In Vitro Evaluation of an Active Heat-and-Moisture Exchanger: The Hygrovent Gold

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BACKGROUND: To improve the heat and humidification that can be achieved with a heat-and-moisture exchanger (HME), a hybrid active (ie, adds heat and water) HME, the Hygrovent Gold, was developed. We evaluated in vitro the performance of the Hygrovent Gold. METHODS: We tested the Hygrovent Gold (with and without its supplemental heat and moisture options activated), the Hygrobac, and the Hygrovent S. We measured the absolute humidity, using a test lung ventilated at minute volumes of 5, 10, and 15 L/min, in normothermic (expired temperature 34°C) and hypothermic (expired temperature 28°C) conditions. We also measured the HMEs' flow resistance and weight after 24 h and 48 h. RESULTS: In its active mode the Hygrovent Gold provided the highest absolute humidity, independent of minute volume, in both normothermia and hypothermia. The respective normothermia and hypothermia absolute humidity values at 10 L/min were 36.3 ± 1.3 mg/L and 27.1 ± 1.0 mg/L with the active Hygrovent Gold, 33.9 ± 0.5 mg/L and 24.2 ± 0.8 mg/L with the passive Hygrovent Gold, 33.8 ± 0.56 mg/L and 24.4 ± 0.4 mg/L with the Hygrobac, and 33.9 ± 0.8 mg/L and 24.6 ± 0.6 mg/L with the Hygrovent S. The efficiency of the tested HMEs did not change over time. At 24 h and 48 h the increase in weight and flow resistance was highest in the active Hygrovent Gold. CONCLUSIONS: The passive Hygrovent Gold provided adequate heat and moisture in normothermia, but the active Hygrovent Gold provided the highest humidity, in both normothermia and hypothermia. *Key words: mechanical ventilation; humidification; humidity; heat-and-moisture exchanger; air flow resistance.* [Respir Care 2010;55(4):460–466.

Introduction

During normal breathing the upper airways heat and humidify inspired gas and thus prevent drying of the mucosal membranes and other structures.[1] Therefore, during invasive mechanical ventilation, when the upper airways are bypassed by an endotracheal tube, the inspired gas must be heated and humidified[2] to avoid damage to the respiratory epithelium, alterations in respiratory function, and heat loss.[3,4] Conversely, animal studies (which used an ultrasonic nebulizer) showed that over-humidification can also cause injuries and alter respiratory function.[1,5] In our opinion, an optimal humidification system has the following properties: adequate heat and humidification, irrespective of the ambient temperature, the patient's temperature, or minute volume ($\dot{V}_E$); the lowest possible dead space and flow resistance; no condensate; ease of use; low cost.

The 2 most commonly used types of humidification device are heated humidifier and heat-and-moisture exchanger (HME).[6,7] Heated humidifier provides adequate humidity and temperature, and does not affect the breathing pattern, but can cause over-humidification at higher

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temperatures, and allow circuit condensation,[8,9] which increases the risk of circuit bacterial colonization.[10,11] Heated humidifiers are also expensive.

HMEs are efficient, avoid circuit condensate, and are less expensive.[12,13] However, HME may not provide adequate heat and humidity during ventilation with large $\dot{V}_E$,[14] or when body temperature is low,[15] or when exhaled gas is lost.[16] Furthermore, because HMEs increase respiratory work load, they should be used with caution in weak or tired patients with respiratory failure, during pressure-support ventilation.[17,18] Nakagawa et al suggested that patients with thick secretions should use the heated humidifier rather than HME.[19]

Recently, heated ventilator circuits were introduced. They are efficient and do not produce condensate (and thus decrease the risk of bacterial contamination), but they are expensive and sometimes difficult to control to provide adequate heat and humidity with intubated patients.[20] To overcome those limitations, a new active HME, the Hygrovent Gold, was developed, which combines the simplicity of an HME with the features of an active humidification system.

