Humidification and Secretion Volume in Mechanically Ventilated Patients

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OBJECTIVE: To determine potential effects of humidification on the volume of airway secretions in mechanically ventilated patients. METHODS: Water vapor delivery from devices providing non-heated-wire humidification, heated-wire humidification, and heat and moisture exchanger (HME) were quantified on the bench. Then, patients requiring 24-hour mechanical ventilation were exposed sequentially to each of these humidification devices, and secretions were removed and measured by suctioning every hour during the last 4 hours of the 24-hour study period. RESULTS: In vitro water vapor delivery was greater using non-heated-wire humidification, compared to heated-wire humidification and HME. In vivo, a total of 9 patients were studied. Secretion volume following humidification by non-heated-wire humidification was significantly greater than for heated-wire humidification and HME ($P = .004$). CONCLUSIONS: The volume of secretions appeared to be linked to humidification, as greater water vapor delivery measured in vitro was associated with greater secretion volume in vivo. *Key words: humidifier, ventilation, sputum, relative humidity, heat and moisture exchange, mechanical ventilation.* [Respir Care 2009;54(10):1329–1335. © 2009 Daedalus Enterprises]

Introduction

In mechanically ventilated patients, humidification devices are used to heat and humidify inspired gas. Heating and humidifying inspiratory gas may prevent complications associated with the drying of the respiratory mucosa, such as mucus plugging and endotracheal tube (ETT) occlusion.[1,2] Commercial humidification systems include non-heated-wire humidifiers, heated-wire humidifiers, and heat and moisture exchangers (HMEs). Previous studies have suggested that different devices can deliver different amounts of humidification, but the potential role of these differences in clinical respiratory problems is unclear.[3-13] In a quantitative comparison study, our group recently compared non-heated-wire humidification to heated-wire humidification over a wide range of minute ventilation ($\dot{V}_E$) values. We found that at the same Y-piece temperature, heated-wire humidification may provide significantly less humidification than physiologic levels.[14]

At our institution, non-heated-wire humidification is no longer utilized because of concerns over respiratory circuit condensation. For patients who are maintained on short-term mechanical ventilation, HME is our device of choice. In patients requiring long-term mechanical ventilation in the medical intensive care unit and respiratory care unit, patients are humidified using heated-wire humidification. Based on our recent in vitro findings, patients on heated-wire humidification may receive significantly less humidification than the previously used non-heated-wire humidification. Adequate humidification is linked to airway clearance, raising some concern that current heated-wire humidification systems may increase the risk of complications. Optimal conditions for humidification are difficult to define, but delivering inspiratory gas significantly dif-

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ferent from physiologic temperature (37°C) and relative humidity (100%) may impair the function of the mucociliary apparatus and affect the amount and quality of airway secretions.[1,2,15,16]

As part of ongoing studies in ventilator-associated tracheobronchitis and ventilator-associated pneumonia, we developed an interest in understanding the delivery of water vapor to patients chronically maintained on mechanical ventilation. In defining the presence of ventilator-associated tracheobronchitis and ventilator-associated pneumonia, early studies from our group indicated that the volume of airway secretions may be affected by the type of humidification used in the ventilator circuit.[17,18] Therefore, we speculated that the amount of water vapor delivery supplied by a humidification device might have a significant impact on the volume and quality of secretions in mechanically ventilated patients.

First, on the bench, using our previously described in vitro method, we determined water vapor delivery for non-heated-wire humidification and heated-wire humidification for our present ventilators. We also adapted our in vitro model to determine water vapor delivery for the hospital HME. Then we performed an in vivo study designed to determine the effects of different modes of humidification with defined differences in water vapor delivery on airway secretions. We postulated that the type of humidification and the amount of water vapor delivery in a ventilator circuit would influence secretion volume. This would be a first step in determining the individual contribution of factors that lead to impaired airway function and clinical outcomes such as infection in the intubated patient.

Methods

In Vitro Water Vapor Delivery Determination

Our method for determining water vapor delivery has been previously discussed and validated.[14] To briefly review our method, the experimental setup is shown in Figure 1. Each experiment was run for one hour at a fixed $\dot{V}_E$. Inspiratory gas passed through a condenser tube, and water vapor was condensed and measured. Then, a hygrometer (Fisher Scientific, Pittsburgh, Pennsylvania) was used to measure the temperature and relative humidity of the gas exiting the condenser, and equations of state were used to calculate the remaining amount of water vapor in the gas.

