

Influence of ambient temperature and minute ventilation on passive and active heat and moisture exchangers

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ABSTRACT

Background: During invasive mechanical ventilation, inspired gases must be humidified. We previously showed that high ambient temperature greatly impaired hygrometric performances of heated wire heated humidifiers. The aim of this bench and clinical study was to assess the humidification performances of passive and active heat and moisture exchangers (HME) and the impact of ambient temperature and ventilator settings.

Methods: We first tested on bench a device with passive and active humidification properties (Humid-Heat, Hudson), and two passive hydrophobic/hygroscopic HMEs (Hygrobac and Hygrobac-S, Mallinkrodt). The devices were tested at three different ambient temperature (from 22 to 30°C), and at two minute ventilations (10 and 20L/min). Inspired gas hygrometry was measured at Y-piece with the psychrometric method. In addition to the bench study, we measured hygrometry of inspired gases in two different clinical studies. In 15 mechanically ventilated patients, we evaluated Humid-Heat at different settings. Additionnaly, we evaluated Humid-Heat and compared it with Hygrobac in a cross-over study in 10 patients.

Results: On bench, with the Hygrobac and Hygrobac S, inspired absolute humidity was around 30 mgH₂O/L and with the Humid-Heat, slightly below 35 mgH₂O/L. Ambient temperature and minute ventilation did not have a clinically significant difference on the performances of the tested devices. During the clinical evaluation, Humid-Heat provided inspired humidity in a range from 28.5 mgH₂O/L to 42.0 mgH₂O/L, depending on settings, and was only weakly influenced by patient's body temperature.

Conclusion: in this study, both passive and active HME had stable humidification performances with negligible influence of ambient temperature and minute ventilation. This contrasts with previous findings with heated wire heated humidifiers. Although there is no clear data demonstrating that higher humidification impact outcomes, it is worth noting that humidity was significantly higher with the active HME.

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INTRODUCTION

Gas delivered to critically ill patients during invasive mechanical ventilation must be warmed and humidified to avoid complications associated with dry gases¹⁻³. The optimal humidification device to use is still not defined and it was recently shown that endotracheal tube resistances were significantly increased in patients using heat and moisture exchangers (HME) as well as heated humidifiers (HH)⁴. Most of the time, the inspiratory gases are humidified with HME or HH^{5, 6}. Active humidifiers have also been proposed to increase humidification performances but the place of these devices is not clear^{7, 8}.

With HH and passive HME, it has been shown that external conditions (ambient temperature, ventilator used or ventilator settings) and internal conditions (patient's core temperature) could interfere with humidification performances⁹⁻¹³. We have demonstrated in a previous study that high ambient temperature and turbine ventilators which generates high outlet temperature lead to the dysfunction of heated humidifiers with heated circuits¹⁰. The low humidification levels reached in these conditions are associated with potential risk of endotracheal tube occlusion or atelectasis^{11, 14-18}. With the first generation hydrophobic HMEs, it was shown that low ambient temperature could be responsible for reduced humidification performances¹³. Moreover, it has been shown in several clinical studies that the use of a hydrophobic HME with a minute ventilation higher than 10L/min could be harmful^{11, 19} and several guidelines recommend to avoid HMEs in this situation^{2, 20}. The impact of ambient temperature and minute ventilation on the latest generation of passive HMEs (hydrophobic and hygroscopic) and on active HMEs is not clear. The purpose of this study was to evaluate the impact of different levels of minute ventilation and different ambient temperatures on humidification performances of an active HME and of passive performing HMEs.

METHODS

Bench study

Protocol

The tested humidification systems were first evaluated on a hygrometric bench previously used for a large HME evaluation ²¹. The hygrometric bench included a motor ventilator (T-Bird ventilator) with two different minute ventilation levels: respiratory rate and tidal volume respectively 20 breath/min at 500 ml and 30 breath/min at 650 ml with positive end expiratory pressure of 5 cmH₂O and FiO₂ 100%. Expiratory gas was simulated by a heated humidifier set to deliver a gas at 33°C and 35 mgH₂O/L ²¹.