The Hygrovent Gold is similar to a common hygroscopic-hydrophobic HME, but it can also add heat and humidity to the inspired gas. The water is continuously added from an external source and wets the heated hygroscopic-hydrophobic membrane. We assessed in vitro the efficiency and stability over time of the Hygrovent Gold and 2 other commercially available HMEs.

Methods

We tested the Hygrovent Gold (Medisize, Hillegom, The Netherlands) with and without its supplemental heat and humidification system activated (ie, active Hygrovent Gold and passive Hygrovent Gold). We also studied the Hygrobac (Nellcor, Boulder, Colorado) and the Hygrovent S (Medisize, Hillegom, The Netherlands). As reported by the manufacturer, the Hygrovent Gold (active or passive) weighs 58 g and has an internal volume of 59 mL (catheter mount excluded). The Hygrobac and Hygrovent S weigh 46.8 g and 34 g and have internal volumes of 92 mL and 55 mL, respectively. All the tested HMEs have microbiological retention greater than 99.99%.

The Hygrovent Gold's active humidification system (Fig. 1) consists of an HME/filter with an adapter into which a heating element is inserted. The membrane in the Hygrovent Gold automatically regulates how much water passes through its calibrated porosity. The filter is constructed of polycarbonate and has a hydrophobic membrane of polytetrafluoroethylene, polyester (Gore-tex), and aluminum. The heating element contains a temperature controller, powered by a 12-volt adapter, which prevents overheating. The heating element has a switch that ensures

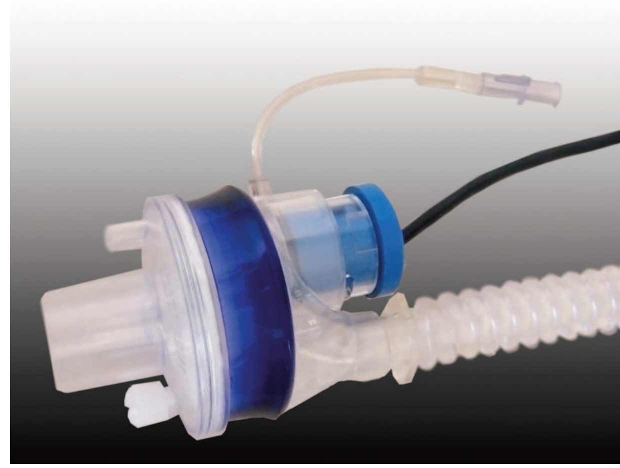

Fig. 1. The Hygrovent Gold heat-and-moisture exchanger has an adapter into which a heating element is inserted, and a line that continuously supplies water.

that it works only when it is connected to the Hygrovent Gold. A light-emitting diode in the switch indicates when the heating element is functioning.

The Hygrovent Gold's filter pore size is 0.2 μm. An aluminum grid inside the Hygrovent Gold protects the Gore-tex membrane from damage, heats the gas by acting as a thermal conductor, and detects the amount of gas passing through the filter and provides a feedback to the heater, which regulates the water evaporation output ($\pm$ 20% of the nominal water output, which is approximately 3 mL/h). The aluminum grid is self-cleaning because it has continuous steam output.

Experimental Protocol

The HMEs were tested in random order. Measurements were taken every 15 min, up to 1 h. Figure 2 shows the experimental setup.[20] We connected a 2-L rubber bag with a plastic non-conducting tube to a ventilator (Evita 2, Dräger, Lubeck, Germany) and a heated humidifier (MR730, Fisher & Paykel, Auckland, New Zealand) that heated and humidified the gas entering the humidifier, to mimic normothermic (34°C) and hypothermic (28°C) conditions. The temperature and humidity output of the lung model were checked before every measurement. We tested 3 $\dot{V}_E$: 5, 10, and 15 L/min. We used volume-controlled ventilation, a tidal volume of 0.5 L, and 100% oxygen in all the tests. To stabilize the system before taking any measurements, we ventilated the model lung for 2 h without any HME.