We used this method to determine water vapor delivery for the active humidification devices ConchaTherm IV (heated-wire humidification) and ConchaTherm III (non-heated-wire humidification) (Hudson RCI, Temecula, California). The ventilators used were the Puritan Bennett 7200 ventilator (Puritan Bennett, Pleasanton, California), which receives its inlet gases from compressed air and oxygen tanks, and the T-Bird AVS III (Susquehanna Micro, Red Lion, Pennsylvania), which uses room air via an internal compressor, with oxygen from a tank. We chose to study these 2 ventilators because they operate using different inlet gases, and they were the ventilators chosen for the in vivo portion of our study. Both humidification devices were set to deliver gas to the Y-piece at 35°C. For the heated-wire humidification, the humidifier column temperature was set to 33.5°C (a standard practice in our hospital).

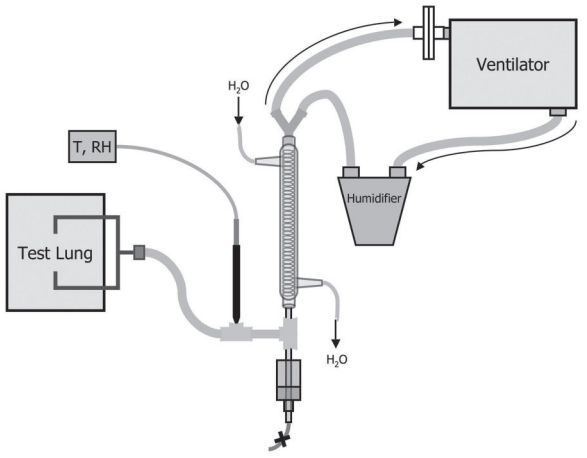

Fig. 1. Experimental setup for measurement of water vapor delivery at different minute ventilations. During inspiration, dry inspiratory gas from the ventilator was heated and humidified by either non-heated-wire or heated-wire humidification and passed through the Y-piece into the condenser. At a given minute ventilation, for 1 hour, water vapor was condensed, drained and measured; the remaining water vapor in the gas was calculated from the temperature (T) and relative humidity (RH), measured distal to the condenser. Water vapor delivery equaled the sum of the condensate volume and the calculated water vapor in the gas.[14]

For the HME, the experimental setup for water vapor delivery determination is shown in Figures 2 and 3. We used the Ballard Flex (Kimberly-Clark Global Sales, Roswell, Georgia), a hygroscopic HME with a manufacturer-quoted absolute humidity output of 30 mg H_2O/L. Since HMEs are passive humidification devices, we used a non-heated-wire humidifier set at 35°C to simulate exhaled heat and humidification from a patient. Previous data indicated that, while set at 35°C, this device actually delivers gas near 37°C, 100% relative humidity.[14] With this setup the HME received gases as if they emanated from a patient at 37°C and 100% relative humidity. We chose these conditions to mimic exhaled gas at alveolar conditions, and to ensure that the HME would be provided with adequate conditioning. In early bench studies we found that an HME has an inherent capacity for heat and humidity, and in "loading" the HME with heat and humidity, exceeding this capacity does not affect subsequent water vapor delivery to the patient, because excess humidity "rains out" in the tubing.

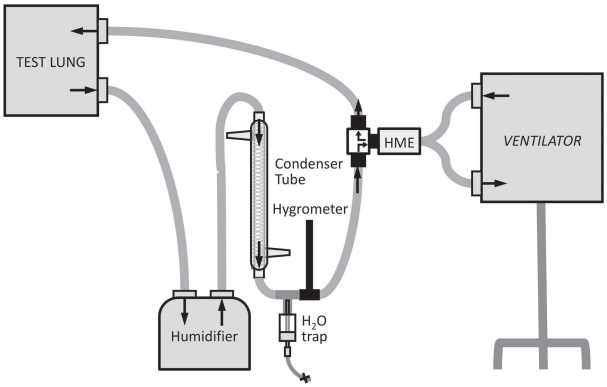

Fig. 2. Experimental setup to confirm adequate conditioning of the heat-and-moisture exchanger (HME). Placement of the condenser/hygrometer system upstream to the Rudolph valve assessed water vapor delivery conditioning the HME.