Three humidification systems were compared:

One active HME: Humid-Heat, dead space 54 ml (Hudson, Teleflex medical, Research Triangle Park, NC). This humidification device is based on a passive hygroscopic HME and an active component that includes external heat and the addition of water to the patients' side of the HME. The minute ventilation of the patient must be entered manually (with a maximum at 30L/min) to determine the quantity of water and heat added to the system ⁸. The aim is to increase the inspiratory humidity delivered to the patient as passive HME performances are limited by the amount of water contained in the expiratory gas. This device was set according to the tested minute ventilation (10 or 20L/min).

Two passive hygroscopic and hydrophobic HMEs:

- Hygrobac, dead space: 95 ml; resistances: 2.1 cmH₂O/l/s at 60L/min²² (Mallinkrodt, Tyco Healthcare, Raleigh, NC)
- Hygrobac S, dead space: 45 ml; resistances: 2.3 cmH₂O/l/s at 60L/min²² (Mallinkrodt, Tyco Healthcare, Raleigh, NC)

The ambient temperature was maintained constant at three different levels:
22-24°C, 24.5-25.5°C and 28-30°C.

Hygrometric measurements: we measured inspired gas humidity with the psychrometric method^{22, 23}. The temperatures recorded by the two probes (Eurotec srl, Bologna, Italy; accuracy at 0°C: $\pm 0.10^\circ\text{C}$, at 100°C: $\pm 0.27^\circ\text{C}$) were measured and displayed on a chart recorder (Yokogawa, Tokyo, Japan). To ensure that we measured the inspiratory gas humidity, the inspiratory and expiratory gases were separated by a specific device including two one-way valves to avoid gas mixing²³. We recorded maximal temperature values obtained during steady state measurements of the dry bulb and wet bulb temperatures, as previously described for the psychrometric method²². Three hygrometric measurements of inspired gases for each condition were performed by the psychrometric method after three hours of stability^{22, 23}. For each measurement, a new HME was used.

Clinical Study

This part of the study was approved by an independent review board (Comité d'Éthique de la Société de Réanimation de Langue Française). The patient's family was informed about the measurements performed. Inclusion criteria were mainly a respiratory stability ($\text{FiO}_2 \leq 80\%$) and hemodynamic stability (epinephrine or norepinephrine $\leq 2 \text{ mg/h}$) and with no procedure or intra-hospital transport planned on the day of the study. The clinical evaluations were unblinded by nature.

The first hygrometric evaluation of Humid-Heat with psychrometry was performed on 15 consecutive mechanically ventilated patients. Humid-Heat was set according to the patient's minute ventilation. The psychrometric measurements were performed 1 hour after the system had been installed.

We also performed a randomized cross-over study comparing humidification performances of Humid-Heat with different settings and Hygrobac. A psychrometric measurement was performed on 10 consecutive patients with the following humidification systems in a randomized order: passive HME (Hygrobac) and active HME (Humid-Heat) in 3 different conditions: setting according to the patient's minute ventilation (13.2 L/min on average), active component turned off (only passive properties evaluated), and set to the maximum setting, which provides humidification levels suitable for patients ventilated at levels of 30 L/min. Four patients participated to both clinical studies.

For the clinical evaluation, hygrometric measurements of inspiratory gases were performed after one hour of stability with the psychrometric method. The measurements were performed between the flex-tube and the HME, with a flow separator device containing two one-way valves inserted to measure only inspiratory gases humidity.

Statistical analysis

Data are expressed as mean \pm SD. Non parametric Friedman test and pairwise comparisons using Wilcoxon or Man-Whitney tests were performed to compare the different humidification devices and conditions tested. Spearman Rank correlation was performed between patient's core temperature and absolute humidity of inspired gas for the Humid-Heat device. *P* values smaller than 0.05 were considered significant.

RESULTS

Bench study

The mean \pm SD absolute humidity of inspired gases with Humid-Heat, Hygrobac and Hygrobac S were 34.5 \pm 0.8, 30.3 \pm 0.8 and 28.9 \pm 0.6 mgH₂O/L (P<0.0001) respectively. Humid-Heat had higher performances in comparison with Hygrobac (+ 4.2 \pm 0.4 mgH₂O/L, P=0.0002) and with Hygrobac S (+ 5.6 \pm 0.5 mgH₂O/L, P=0.0002) (figures 1 and 2).