With each HME we measured the flow resistance and weight at baseline and after 24 h and 48 h of continuous use at a $\dot{V}_E$ of 10 L/min. To determine flow resistance we measured the pressure drop across the HME, at constant

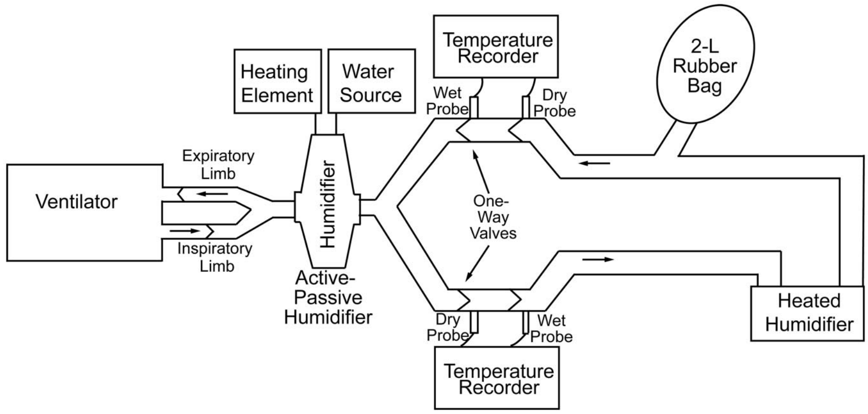

Fig. 2. Experimental setup to test heat-and-moisture exchangers (HMEs).

flows of 0, 10, 20, 30, and 40 L/min. The gas flow rate was measured with a heated pneumotachograph (Fleish 2, Fleish, Lausanne, Switzerland) positioned next to the flow generator (Venturi, Starmed, Mirandola, Italy). The airway pressure was measured with a pressure transducer (MPX 2010 DP, Motorola, Phoenix, Arizona) positioned across the HME. The ambient room temperature was 24–26°C. We measured the weight of the entire HME with a precision balance (PM100, Mettler Instrument, Hightstown, New Jersey). To standardize the weight measurements we measured the absolute change in weight at baseline, at 24 h, and at 48 h.

Hygrometric Measurements

We measured average temperature and absolute humidity during the inspiratory phase, with a psychrometric method. We placed the HME between the Y-piece of the ventilator circuit and the test lung. Between the HME and the lung model we inserted a device with 4 unidirectional valves to separate the inspiratory and expiratory gas flows. The psychrometric method is the one most commonly used by clinicians to measure humidity[21]; it is based on 2 thermal probes: one dry and one wet.[22] We used platinum flow-resistance thermometers (error range ± 0.3°C, and no variation over time). The 2 probes were placed in the inspiratory side of the circuit, after the filter. Thus, the probe always had to measure the same amount of flow (ie, same velocity of air), without causing any measurement artifacts. Temperatures were measured electronically, displayed and printed on a chart recorder (436004 uR1000, Yokogawa, Tokyo, Japan). The dry probe measures the gas temperature. The wet probe is coated with cotton that is wetted with sterile water, the evaporation of which is proportional to the dryness of the gas, so the temperature difference between the dry and wet probe is related to the gas humidity. To calibrate the 2 thermometer probes we inserted them in ice water to test their readings and reading-difference at 0°C. The reading-difference was 0.1–0.2°C. We then took readings in room air, and again the reading-difference was 0.1–0.2°C, so we used that reading-difference value to correct the measurements obtained during the study. In each condition we computed the average of 3 or 4 readings from the wet and dry probes.

Statistical Analysis

All data are expressed as mean ± standard deviation. We compared the data from the 4 HMEs (ie, the Hygrobac, the Hygrovent S, the active Hygrovent Gold, and the passive Hygrovent Gold) with the Mann-Whitney test for independent samples and unpaired data.