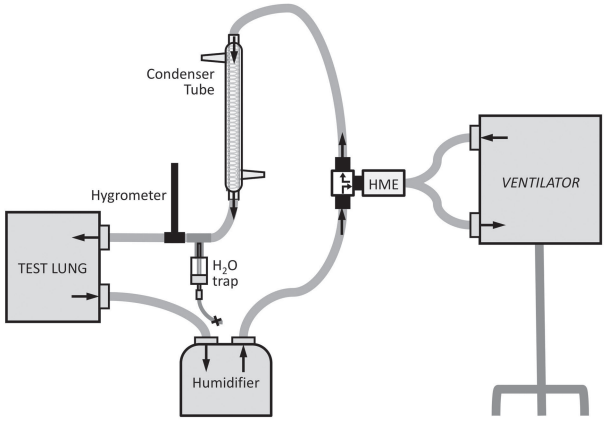

Fig. 3. Experimental setup for measurement of water vapor delivery (water vapor delivery) from the heat-and-moisture exchanger (HME). Placement of the condenser/hygrometer system downstream to the Rudolph valve allowed measurement of water vapor delivery from the HME to the "patient".

Figures 2 and 3 are identical except for the position of the condenser/hygrometer. Humidified gas from the non-heated-wire humidifier passed through the HME, conditioning it with heat and humidity. The Rudolph valve separated the gases into "gases from the patient" (the so-called conditioning breath, which comes from the "patient" to the HME) and "gases to the patient" (the gases provided to the patient by the HME). The gases were moved through this circuit by the ventilator. Placement of the condenser/hygrometer system upstream to the Rudolph valve assessed water vapor delivery conditioning the HME (see Fig. 2). This arrangement was designed to confirm that the HME received saturated gases at least at 37°C and 100% relative humidity. Placement of the condenser/hygrometer system downstream to the Rudolph valve allowed measurement of water vapor delivery from the HME to the "patient" (see Fig. 3).

We tested each humidification device/ventilator combination at $\dot{V}_E$ of 5, 10, and 15 L/min. The ambient temperature for all experiments was 25°C, and ambient relative humidity was 30%. Each experiment was run in duplicate, and water vapor delivery was plotted versus $\dot{V}_E$. For the HME, water vapor delivery to and from the HME was plotted on the same axis, showing water vapor delivery to and from the HME at different $\dot{V}_E$.

In Vivo Secretion Volume Measurement

Subjects. Study subjects were patients enrolled from 2 sites: a chronic care facility with a ventilator unit, and the respiratory care unit in a university hospital. The patients were maintained on mechanical ventilation for chronic medical conditions (Table 1). They were free of signs or symptoms of acute illness, and all produced more than 2 mL of sputum per 4 hours over a defined period of observation. All patients were ventilated via tracheostomy. The institutional review boards at the university hospital and nursing facility approved the study, and informed consent was obtained from all patients.

Equipment. At the nursing facility (6 patients), the T-Bird AVS III ventilator was used on all subjects. At the university hospital (3 patients), the Puritan Bennett 7200 ventilator and the Evita 4 with Neoflow option ventilator (Dräger, Telford, Pennsylvania) were used. The Dräger, like the Puritan Bennett 7200, uses inlet gases completely supplied by the hospital wall circuit (compressed air and oxygen). The ConchaTherm IV was used as the heated-wire humidifier, and the ConchaTherm III as the non-heated-wire humidifier at both sites. The Ballard Flex was used as the HME at both sites. Both active humidifiers were set to deliver gas at 35°C to the Y-piece. The heated-wire humidifier was set the same as in our in vitro study (ie, column temperature set at 33.5°C). At the nursing facility the ambient temperature was 23–25°C, and ambient relative humidity was 50–75%. In the respiratory care unit the ambient temperature was 23–27°C, and ambient relative humidity was 20–50%.