The hygrometric performances of active and passive HMEs were not different at 10 or 20 L minute ventilation (figure 1). There was a statistically significant difference but not a clinically relevant influence of ambient temperature on these humidification devices (figure 2). The maximum differences in inspiratory humidity between the tested ambient temperatures were 1.5 mgH₂O/L with Humid-Heat, 1.7 mgH₂O/L with Hygrobac and 0.4 mgH₂O/L with Hygrobac S (figure 2).

Clinical study

Humid-Heat initial evaluation was conducted in 15 consecutive stable patients. Eight of them were ventilated with pressure support and seven in assist control ventilation. The humidification performances were slightly above those found in the bench study (37.5 \pm 3.1 vs. 34.5 \pm 0.8, P=0.0004). Patients mean core temperature was 37.7 \pm 0.9°C and ranged from 35.6 to 38.9°C, mean ambient temperature was 25.3 \pm 1.6°C. Mean minute ventilation was 12.4 \pm 3.7 L/min. There was no correlation between patient's core temperature and water content of inspired gases (figure 3).

The randomized cross-over study was performed on 10 patients with a mean minute ventilation of 13.2 \pm 4.8 L/min; six patients were ventilated with pressure support and four in

assist control ventilation. The mean ambient temperature was 24.2°C, and the patient's mean temperature was 37.6±0.8°C. Humidification performances of the different conditions are presented in the figure 4.

Humid-Heat humidification performances (i) were significantly higher than those of the tested HME (38.0±2.6 vs. 30.9±2.0 mgH₂O/L, P<0.001) when Humid Heat was set according to the manufacturer's recommendations, (ii) were slightly below the recommended threshold (28.5±2.2 mgH₂O/L) when the heated component of the Humid Heat was turned off (absence of heating and external water supply), which corresponds to a passive humidification. It must be noted that lowest absolute humidity values were around 25 mgH₂O/L in this condition (iii) were very high (42.0±1.4 mgH₂O/L) when minute ventilation was set to the maximum level (30L/min).

In the bench study as well as in the clinical study, the inspired gas temperatures were between 30 and 32°C with HMEs and between 34 and 37°C with the Humid-Heat.

DISCUSSION

In this study, we have demonstrated on a hygrometric bench that ambient temperature and minute ventilation had negligible influence on the humidification performances of two passive hygroscopic and hydrophobic HMEs (Hygrobac and Hygrobac S) and one active HME (Humid-Heat). The active HME provided water content in the inspiratory gas from 4.2 to 5.6 mgH₂O/L higher than the tested HMEs, depending on the conditions. In mechanically ventilated patients, active HME provided high levels of humidity (from 38 to 42 mgH₂O/L). Even when tested with the active component turned off, the active HME still provided satisfactory water content to most of the patients.

It was previously shown that heated wire HH performances could be strongly influenced by ambient temperature. Due to their working principles, in the case of high ambient temperatures, water content of inspired humidity fell around 20 mgH₂O/L with heated wire HH, well below the stated manufacturer's specifications, but with a partial correction when the compensation algorithm was activated¹⁰. However, it must be noted that this compensation algorithm was not available in North America, until very recently. In the present study, we demonstrated that ambient temperature had minimal influence on two hydrophobic-hygroscopic HMEs and one active HME. With the tested devices, we have observed a slight increase in absolute humidity delivered when measured at the highest ambient temperature (28-30°C). However, the psychrometric method may be slightly influenced by ambient temperature, which could in part explain these results¹³. The differences between high and low ambient temperatures was less than 2 mgH₂O/L for all the tested devices, which may not be clinically relevant. Overall, the performances of passive and active HMEs remained stable whatever the tested conditions. We measured humidity in the inspiratory gases near 30 mgH₂O/L (Hygrobac-S) or slightly above (Hygrobac), which is

close to the values found in the literature ^{11, 17} and in our previous studies with the same hygrometric method ^{9, 21}. With active HME, the delivered humidity was around 35 mgH₂O/L in the bench study and close to 40 mgH₂O/L in the clinical study.

