# Influence of Ambient Temperature and Minute Ventilation on Passive and Active Heat and Moisture Exchangers

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**OBJECTIVE: During invasive mechanical ventilation, inspired gases must be humidified. We previously showed that high ambient temperature greatly impaired the hygrometric performance of heated wire-heated humidifiers. The aim of this bench and clinical study was to assess the humidification performance of passive and active heat and moisture exchangers (HMEs) and the impact of ambient temperature and ventilator settings. METHODS: We first tested on the bench a device with passive and active humidification properties (Humid-Heat, Teleflex), and 2 passive hydrophobic/hygroscopic HMEs (Hygrobac and Hygrobac S, Tyco Healthcare). The devices were tested at 3 different ambient temperatures (from 22 to 30°C), and at 2 minute ventilation settings (10 and 20 L/min). Inspired gas hygrometry was measured at the Y-piece with the psychrometric method. In addition to the bench study, we measured the hygrometry of inspired gases in 2 different clinical studies. In 15 mechanically ventilated patients, we evaluated Humid-Heat at different settings. Additionally, we evaluated Humid-Heat and compared it with Hygrobac in a crossover study in 10 patients. RESULTS: On the bench, with the Hygrobac and Hygrobac S the inspired absolute humidity was ~30 mg $H_2O$/L, and with the Humid-Heat, slightly < 35 mg $H_2O$/L. Ambient temperature and minute ventilation did not have a clinically important difference on the performance of the tested devices. During the clinical evaluation, Humid-Heat provided inspired humidity in a range from 28.5 to 42.0 mg $H_2O$/L, depending on settings, and was only weakly influenced by the patient's body temperature. CONCLUSIONS: In this study both passive and active HMEs had stable humidification performance with negligible influence of ambient temperature and minute ventilation. This contrasts with previous findings with heated wire-heated humidifiers. Although there are no clear data demonstrating that higher humidification impacts outcomes, it is worth noting that humidity was significantly higher with the active HME.** *Key words: Mechanical ventilation; humidification; critically ill patients; heat and moisture exchangers.* [Respir Care 2014;59(5):637–643. 

## Introduction

Gas delivered to critically ill patients during invasive mechanical ventilation must be warmed and humidified to avoid complications associated with dry gases.[1-3] The optimal humidification device to use is still not defined, andit was recently shown that endotracheal tube resistances were significantly increased in patients using heat and moisture exchangers (HMEs) as well as heated humidifiers (HHs).[4] Most of the time, the inspiratory gases are humidified with

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HMEs or HHs.[5,6] Active humidifiers have also been proposed to increase humidification performance, but the place of these devices is not clear.[7,8]

With HHs and passive HMEs, 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 performance.[9-13] We demonstrated in a previous study[10] that high ambient temperature and turbine ventilators that generate high outlet temperature led to the dysfunction of HHs with heated circuits. 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 performance.[13] Moreover, it has been shown in several clinical studies that the use of a hydrophobic HME with a minute ventilation > 10 L/min could be harmful,[11,19] and several guidelines recommend avoiding 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 performance of an active HME and of passive performing HMEs.

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**QUICK LOOK**

**Current knowledge**

Following tracheal intubation for invasive mechanical ventilation, heating and humidifying inspired gas is a standard of care. Both heated humidifiers and heat and moisture exchangers (HMEs) are commonly used.

**What this paper contributes to our knowledge**

The humidification performance of passive and active HMEs is not influenced by minute ventilation up to 30 L/min.

## 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 2 different minute ventilation levels (respiratory rate 20 breaths/min at 500 mL; tidal volume 30 breath/min at 650 mL; PEEP 5 cm $H_2O$; and $F_{IO_2}$ 100%). Expiratory gas was simulated by an HH set to deliver a gas at 33°C and 35 mg $H_2O$/L.[21]