Protocol. All patients required around-the-clock ventilation. Studies were carried out from September to November 2004. Each patient was studied for 9 consecutive days. Ventilator settings were not changed during the study period. Patients were assigned randomly to start with a device, and then were cycled sequentially to each of the 3 humidification devices. Patients were cycled between devices every 24 hours for 9 days. Secretions were collected and quantified as "secretion volume" according to our routine protocol, previously described in detail.[17,18] Briefly,

Table 1. Patient Demographics and Ventilator Settings for In Vivo Study

Patient	Age	Sex	Diagnosis	V_T (mL)	f (breaths/min)	F_{IO_2}	PEEP (cm H_2O)
1	68	F	ALS	600	14	45	5
2	75	F	COPD	450	15	60	5
3	63	F	ALS	600	10	28	5
4	71	F	COPD	600	14	40	5
5	55	M	Muscular dystrophy	700	14	30	5
6	33	F	Down syndrome	600	10	40	5
7	77	F	Multiple myeloma	500	10	50	5
8	36	M	Chest trauma	700	10	35	5
9	72	F	COPD	600	12	40	5

V_T = tidal volume
f = respiratory frequency
F_{IO_2} = fraction of inspired oxygen
PEEP = positive end-expiratory pressure
ALS =amyotrophic lateral sclerosis
COPD = chronic obstructive pulmonary disease

after suctioning and discarding residual secretions, we measured subsequent accumulated secretions by suctioning every hour during the last 4 hours of the 24-hour study period. Patients were suctioned as necessary during all other times.

Statistical Analysis

All statistics were performed using statistical software (SPSS 15.0, SPSS, Chicago, Illinois) using non-parametric methods. Sputum samples were collected several times on each subject, on each of the 3 different devices. The mean sputum volumes for each subject on each device were calculated and compared, within subject, using Friedman's test (to compare all 3 groups with repeated measures) and then the Wilcoxon signed rank test for repeated measures to compare 2 groups at a time.

Results

In Vitro Water Vapor Delivery

Bench data for all devices are shown in Figure 4. Non-heated-wire humidification provided more water vapor delivery than HME and heated-wire humidification at all $\dot{V}_E$ values. Ventilator type did not affect water vapor delivery for any humidification device. In addition, the upper points describe water vapor delivery from the humidifier to the HME mimicking a patient "conditioning" the HME. The data demonstrate that water vapor delivered to the HME in our test setup met or exceeded water vapor that would be supplied from any patient in vivo, indicating that the HME was adequately conditioned for optimal performance. The

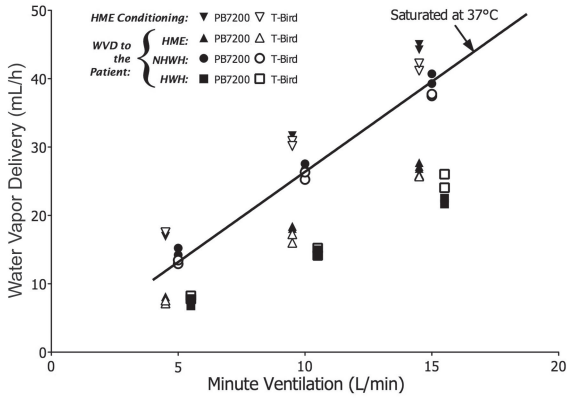

Fig. 4. Bench data. Water vapor delivery (WVD) versus minute ventilation for all devices. For reference, the solid line represents water vapor delivery at alveolar conditions (37°C and 100% relative humidity). Data points were measured at precisely 5, 10, and 15 L/min, but points were separated about the minute ventilation value to allow better visualization. Points are described from the top of the figure downwards. Heat-and-moisture exchanger (HME) conditioning (downward triangles, filled = Puritan Bennett [PB] 7200 ventilator, unfilled = T-Bird): water vapor delivery provided to the HME exceeded the saturated line, indicating that the HME received adequate conditioning heat and humidity. Non-heated-wire humidification (NHWH, Y-piece set at 35°C, circles, filled = PB7200 ventilator, unfilled = T-bird ventilator): by inspection, NHWH delivered saturated air at 37°C. HME: water vapor delivery to the patient (upward pointing triangles, filled = PB7200 ventilator, unfilled = T-Bird): water vapor delivery from the HME to the patient was below physiologic saturation. Heated-wire humidification (HWH, Y-piece set at 35°C, column temperature of 33.5°C, rectangles, filled = PB7200 ventilator, unfilled = T-Bird): water vapor delivery at all minute ventilations was greater using NHWH, compared to HWH. HME data points indicated slightly more water vapor delivery than NHWH at minute ventilation equal to or greater than 10 L/min. Ventilator type did not significantly affect water vapor delivery.