Results

The temperature and absolute humidity of the expiratory gas from the model lung were, respectively, 34.2 ± 0.3°C and 39.9 ± 0.6 mg H_2O/L in the normothermic condition, and 28.1 ± 0.4°C and 28.5 ± 0.5 mg H_2O/L in the hypothermic condition, with no differences between the settings. This confirms the previously reported good stability of this setup.[20]

Normothermic Condition

The temperature and absolute humidity of the inspired gas significantly differed between the tested HMEs. In every normothermic test condition the active Hygrovent Gold had the highest temperature and absolute humidity (Fig. 3). With the active Hygrovent Gold, while temperature was held constant, absolute humidity decreased linearly with increasing $\dot{V}_E$. The 3 passive HMEs increased temperature and absolute humidity at $\dot{V}_E$ values higher than 5 L/min.

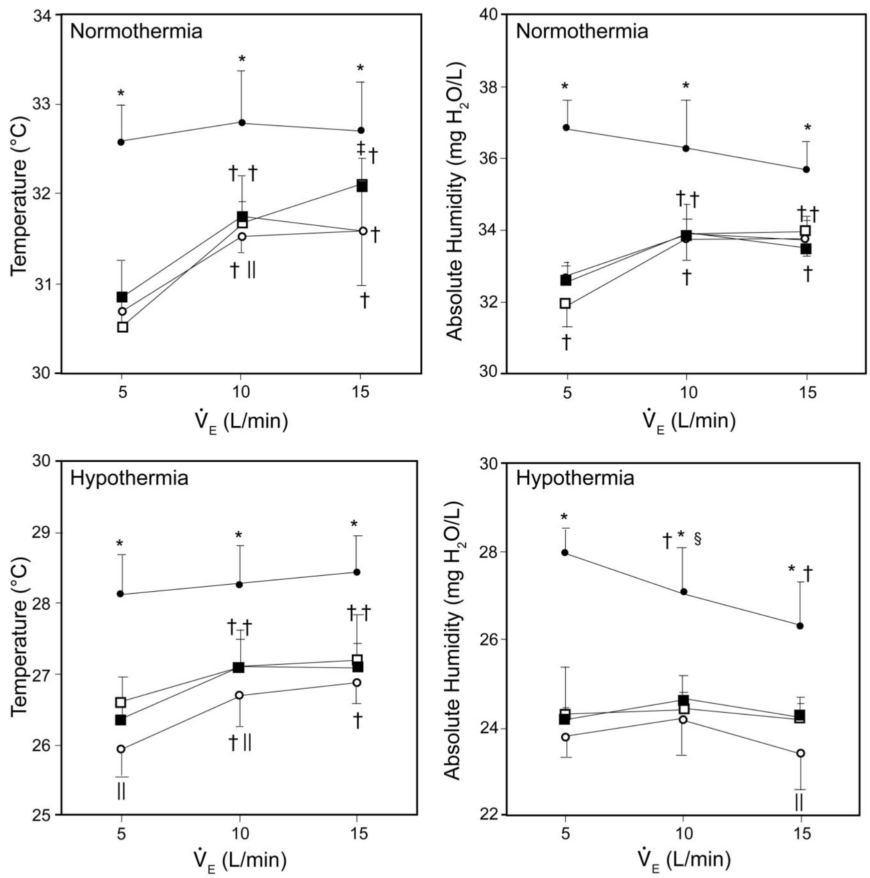

Fig. 3. Mean ± SD temperature and absolute humidity, in normothermic and hypothermic conditions, at minute volumes of 5, 10, and 15 L/min, with 3 heat-and-moisture exchanger models: Hygrovent Gold (with and without its active humidification option), Hygrobac, and Hygrovent S. Between the devices: * $P < .001$ versus passive Hygrovent Gold, Hygrobac, and Hygrovent S. ‡ $P = .001$ versus passive Hygrovent Gold and Hygrovent S. ‖ $P = .001$ versus Hygrobac and Hygrovent S. For a given device: † $P = .001$ versus 5 L/min. § $P = .001$ versus 15 L/min. Passive Hygrovent Gold (empty circles); active Hygrovent Gold (black circles); Hygrobac (empty squares); Hygrovent S (black squares).