There is no previous study, to our knowledge, that assessed the impact of ambient temperature on active HME performance to compare with our data. One study evaluated the impact of this factor on a passive HME. Croci and al. had demonstrated in a bench study using the psychrometric method, that hydrophobic HMEs could be slightly influenced by ambient temperature ¹³. The differences were little, about 2 mgH₂O/L, favouring 26°C of ambient temperature in comparison with 20°C. The authors concluded that clinical impact was likely negligible.

Likewise, the minute ventilation did not influence the performances of the tested devices in this study, unlike the initial report by Martin et al. ^{11, 19}. In these studies, the HME used (Pall BB2215) was less efficient than the ones we used in the present study and was only hydrophobic, while the HMEs used in our study are both hygroscopic and hydrophobic ²². In a subsequent study, Martin et al. also demonstrated that hygroscopic and hydrophobic HMEs maintained acceptable performances in patients with minute ventilation higher than 10L/min ²⁴. Therefore, the minute ventilation should no longer be considered a contra indication to using the last generation's HMEs, as previously stated ^{2, 20}.

Active heat and moisture exchangers were developed to improve humidification performances of HMEs ⁷. At this time, hydrophobic HMEs had poor performances leading to high rates of endotracheal tube occlusions ^{11, 14-18}. Larsson et al. evaluated Humid-Heat with gravimetric method ⁸. They found humidification levels higher than 40 mgH₂O/L, but the water content of expiratory gases was 40.7 mgH₂O/L, which is higher than we used on our

bench (35 mgH₂O/L). This difference in water content in the expiratory gases on these two models probably explains the discrepancy in the Humid-Heat performances. We based our simulation of the expiratory gases on the clinical data in the literature reporting measured expiratory humidity^{9,25}. In our study, Humid-Heat delivered inspiratory water content of 34.5 mgH₂O/L on the bench and 37.5 mgH₂O/L in patients. This difference is likely related to the patient's temperature, leading to higher expiratory humidity and consequently higher inspiratory humidity⁹. In our study there was no statistically significant correlation between the patient's core temperature and inspiratory temperature with the Humid-Heat. This is different to what has been previously been reported with HMEs⁹. In a previous study, we evaluated Humid-Heat and Hygrobac in the setting of hypothermia and showed the influence of core temperature on the humidification performances of HMEs⁹. Pelosi et al evaluated the Hygrovent Gold active humidifier (Medisize) and the Hygrobac HME in a bench study and demonstrated the absence of any impact of minute ventilation on these devices¹². They also noted reduced humidification performances with both passive and active HME in the case of simulated hypothermia¹². Other active HMEs were tested and provided data in line with our results, with better hygrometric performances in comparison with last generation HMEs and with the possibility to maintain adequate humidity when the active function is turned on or is turned off^{26,27}.

It may be justified to seek systems that improve humidification performances with stable levels above 35 mgH₂O/L. Indeed, there are very seldom endotracheal tube occlusions when humidification devices deliver inspiratory water content around 30 mgH₂O/L^{3,22}. However, more subtle and early markers demonstrate that optimal humidification is still not achieved with the current humidification devices. Moran et al. compared the endotracheal tube resistance before and after utilization in 44 mechanically ventilated patients with gas humidified by heated humidifier or HME⁴. They found in both groups similar and clinically

relevant increase of the tube resistance by an average of 53 %. Other authors found progressive reduction of endotracheal tube diameter with different humidification devices²⁸⁻³⁰. In this regard, active HMEs providing humidity near 40 mgH₂O/L may theoretically be interesting to consider, but there is currently no clinical demonstration of the superiority of delivering 40 vs 30 mgH₂O/L. We have demonstrated higher humidification performance with the Humid-Heat than the comparison HMEs in both a bench and clinical study. The comparator HMEs chosen were amongst the best performing in a previous study of 48 different HMEs. However, active HMEs are more expensive and more complex to use than passive HMEs²². When compared with previous studies, Humid-Heat outperformed heated humidifiers in the case of high ambient temperature¹⁰ but important issues with existing passive HMEs (i.e dead space) are still present with active HME. Finally, due to the possible condensation in the small airways, there is a risk of over-humidification when inspiratory gases are above 44 mgH₂O/L^{31,32}, or even below if core temperature is below 37°C⁹. We do not have clinical experience with humidification devices that really provide 40 mgH₂O/L or above, such as Humid-Heat. Indeed, when considering independent evaluations, best performing HME provide 30 mgH₂O/L or slightly above²² and heated wire HH provides 36 mgH₂O/L within optimal conditions of utilization^{10,33}. The hygrometric levels reached with the maximal minute ventilation (30L/min), approaching 44 mgH₂O/L, could eventually lead to over-humidification. For all of these reasons, the clinical indication of active HMEs remains unclear.