Three humidification systems were compared. (1) One active HME (dead space 54 mL; Hudson Humid-Heat, Teleflex Medical, Research Triangle Park, North Carolina) was studied. 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 30 L/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 because passive HME performance is limited by the amount of water contained in the expiratory gas. This device was set according to the tested minute ventilation (10 or 20 L/min). There were also 2 passive hygroscopic and hydrophobic HMEs: (2) Hygrobac (dead space 95 mL; resistances 2.1 cm $H_2O$/L/s at 60 L/min[21]; Tyco Healthcare, Raleigh, North Carolina) and (3) Hygrobac S (dead space 45 mL; resistances 2.3 cm $H_2O$/L/s at 60 L/min[21]; Tyco Healthcare). The ambient temperature was maintained constant at 3 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.[21,22] The temperatures recorded by the 2 probes (Eurotec srl, Bologna, Italy; accuracy at 0: ±0.10°C; accuracy at 100°C: ±0.27°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 2 one-way valves to avoid gas mixing.[22] We recorded maximal temperature values obtained during steady-state measurements of the dry bulb and wet bulb temperatures, as previously described for the psychometric method.[21] Three hygrometric measurements of inspired gases for each condition were performed by the psychrometric method after 3 h of stability.[21,22] For each measurement, a new HME was used.

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### 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 respiratory stability ($F_{IO_2} \leq 80\%$) and hemodynamic stability (epinephrine or norepinephrine $\leq$ 2 mg/h) and with no procedure or intrahospital transport planned on the day of the study. The clinical evaluations were unblinded by nature.

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

We also performed a randomized crossover study comparing the humidification performance of the Humid-Heat device with different settings and the Hygrobac device. 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 (set according to the patient's minute ventilation [13.2 L/min on average]; set with the 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 in both clinical studies.

For the clinical evaluation, hygrometric measurements of inspiratory gases were performed after 1 h of stability with the psychrometric method. The measurements were performed between the flex-tube and the HME, with a flow separator device containing 2 one-way valves inserted to measure only the humidity of inspiratory gases.

### Statistical Analysis

Data are expressed as the mean ± SD. Nonparametric Friedman test and pairwise comparisons using Wilcoxon or Mann-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 $< .05$ were considered significant.

## Results

### Bench Study

The mean ± SD absolute humidity of inspired gases with the Humid-Heat, Hygrobac, and Hygrobac S devices were 34.5 ± 0.8, 30.3 ± 0.8 and 28.9 ± 0.6 mg $H_2O$/L ($P < .0001$), respectively. The Humid-Heat device had higher performance values compared with the Hygrobac device (4.2 ± 0.4 mg $H_2O$/L, $P = .0002$) and the Hygrobac S device (5.6 ± 0.5 mg $H_2O$/L, $P = .0002$) (Figs. 1 and 2).

The hygrometric performance of active and passive HMEs were not different at 10 or 20 L/min ventilation (Fig. 1). There was a statistically significant difference but not a clinically relevant influence of ambient temperature on these humidification devices (Fig. 2). The maximum

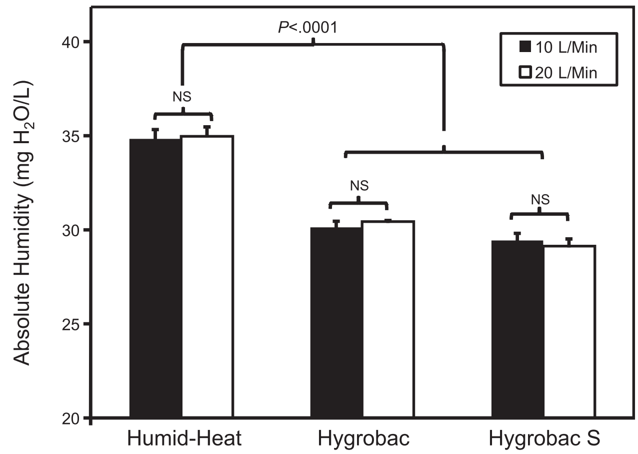


Fig. 1. Bench hygrometric performance of the active HME (Humid-Heat) and 2 passive HMEs (Hygrobac and Hygrobac S) at 2 levels of minute ventilation (10 and 20 L/min). Data for an ambient temperature of 25°C are displayed. Bars represent the mean, and error bars represent the SD.