Hypothermic Condition

The active Hygrovent Gold also had the highest temperature and absolute humidity in the hypothermic test condition, at each $\dot{V}_E$, but absolute humidity progressively decreased with increasing $\dot{V}_E$. Increasing the $\dot{V}_E$ increased the temperature with all the HMEs, but the passive Hygrovent Gold had a lower temperature at 5 L/min and 10 L/min. With the Hygrobac and Hygrovent S, absolute humidity was unaffected by increasing $\dot{V}_E$. Conversely, compared to the other HMEs tested, with the passive Hygrovent Gold, absolute humidity decreased at $\dot{V}_E \leq 15$ L/min. The temperature and absolute humidity with these 4 HMEs was not different at 24 h or 48 h.

Flow Resistance and Weight

Figure 4 shows the flow-resistance values at baseline, 24 h and 48 h. The flow resistance progressively increased over time. At 24 h and 48 h the flow resistance was lowest with the Hygrobac, at all the tested flows. The weight-increase values with the active Hygrovent Gold, passive Hygrovent Gold, Hygrobac, and Hygrovent S were, respectively, 0.3 ± < 0.1 g, 0.1 ± < 0.1 g, 0.3 ± < 0.1 g, and 0.1 ± < 0.1 g at 24 h, and 7.7 ± < 0.1 g, 4.6 ± < 0.1 g, 1.1 ± < 0.1 g, and 4.6 ± < 0.1 g at 48 h. The active Hygrovent Gold had the highest weight increase, and the Hygrobac had the lowest.

Flow resistance at 40 L/min significantly correlated with the weight increase ($r^2 = 0.66$, $P < .002$).

We found no condensate in the ventilator circuit with any of the HMEs tested.

Discussion

So far as we are aware, this is the first study of the efficiency of the Hygrovent Gold. The passive Hygrovent Gold, in the normothermic condition, provided heat and

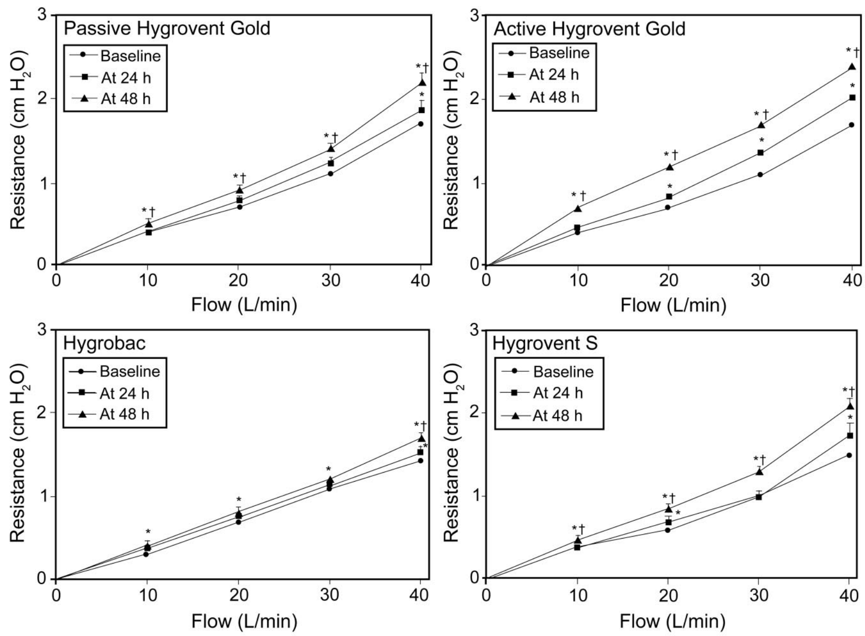

Fig. 4. Mean ± SD flow resistance at baseline, 24 h, and 48 h, at flows of 10, 20, 30, and 40 L/min, in 3 heat-and-moisture exchanger models: Hygrovent Gold (with and without its active humidification option), Hygrobac, and Hygrovent S. Between the devices: * *P* = .001 versus baseline. † *P* = .001 versus at 24 h.

humidity at least comparable to that of the other HMEs. The active Hygrovent Gold's heat and humidification were well above that of the passive HMEs, in both the normothermic and the hypothermic conditions. However, the active Hygrovent Gold's increase in flow resistance and weight was higher than the other HMEs.