Table 2. Sputum Volume

Patient*	Non-Heated-Wire Humidifier		Heated-Wire Humidifier		Heat and Moisture Exchanger	
	No.†	Sputum Volume (mean ± SD mL/4 h)	No.†	Sputum Volume (mean ± SD mL/4 h)	No.†	Sputum Volume (mean ± SD mL/4 h)
1	2	26.00 ± 5.66	2	22.00 ± 1.41	5	25.60 ± 7.67
2	0	ND	3	5.17 ± 3.33	5	10.40 ± 5.90
3	2	5.50 ± 2.12	2	0.35 ± 0.21	5	2.50 ± 1.41
4	0	ND	3	7.00 ± 5.00	4	3.08 ± 2.02
5	3	5.17 ± 2.47	3	1.13 ± 1.62	3	2.43 ± 1.91
6	3	11.33 ± 5.03	3	10.00 ± 5.29	3	8.17 ± 10.40
7	5	6.20 ± 2.86	4	5.75 ± 2.63	4	3.75 ± 1.71
8	5	11.80 ± 7.76	5	6.00 ± 3.39	6	6.58 ± 2.84
9	3	13.33 ± 1.53	5	4.80 ± 1.79	3	5.67 ± 2.52
All replications in all patients	23	10.54 ± 7.14	30	6.39 ± 5.63	38	8.11 ± 8.54

* Patients 1–6 in nursing home; patients 7–9 in respiratory care unit, university hospital
† Number of replications on each device.
ND = no data collected

lower set of data points represents water vapor delivery from the "fully saturated" HME back to the patient.

In Vivo Secretion Volume Measurement

Sputum samples were collected from 9 subjects. Table 2 shows the mean value of sputum volume and the number of replications on each device for each subject. Most subjects were evaluated with multiple replications on all 3 humidification devices: non-heated-wire humidification, heated-wire humidification, and HME; but some received collection on only 2 of the devices, due to subject refusal to participate. There was wide variation in the sputum volume *between subjects* on the same device. However, when the mean sputum volume was compared *within subjects* in the 7 subjects who received all 3 devices, there was a significant difference between devices using non-parametric analysis ($P = .004$, Fig. 5). Based on the Wilcoxon signed rank test, this difference was attributable to the consistently higher sputum volume for each subject using non-heated-wire humidification, versus either of the other devices.

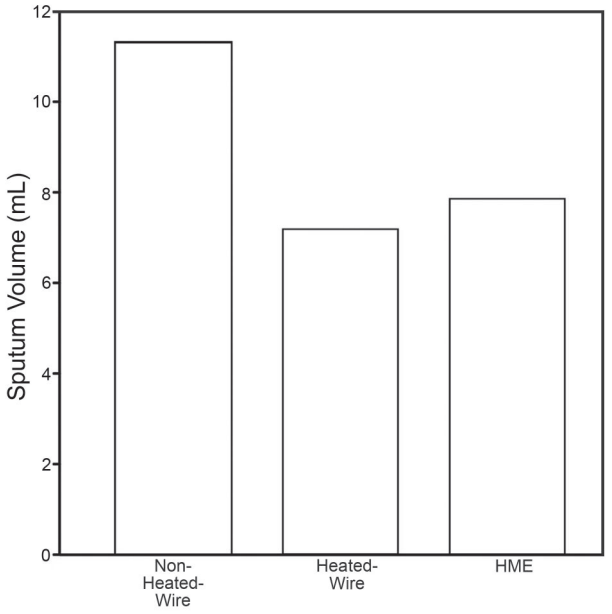

Fig. 5. In vivo data. Mean sputum volumes for different devices for the 7 subjects who completed testing with all 3 devices (mean ± SD; non-heated-wire [NHW] 11.33 ± 7.28 mL, heat-and-moisture exchanger [HME] 7.81 ± 8.13 mL, heated-wire [HW] 7.15 ± 7.30 mL). Within-subject differences in mean volume between devices were significant for NHW humidification, compared to heated-wire humidification and HME ($P = .004$). This difference was attributable to the consistently higher sputum volume for each subject using NHW humidification versus either of the other devices.

Discussion

Our results demonstrate that humidification appears to be associated with the volume of secretions in chronically mechanically ventilated patients. Devices with detectably different water vapor delivery were associated with differences in secretion volume. In vivo there were greater secretion volumes measured with non-heated-wire humidification, compared to heated-wire humidification and HME. This can be explained by our in vitro observations. The greater secretion volume measured during non-heated-wire humidification was probably due to greater water vapor delivery for non-heated-wire humidification, compared to heated-wire humidification and HME. While small, differ-

ences between the HME and heated-wire humidification systems were predicted by our bench data, with HME slightly greater than heated-wire humidification (see Fig. 4).