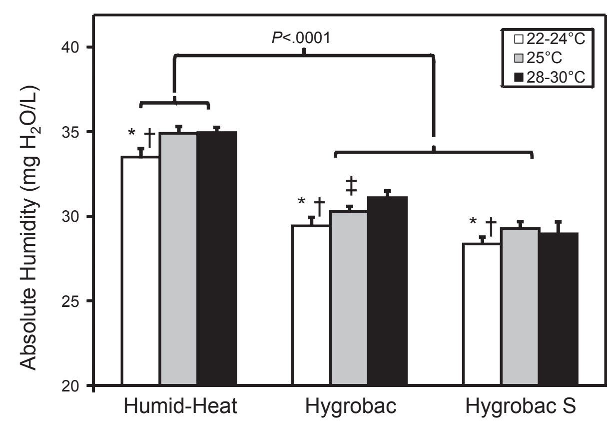


Fig. 2. Bench hygrometric performance of the active HME (Humid-Heat) and 2 passive HMEs (Hygrobac and Hygrobac S) at different ambient temperatures (22–24, 25, and 28–30°C). Mean ± SD temperatures during the different study conditions for ambient temperature were 22.4 ± 0.4°C, 25.1 ± 0.3°C, and 29.4 ± 0.6°C. Data for a minute ventilation of 10 L/min are displayed. Bars represent the mean, and error bars represent the SD. * $P < .05$ comparison between 22–24 and 25°C. † $P < .05$ comparison between 22–24 and 28–30°C. ‡ $P < .05$ comparison between 25 and 28–30°C.

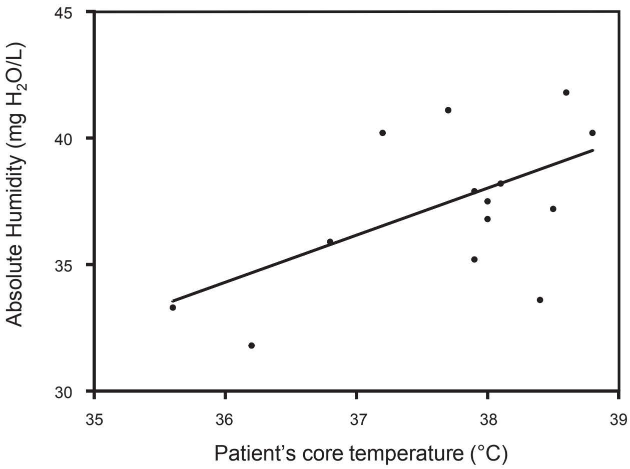


Fig. 3. Spearman rank correlation between absolute humidity and the patient's core temperature with the Humid-Heat device. There is no correlation for these parameters with the Humid-Heat device ($R = 0.37$, $P = .17$) because core temperature, correlated with the humidity of gas during exhalation, is not the only explanation of the humidification performance with the active HME.

differences in inspiratory humidity between the tested ambient temperatures were 1.5 mg $H_2O$/L with the Humid-Heat, 1.7 mg $H_2O$/L with the Hygrobac, and 0.4 mg $H_2O$/L with the Hygrobac S (Fig. 2).

### Clinical Study

The initial evaluation of the Humid-Heat device was conducted in 15 consecutive stable patients. Eight of the patients received ventilation with pressure support, and 7 in continuous mandatory ventilation. The humidification performance was slightly above those found in the bench study (37.5 ± 3.1 vs 34.5 ± 0.8, $P = .0004$). Patients' mean core temperature was 37.7 ± 0.9°C (range 35.6–38.9°C), and the mean ambient temperature was 25.3 ± 1.6°C. The mean minute ventilation was 12.4 ± 3.7 L/min. There was no correlation between the patient's core temperature and the water content of inspired gases (Fig. 3).

The randomized crossover study was performed on 10 patients with a mean minute ventilation of 13.2 ± 4.8 L/min; 6 patients received ventilation with pressure support, and 4 received continuous mandatory ventilation. The mean ambient temperature was 24.2°C, and the patient's mean temperature was 37.6 ± 0.8°C. Humidification performance values under the different conditions are presented in Figure 4.