The optimal levels of heat and humidity remain debatable.[1] Some have suggested an inspiratory absolute humidity of 44 mg H_2O/L, while others[2] have suggested an absolute humidity of 28–35 mg H_2O/L. Two studies[23,24] found that an HME that delivered a mean absolute humidity of 30 mg H_2O/L could be safely used for up to 7 days in mechanically ventilated patients, which suggests that, in general, it is not necessary to provide an absolute humidity greater than 30 mg H_2O/L.

Passive Hygrovent Gold

In the normothermic condition the passive Hygrovent Gold provided an average absolute humidity of 33.9 ± 0.5 mg H_2O/L, at 10 L/min, which had not changed at 48 h of continuous use, and was comparable to the other tested HMEs. We used the Hygrobac as a reference because it has been reported to be one of the most efficient HMEs,[21] and the Hygrovent S to determine the influence of internal volume on HME efficiency.

In previous clinical investigations, a satisfactory absolute humidity (ie, ≥ 30 mg H_2O/L) was reported with HMEs at high $\dot{V}_E$ (10.5–16.5 L/min).[25] In the present study we found that a $\dot{V}_E$ of 5 L/min decreased the absolute humidity with all the tested HMEs, compared to 10 L/min and 15 L/min. Our data suggest that HME internal volume did not significantly affect the delivered heat and humidity in the normothermic condition, as the temperature and absolute humidity were similar between the Hygrovent S and the other HMEs.

As expected, the hypothermic condition markedly reduced the humidity with all the HMEs. Although the passive Hygrovent Gold had the lowest humidification at 15 L/min, our data suggest that passive HMEs should be used with caution in moderately or severely hypothermic patients.

Active Hygrovent Gold

In the normothermic condition the active Hygrovent Gold gave the highest humidification (absolute humidity 36.3 ± 1.3 mg H_2O/L at 10 L/min), at all the tested $\dot{V}_E$. Although absolute humidity decreased with increasing $\dot{V}_E$, it always remained in the recommended range.

Three other HME devices that have been reported are the Performer (StarMed, Mirandola, Italy), the Booster (TomTec, Kapellen, Belgium), and the Humid-Heat (Hudson, Dardilly, France).

The Performer was a prototype that was never commercially available; it was used just for testing a new humidification concept. In the Performer the heating element was inserted between 2 cellulose membranes, whereas in the Hygrovent Gold the heating element is apart from the membranes. And in the Performer, but not in Hygrovent Gold, the plate temperature could be individually set.

The Booster is a small electrically powered heating element that is placed between the HME and the patient. The element has a Gore-tex membrane on which water (added from the outside) vaporizes and humidifies the inspired gas.[26] The Hygrovent Gold represents an evolution of the Booster. The main differences are that the Booster's heating system and external water source are separate from the HME, and the Booster's performance depends on the HME efficiency. In patients ventilated with the Booster for 96 h, the inspired gas temperature and absolute humidity were higher (2–3°C and 2–3 mg H_2O/L) than with a standard HME, and there was no bacterial colonization of the ventilator circuit.[26]

The Humid-Heat, which adds water and heat on the patient side of the HME circuit, can boost temperature and absolute humidity up to 37°C and 44 mg H_2O/L, which are close to the temperature and humidity with a conventional heated humidifier.[9,27,28]

With all the above devices, if the water supply runs out, the HME continues to work as passive HME, which avoids the risk that dry gas will be delivered to the patient.

The Hygrovent Gold is a commercially available hybrid active/passive humidification system, intended to replace the Booster, so it is important to evaluate the performance of the Hygrovent Gold in vitro in various experimental conditions.