What secretion volume should be "expected" for intubated patients? Tracheostomized patients with chronic tracheobronchitis produce volumes of approximately 1–5 mL/h.[18] As shown in Table 2, the wide variation in the sputum volume between subjects on the same device points to factors other than the humidification device that contributed to volume, such as airway inflammation, antibiotic therapy, inhaled medications, and breathing pattern.

In patients requiring chronic mechanical ventilation, with impaired mucociliary clearance, impaired cough, and the necessity to suction secretions for final removal, appropriate humidification may be a key factor in both the prevention and removal of abnormal secretions. Increased water content of secretions tends to reduce the chance of mucus plugging or ETT occlusion.[1,2,7,12,19-22] At the same time, it seems reasonable to control humidification and prevent excessive secretions.[2,23]

Konrad et al demonstrated that reduced bronchial mucus transport velocity led to increased retention of secretions and pneumonia.[24] By reducing the inspiratory gas temperature and therefore lowering absolute humidity output and water vapor delivery, Kilgour et al measured reduced ciliary beat frequency and mucus transport velocity in sheep tracheae.[25] In a meta-analysis by Williams et al, mucociliary transport velocity was found to be a sensitive indicator of adequate humidification in animal and human studies.[2] They also found that a reduction in absolute humidity output led to worsening mucociliary dysfunction scores. It has been shown that decreased water content in respiratory secretions leads to increased mucus tenacity and mucus plugging.[1,2,16] Beydon et al studied the effect of different HMEs on mucus quality and found increased viscosity and increased ETT suction catheter adherence when using an HME with lower absolute humidity output.[26] There are also reports of partial occlusion of ETTs using devices with low absolute humidity output, possibly due to drying of secretions.[1,2,19,21,27] Our findings, coupled with those cited above, suggest that it is possible that some humidification systems may increase the risk of retention of secretions and the potential for pneumonia.

Our secretion volume measurements were performed in stable, chronically ill patients requiring chronic mechanical ventilation. Further studies are necessary to determine the potential relationship between humidification and secretion volume in other clinical situations, such as acutely ill patients, patients with purulent secretions secondary to respiratory tract infection, or patients requiring short-term mechanical ventilation (ie, short surgical procedures requiring elective intubation).

Our data were not intended to show superiority of one humidification device versus another. Our intent was to show that differences in water vapor delivery may influence secretion volume. There are many humidification devices with varying performance characteristics and settings. For example, both active humidification devices used in our study were set at 35°C at the Y-piece. The operator might assume that since both devices were set at the same temperature, humidification performance should be similar. However, because of differences in humidifier column temperature between heated-wire humidification and non-heated-wire humidification, there were differences in water vapor delivery and therefore secretion volume measured using each device. This highlights the need for in vitro characterization of device performance in order to ensure that adequate humidification is being delivered in vivo.

Limitations of our study include small sample size, use of different ventilators at each site, and variations in ambient conditions at each site. However, our in vivo results, combined with our in vitro measurements, suggest a link between secretion volume and humidification and draw attention to the relationship between humidification and airway function. Our study does not provide a complete connection between water vapor delivery and actual disease. Additionally, we studied only one brand of each type of humidification device. Our results may be limited to the devices tested, and further testing using other devices may be necessary.

For the HME we chose to mimic exhaled gas at alveolar conditions (ie, 37°C, 100% relative humidity) to ensure the HME was provided with adequate conditioning. In vivo, the temperature and relative humidity of exhaled gas may vary according to the clinical setting (ie, fever, dehydration, $\dot{V}_E$, ambient conditions), and may affect HME conditioning, water vapor delivery, and secretion volume during HME use. For our in vitro data, any additional humidity that was present that the HME could not use rained out, and condensation was noted in the expiratory line proximal to the HME. Since the HME had a certain capacity for heat and humidity, we do not feel we overestimated the in vitro water vapor delivery from the HME. However, HME performance may have varied in vivo, depending on the clinical situation.

In our previous paper we demonstrated that usual variables monitored at the bedside, such as Y-piece temperature, will not ensure control of water vapor delivery.[14] Future studies measuring airway clearance, secretion characteristics (ie, color, viscosity), and bacterial colonization during mechanical ventilation, combined with knowledge of water vapor delivery, will further define the clinical relevance of control of airway humidity.

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