Our study provides data of clinical relevance as we have demonstrated stable humidification performances of the tested devices (passive and active HMEs) when minute ventilation or ambient temperature vary, which are frequent clinical situations. Clinicians must be aware of the variability in performance of heated wire HH during conditions leading to high temperatures in the humidification chamber (i.e high ambient temperature, sun on the

humidifier or some turbines ventilators)¹⁰. In addition, clinicians must know the impact of the patient's core temperature on passive and active HMEs with reduced humidification performances seen in the case of hypothermia^{9, 12}.

Our study has a number of limitations. First, the study design did not allow evaluation of the long term impact of these humidification devices on important clinical outcome such as tube resistance or endotracheal tube occlusions. It is not possible to conclude with the current data that *higher* humidification performances are *better* for patients. Second, there are differences of 3 mgH₂O/L in inspiratory humidity between the bench and the clinical evaluation. This discrepancy may be related to the patient core temperature of 37.7°C in the clinical evaluation, while the bench delivers an expiratory humidity based on clinical measurements while patient's core temperature was 36.5°C^{9, 34}. One degree of difference, may account for a difference of 2 mgH₂O/L for a saturated gas, which may explain in part the difference between the bench and the clinical evaluation. Finally, in our study, there was no evaluation of the clinical tolerance with prolonged use of systems that deliver humidity above 40 mgH₂O/L. Clinicians should be cautious as there is limited clinical experience with such conditions of humidification, which could lead to increased secretions and micro-atelectasis as described in animals^{35, 36}.

In conclusion, humidification performances of passive, performing, hygroscopic and hydrophobic HMEs and of active HME are not influenced by minute ventilation in the conditions tested in the present study, and ambient temperature has only a negligible influence. These systems are stable over a range of tested external conditions, and there is no reason to avoid their use in the case of high ambient temperature or in the case of high minute ventilation². Clinicians should know the working principles of the humidification devices and must be aware of the influence of patient's temperature on these devices, with reduced

humidity delivered to the patients in the case of hypothermia^{9, 12}. Heated wire HH are influenced by external factors (especially by high ambient temperature)¹⁰ but not by patient's temperature⁹. These influences should be known by the clinicians and new devices with limited influence should be developed to optimize humidification strategies. Among alternative humidification devices, the active HME evaluated in this study demonstrated very high levels of humidification, but these systems share with HME the problems related to dead space³⁷⁻³⁹ and are more complex to use. To date, there is no clinical data to recommend utilization of active HMEs.

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FIGURE LEGENDS

Figure 1: Bench hygrometric performances of the active HME (Humid-Heat) and of two passive HMEs (Hygrobac and Hygrobac S) at two levels of minute ventilation, 10 L/min and 20 L/min. Data for ambient temperature of 25°C are displayed. Bars represent the mean and error bars represent standard deviation.

Figure 2: Bench hygrometric performances of the active HME (Humid-Heat) and of two passive HMEs (Hygrobac and Hygrobac S) at different ambient temperatures (22-24, 25 and 28-30°C). Mean±SD temperatures during the different study conditions for ambient temperature were 22.4±0.4°C; 25.1±0.3°C and 29.4±0.6°C. Data for a minute ventilation of 10L/min are displayed. Bars represent the mean and error bars represent standard deviation.

* p<0.05 comparison between 22-24 and 25°C

† p<0.05 comparison between 22-24 and 28-30°C

□ p<0.05 comparison between 25 and 28-30°C

Figure 3: Spearman Rank correlation between absolute humidity and patient's core temperature with Humid Heat. There is no correlation for these parameters with Humid-Heat (R=0.37, p=0.17), as not only core temperature, correlated with humidity of gas during exhalation, explains the humidification performances with active HME.

