Specific settings		*10 L/min*		*20 L/min*	
No gradient		**Normal AAT**	**High AAT**	**Normal AAT**	**High AAT**
MR 730					
EVITA 4	40/40	36.7±0.2	35.0±0.4	40.5±0.3	29.3±2.5
T-Bird 100%	40/40	35.8±1.7	32.6±1.6	36.9±1.8	26.6±2.5
Aerodyne					
EVITA 4	39/39	41.5±1.2	39.6±2.1	40.6±1.2	32.9±1.7
T-Bird 100%	39/39	40.1±1.5	32.5±1.9	35.7±1.5	27.4±1.1

T-Bird 21%	*10 L/min*		*20 L/min*	
	Normal AAT	**High AAT**	**Normal AAT**	**High AAT**

MR 730				
37/40	34.3±1.2	27.6±1.6	33.5±3.5	**22.7±1.1**
40/40	36.4±1.0	38.5±2.0	38.3±1.7	31.2±2.3
Aerodyne				
37/39	39.5±0.5	30.6±1.3	32.0±1.5	27.7±1.3
39/39	41.1±1.0	36.8±1.5	39.1±0.6	33.7±1.3
Long dry line			*20 L/min*	
			Normal AAT	**High AAT**
MR 730				
37/40			35.8±1.7	**23.3±0.5**

Figure E1:

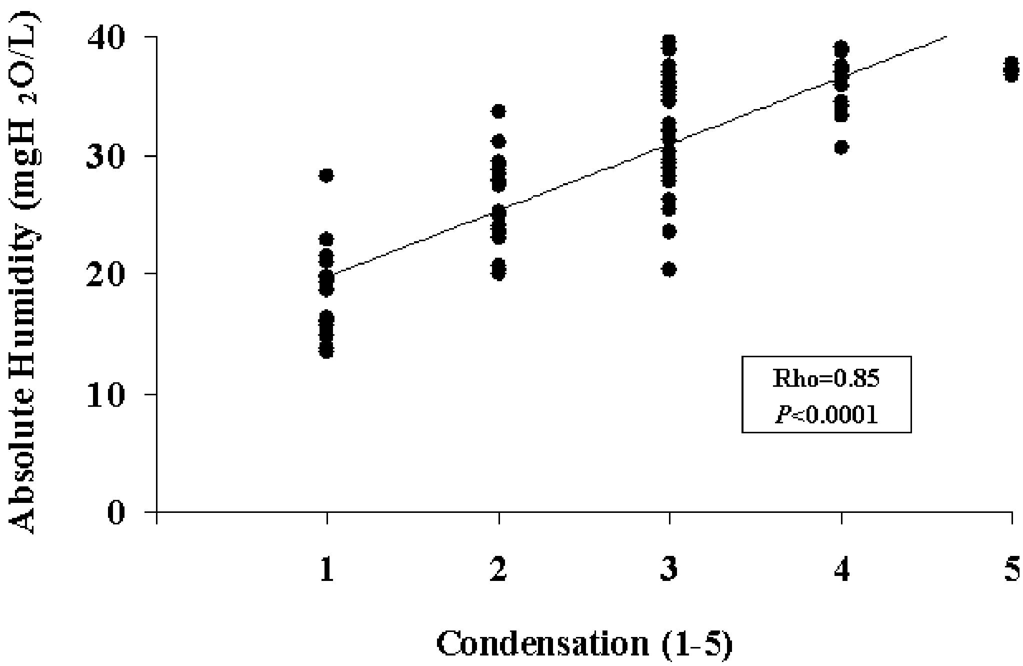
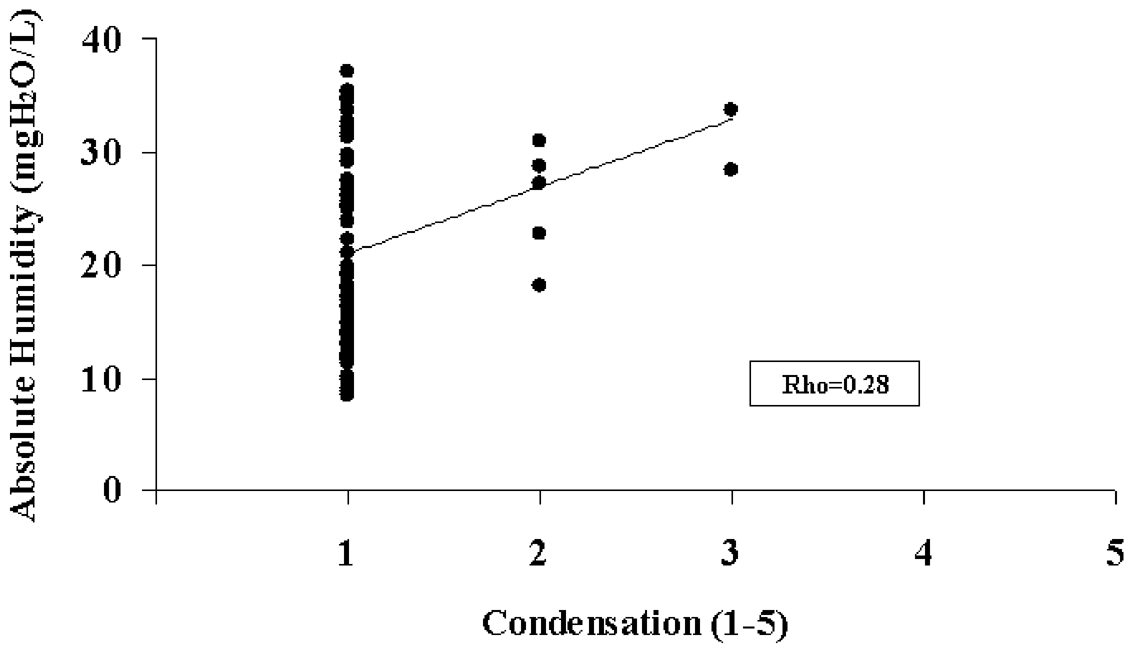

Absolute Humidity (mgH $_2$O/L)
40
30
20
10
0
1
2
3
4
5
Condensation (1-5)
Rho=0.85
P<0.0001

Figure E2:



Absolute Humidity (mgH2O/L)
40
30
20
10
0
Rho=0.28
1
2
3
4
5
Condensation (1-5)