The humidification performance values of the Humid-Heat device (1) were significantly higher than those of the tested HME (38.0 ± 2.6 vs 30.9 ± 2.0 mg $H_2O$/L, $P < .001$) when the Humid Heat was set according to the manufacturer's recommendations; (2) were slightly below the rec-

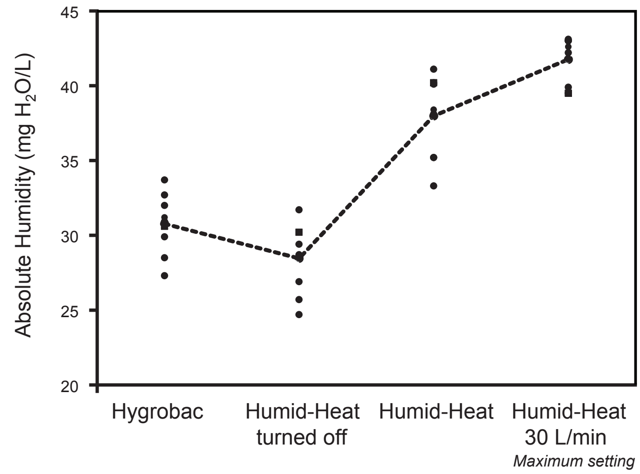


Fig. 4. Clinical measurements of inspiratory humidity of a passive HME (Hygrobac) and an active HME with different settings: HH turned off; Humid-Heat device set with patient's minute ventilation; and HH set at 30 L/min. Individual data of 10 mechanically ventilated patients and the mean value (black dotted line) are displayed. All 6 comparisons were statistically significant with Wilcoxon pairwise comparison (all $P$ values < .05). The patients' core temperatures were 37.8 ± 0.8, 37.6 ± 0.8, 37.4 ± 1.1, and 37.8 ± 0.4°C ($P$ value = .80).

ommended threshold (28.5 ± 2.2 mg $H_2O$/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 the lowest absolute humidity values were ~25 mg $H_2O$/L in this condition); and (3) were very high (42.0 ± 1.4 mg $H_2O$/L) when minute ventilation was set to the maximum level (30 L/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 device.

## Discussion

In this study, we have demonstrated on a hygrometric bench that ambient temperature and minute ventilation had negligible influence on the humidification performance of 2 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 mg $H_2O$/L higher than in the tested HMEs, depending on the conditions. In mechanically ventilated patients, the active HME provided high levels of humidity (from 38 to 42 mg $H_2O$/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 performance 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 ~20 mg $H_2O$/L with heated wire HH, well below the manufacturer's stated specifications, but with a partial correction when the compensation algorithm was activated.[10] 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 2 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 psychrometic method may be slightly influenced by ambient temperature, which could in part explain these results.[13] The differences between high and low ambient temperatures was $< 2$ mg $H_2O$/L for all the tested devices, which may not be clinically relevant. Overall, the performance of passive and active HMEs remained stable whatever the tested conditions. We measured humidity in the inspiratory gases near 30 mg $H_2O$/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 the active HME, the delivered humidity was ~35 mg $H_2O$/L in the bench study and close to 40 mg $H_2O$/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 et al[13] had demonstrated in a bench study using the psychrometric method that hydrophobic HMEs could be slightly influenced by ambient temperature. The differences were small, ~2 mg $H_2O$/L, favoring 26°C of ambient temperature in comparison with 20°C. The authors concluded that the clinical impact was likely negligible.

Likewise, the minute ventilation did not influence the performance of the tested devices in this study, unlike the initial report by Martin et al.[11,19] In these studies, the HME used (BB2215, Pall) was less efficient than the ones we used in the present study and was only hydrophobic, whereas the HMEs used in our study were both hygroscopic and hydrophobic.[21] In a subsequent study, Martin et al[23] also demonstrated that hygroscopic and hydrophobic HMEs maintained acceptable performance in patients with minute ventilation $> 10$ L/min. Therefore, the minute ventilation should no longer be considered a contraindication to using HMEs of the last generation, as previously stated.[2,20]