Figure 4: Clinical measurements of inspiratory humidity of a passive HME (Hygrobac) and of active HME with different settings: HH turned off, Humid-Heat set with patient's minute ventilation and HH set at 30L/Min. Individual data of 10 mechanically ventilated patients and mean value (black dotted line) are displayed.

All six comparisons were statistically significant with Wilcoxon pairwise comparison (all P values < 0.05). Patient's core temperature were 37.8±0.8, 37.6±0.8, 37.4±1.1 and 37.8±0.4°C (p value=0.80).

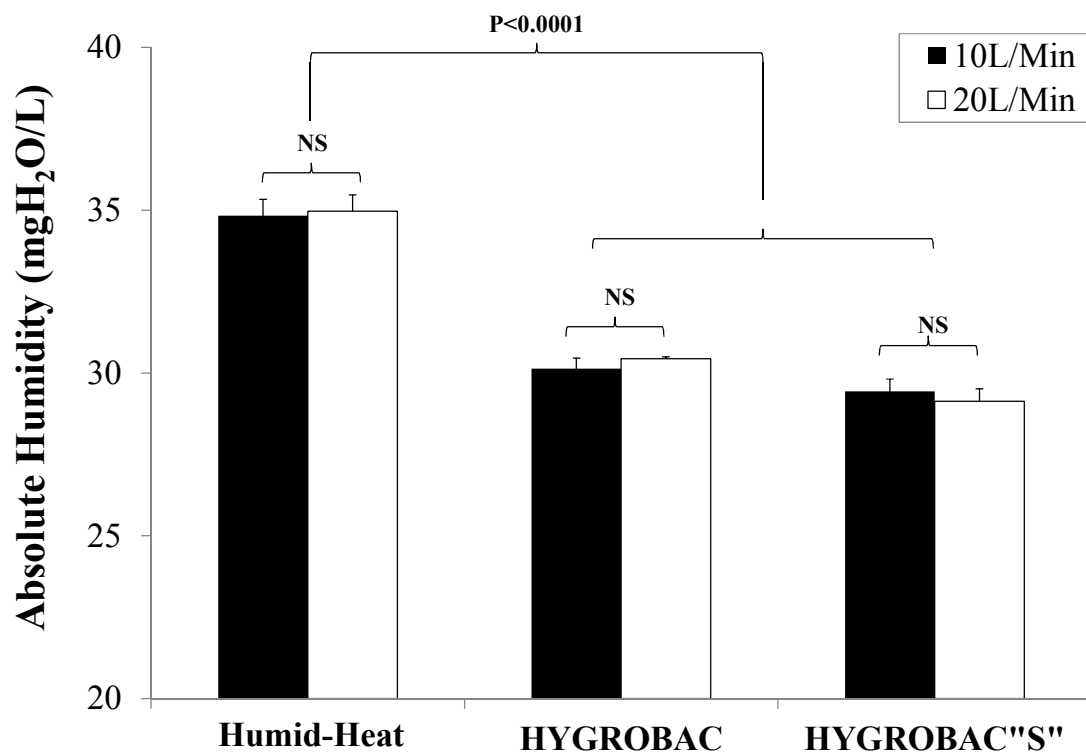


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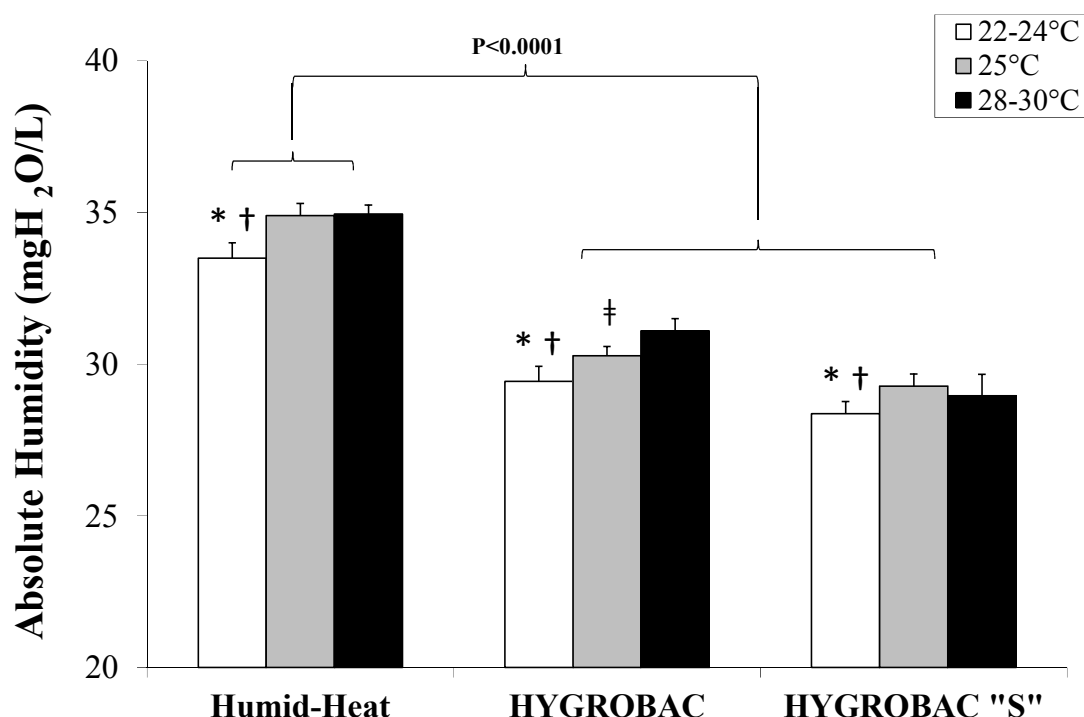


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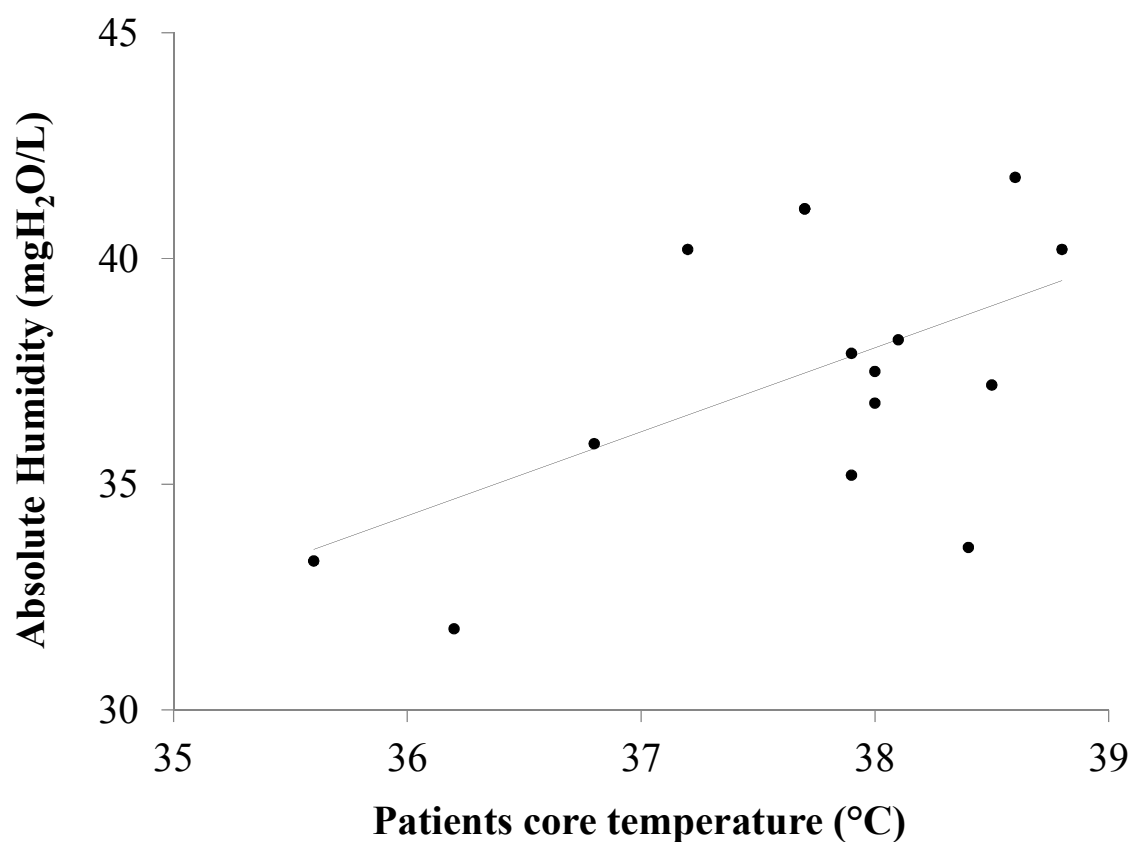