It is usually recommended not to use a passive HME when the patient's core temperature and, consequently, expired absolute humidity are low, and to use HME cautiously in patients with thick secretions.[1] On the other hand, during hypothermia, with the currently recommended settings, heated humidifier carries the risk of over-humidification and harmful effects on respiratory mechanics (micro-atelectasis, decrease in lung compliance, and surfactant impairment), in addition to other problems related to HMEs. In the hypothermic condition we found that the active Hygrovent Gold was more efficient than the passive HMEs. The difference between the absolute humidity delivered from the HME and the expired humidity was 0.6 mg H_2O/L at 5 L/min, 1.5 mg H_2O/L at 10 L/min, and 1.8 mg H_2O/L at 15 L/min. This indicates that, within the $\dot{V}_E$ range we tested, the active Hygrovent Gold maintained a balance between the inspiratory and expiratory absolute humidity.

However, the fact that temperature increases while absolute humidity decreases with the Hygrovent Gold suggests that the Hygrovent Gold has a fixed moisture output that is not able to adapt to changing $\dot{V}_E$. Furthermore, the lower $\dot{V}_E$ resulted in lower moisture output. This can be related to cooling of the device during a prolonged expiratory time, and to a smaller expired volume reaching the HME during expiration. In agreement with our results, Lellouche and co-workers reported more physiologic heating and humidification in hypothermic patients with the Humid-Heat than with conventional passive HME or heated humidifier.[29] However, heated humidifier may be preferable in the presence of extreme hypothermia.

Flow Resistance and Dead Space

The presence of any HME in the circuit increases flow resistance and dead space.[30] We found that among the passive HMEs the Hygrobac had the least flow-resistance increase over time, and the active Hygrovent Gold had the most. However, the flow resistance increased with all the HMEs after 48 h. That the active Hygrovent Gold had the greater flow-resistance increase is probably due to accumulation of water in the device, as indicated by the weight increase. This might suggest that the active Hygrovent Gold should not be used for over 24 h. Although the added flow resistance is less than that from an endotracheal tube, the flow resistance may be additive in the breathing circuit and might increase the work of breathing and air-trapping, especially during assisted ventilation.[18] Because the internal volume of the Hygrovent Gold is less than that of the Hygrobac (59 mL vs 92 mL), its possible negative effect on respiratory function during controlled[31] or assisted[18] ventilation should be minimized. However, HME should be cautiously used in patients who are difficult to wean, unless the level of ventilatory assistance is increased.[17]

Limitations

First, we did not examine in vivo the effects of the tested HMEs on respiratory function, secretions, or microbiological contamination of the ventilator circuit, so our data apply only to our specific experimental conditions, and should be tested in a clinical setting. Second, we compared the Hygrovent Gold to only 2 other brands of passive HMEs. However, the Hygrobac, which was included in the study, has been reported as one of the most efficient available HMEs. Third, we did not compare Hygrovent Gold to other hybrid active/passive HMEs. Fourth, a comparison with heated humidifier could have been interesting, but a previous study[20] found that the absolute humidity range from a heated humidifier was 37–40 mg H_2O/L at 5 L/min and 39–47 mg H_2O/L at 15 L/min, at 35°C and 39°C, respectively. We found lower absolute humidity with Hygrovent Gold than with heated humidifier. Fifth, we only made flow-resistance measurements at flows up to 40 L/min, because that value represents the average inspiratory flow usually reached during conventional mechanical ventilation. Sixth, we did not evaluate cost and economic issues. Although most HMEs are relatively inexpensive, daily changing of the HME would increase the cost of humidification.

Conclusions

Although HMEs can be safely used during long-term ventilation,[23,24] many centers do not routinely use HME, for fear of obstruction and insufficient humidification.[32] Because the active Hygrovent Gold can deliver higher temperature and absolute humidity, it may be useful in patients in whom passive HME appears to worsen the clinical characteristics of secretions, and in hypothermic patients who would otherwise require heated humidifier. As compared to conventional HMEs, the passive Hygrovent Gold provided adequate heat and humidification during normothermia, but the active Hygrovent Gold provides higher humidification in both normothermia and hypothermia.

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