Active HMEs were developed to improve the humidification performance of the HMEs.[7] At that time hydrophobic HMEs had poor performance, leading to high rates of endotracheal tube occlusions.[11,14-18] Larsson et al[8] evaluated the Humid-Heat device using the gravimetric method. They found humidification levels $> 40$ mg $H_2O$/L, but the water content of expiratory gases was 40.7 mg $H_2O$/L, which is higher than we used on our bench (35 mg $H_2O$/L). This difference in water content in the expiratory gases on these 2 models probably explains the discrepancy in the Humid-Heat performance. We based our simulation of the expiratory gases on the clinical data in the literature reporting measured expiratory humidity.[9,24] In our study, the Humid-Heat device delivered inspiratory water content of 34.5 mg $H_2O$/L on the bench and 37.5 mg $H_2O$/L in patients. This difference is likely related to the patient's temperature, leading to higher expiratory humidity and consequently higher inspiratory humidity.[9] 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 previously been reported with HMEs.[9] In a previous study we evaluated the Humid-Heat and Hygrobac devices in the setting of hypothermia, and showed the influence of core temperature on the humidification performance of HMEs.[9] Pelosi et al[12] 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 devices. They also noted reduced humidification performance with both passive and active HMEs in the case of simulated hypothermia.[12] Other active HMEs were tested and provided data in line with our results, with better hygrometric performance in comparison with the last generation of HMEs and with the possibility of maintaining adequate humidity when the active function is turned on or off.[25,26]

It may be justified to seek systems that improve humidification performance with stable levels $> 35$ mg $H_2O$/L. Indeed, there are very seldom endotracheal tube occlusions when humidification devices deliver inspiratory water content of ~30 mg $H_2O$/L.[3,21] However, more subtle and early markers demonstrate that optimal humidification is still not achieved with the current humidification devices. Moran et al[4] compared the endotracheal tube resistance before and after utilization in 44 mechanically ventilated patients with gas humidified by HH or HME. They found in both groups a similar and clinically relevant increase in tube resistance by an average of 53%. Other authors found progressive reduction of endotracheal tube diameter with different humidification devices.[27-29] In this regard, active HMEs providing humidity near 40 mg $H_2O$/L may theoretically be interesting to consider, but there is currently no clinical demonstration of the superiority of delivering 40 versus 30 mg $H_2O$/L. We have demonstrated higher humidification performance with the Humid-Heat device than in the comparison HMEs in both a bench and a clinical study. The comparator HMEs chosen were among the best performing in a previous study of 48 different HMEs. However, active HMEs are more expensive and more complex to use than passive HMEs.[21] When compared with previous studies, the Humid-Heat device outperformed HHs in the case of high ambient temperature,[10] but important issues with existing passive HMEs (ie, dead space) are still present with active HMEs. Finally, due to the possible condensation in the small airways, there is a risk of overhumidification when inspiratory gases are > 44 mg $H_2O$/L,[30,31] or even below that level if core temperature is < 37°C.[9] We do not have clinical experience with humidification devices that really provide ≥ 40 mg $H_2O$/L, such as the Humid-Heat device. Indeed, when considering independent evaluations, the best-performing HMEs provide a level of 30 mg $H_2O$/L or slightly above[21] and heated wire HHs provide a level of 36 mg $H_2O$/L within optimal conditions of utilization.[10,32] The hygrometric levels reached with the maximal minute ventilation (30 L/min), approaching 44 mg $H_2O$/L, could eventually lead to overhumidification. For all of these reasons, the clinical indication of active HMEs remains unclear.

Our study provides data of clinical relevance as we have demonstrated the stable humidification performance 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 HHs during conditions leading to high temperatures in the humidification chamber (ie, high ambient temperature, sun on the humidifier or some turbine ventilators).[10] In addition, clinicians must know the impact of the patient's core temperature on passive and active HMEs with reduced humidification performance 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 outcomes such as tube resistance or endotracheal tube occlusions. It is not possible to conclude with the current data that higher humidification performance is better for patients. Second, there are differences of 3 mg $H_2O$/L in inspiratory humidity between the bench and the clinical evaluation. This discrepancy may be related to the patient's 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.[9,33] One degree of difference, may account for a difference of 2 mg $H_2O$/L for a saturated gas, which may in part explain 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 > 40 mg $H_2O$/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 has been described in animals.[34,35]

In conclusion, the humidification performance of passive, performing, hygroscopic and hydrophobic HMEs, and of active HMEs is 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 ventilation.[2] Clinicians should know the working principles of the humidification devices and must be aware of the influence of a patient's temperature on these devices, with reduced humidity delivered to the patients in the case of hypothermia.[9,12] Heated wire HHs are influenced by external factors (especially by high ambient temperature)[10] but not by the patient's temperature.[9] 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 space[36-38] and are more complex to use. To date, there are no clinical data to recommend the use of active HMEs.

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