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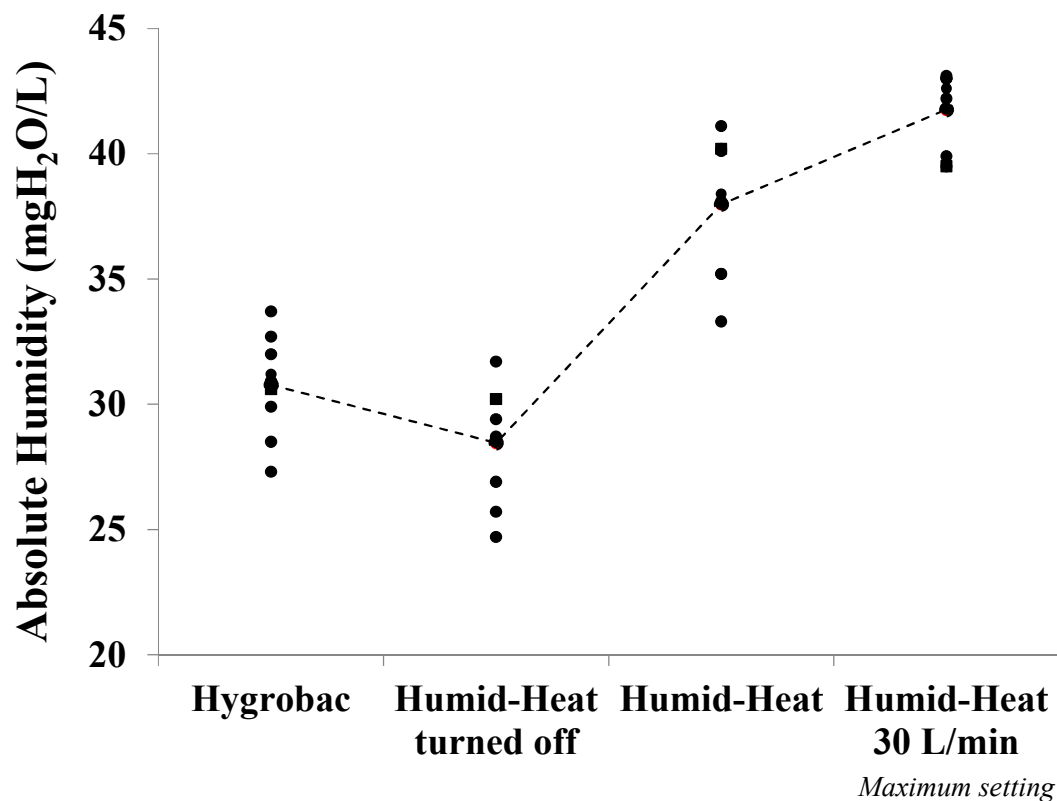


Figure 4: Clinical measurements of inspiratory humidity of a passive HME (Hygrobac) and of active HME with different settings: HH turned off, Humid-Heat set with patient's minute ventilation and HH set at 30L/Min (maximum setting). Individual data of 10 mechanically ventilated patients and mean value (black dotted line) are displayed. All six comparisons were statistically significant with Wilcoxon pairwise comparison (all P values < 0.05). Patient's core temperature were 37.8 ± 0.8 , 37.6 ± 0.8 , 37.4 ± 1.1 and $37.8 \pm 0.4^\circ\text{C}$ (p value=0.80).