

Y-Piece Temperature and Humidification During Mechanical Ventilation

Mario Solomita DO, Feroza Daroowalla MD MPH, Deniese S LeBlanc RRT,
and Gerald C Smaldone MD PhD

BACKGROUND: Practitioners often presume there is adequate humidification in the ventilator circuit if the Y-piece is at a specified temperature, but control of Y-piece temperature may be inadequate to ensure adequate humidification. **METHODS:** In an in vitro bench model we measured water-vapor delivery with several heated humidification setups and a wide range of minute volume (\dot{V}_E) values. The setup included a condenser, hygrometry, and thermometer. First, we calibrated the system with a point-source humidifier and water pump. Then we tested the water-vapor delivery during non-heated-wire humidification and during heated-wire humidification with a temperature gradient of +3°C, 0°C, and -3°C between the humidifier and the Y-piece. We compared the results to 2 recommended humidification values: 100% saturated (absolute humidity 44 mg H₂O/L) gas at 37°C (saturated/37°C); and 75% saturated (absolute humidity 33 mg H₂O/L), which is the humidity recommended by the International Organization for Standardization (the ISO standard). In all the experiments the setup was set to provide 35°C at the Y-piece. **RESULTS:** Our method for measuring water-vapor delivery closely approximated the amount delivered by a calibrated pump, but slightly underestimated the water-vapor delivery in all the experiments and the whole \dot{V}_E range. At all \dot{V}_E values, water-vapor delivery during non-heated-wire humidification matched or exceeded saturated/37°C and was significantly greater than that during heated-wire humidification. During heated-wire humidification, water-vapor delivery varied with the temperature gradient and did not reach saturated/37°C at $\dot{V}_E > 6$ L/min. Water-vapor delivery with the negative temperature gradient was below the ISO standard. **CONCLUSIONS:** Maintaining temperature at one point in the inspiratory circuit (eg, Y-piece), does not ensure adequate water-vapor delivery. Other factors (humidification system, \dot{V}_E , gradient setting) are critical. At a given temperature, humidification may be significantly higher or lower than expected. *Key words:* humidifier, humidification, ventilation, airway, sputum. [Respir Care 2009;54(4):480-486. © 2009 Daedalus Enterprises]

Introduction

In the intubated, mechanically ventilated patient, heating and humidifying the inspired gas prevents drying of

the respiratory mucosa, airway ulceration, and impaired secretion clearance.^{1,2} Available active humidifiers operate with a feedback loop that responds to the temperature of the humidifier chamber and the Y-piece. The heat is supplied by either (1) the heated water vapor from the

Mario Solomita DO, Feroza Daroowalla MD MPH, Deniese S LeBlanc RRT, and Gerald C Smaldone MD PhD are affiliated with the Department of Pulmonary and Critical Care Medicine, Stony Brook University Medical Center, State University of New York at Stony Brook.

Dr Smaldone has had a relationship with PARI Respiratory Equipment.

Correspondence: Gerald C Smaldone MD PhD, Department of Pulmonary and Critical Care Medicine, Stony Brook University Medical Center, State University of New York at Stony Brook, HSC T 17-040, Stony Brook NY 11794. E-mail: gsmaldone@notes.cc.sunysb.edu.

SEE THE RELATED EDITORIAL ON PAGE 450

humidifier (non-heated-wire humidification), or (2) the heated water vapor from the humidifier plus a heated wire in the circuit (heated-wire humidification). In clinical use, only the Y-piece temperature is monitored; actual water-vapor delivery is not measured.

The International Organization for Standardization (ISO) has developed water-vapor delivery standards for active humidification systems. Though the optimal levels of heat and humidification for intubated patients is debatable,^{1,3-10} it seems reasonable that the inspired gas should mimic the conditions during spontaneous ventilation. In the normal airway, inspired air is heated and humidified by the respiratory mucosa to core body temperature (37°C) and 100% saturation with water vapor, along the isothermic saturation boundary,¹ which is normally at the fourth-to-fifth generation of subsegmental bronchi.¹ At 37°C, 100% saturation corresponds to an absolute humidity of 44 mg H₂O/L.

The ISO suggests a minimum absolute humidity of 33 mg H₂O/L for inspired gas.¹¹ For active humidification the ISO standards are based on measurement of the absolute humidity at a constant flow, over the range of flows expected during mechanical ventilation. However, the testing conditions may not be representative of typical clinical use.¹¹ For example, in the intubated patient, gas reaches the Y-piece at various flows and volumes—conditions very different from the ISO testing standard of constant flow.

Potential differences between water-vapor delivery at ISO conditions and during mechanical ventilation have been addressed in previous studies. For instance, water-vapor delivery has been estimated indirectly with thermometer and hygrometer measurements at the Y-piece.^{6,8,12-15} Those papers suggest that humidifiers differ in function but were limited by their use of indirect estimation of water-vapor delivery. It is uncertain whether the temperature and/or humidity measured at the Y-piece reflects water-vapor delivery to the patient. To estimate water-vapor delivery with temperature and relative humidity measurements, an average inspiratory-phase value is calculated. However, the gas in the inspiratory limb is pushed into the patient as a bolus, and the water content of that bolus may not be adequately described by the average temperature and humidity at the Y-piece, so there is some uncertainty about the actual water-vapor delivery in different forms of humidification. We posed 5 questions:

1. Is the Y-piece temperature a suitable variable for monitoring humidification?
2. Do different humidification systems and setups deliver equal amounts of water vapor with a given temperature at the Y-piece?
3. Are the ISO standards predictive of water-vapor delivery during mechanical ventilation?
4. Is water-vapor delivery during mechanical ventilation maintained at the physiologic levels?
5. What level of water-vapor delivery is necessary for preserving airway integrity and functioning in the intensive care unit?

That last question is the most important, but to address it we must be able to quantitate water-vapor delivery in

any given clinical situation. Therefore, before designing clinical studies to assess the effects of humidification on airway function, we designed the present study to answer the above questions. First we designed and validated an *in vitro* method to quantify water-vapor delivery during mechanical ventilation. Then we used that method to evaluate non-heated-wire and heated-wire humidification over a wide range of minute volume (\dot{V}_E). We compared our findings to the ISO standards, to the findings of previous investigators, and to our present understanding of the “ideal” physiologic conditions in the ventilated airway.

Methods

Principles

The water content of a gas can be calculated if the temperature and relative humidity are known. As the bolus of gas traverses the inspiratory limb, changes in temperature and relative humidity cannot be described at each point. The ISO standard suggests measuring the humidifier’s change in weight during carefully controlled steady flow,¹¹ but during ventilation the gas in the inspiratory limb is under dynamic conditions. In preliminary experiments we found that temperature and relative humidity varied, depending on the type of heater, the distance from the humidifier, and the phase of respiration. We concluded that to reliably determine the water vapor content during mechanical ventilation we had to measure the water vapor in all the gas delivered to the patient. We designed an experimental setup (Fig. 1) that combined (1) measurement of water condensed out of the gas, and (2) temperature and relative-humidity measurement at one point in the circuit, from which we estimated the water content that remained in the gas after the condenser. As shown in Figure 1, we added a condenser to a standard ventilator circuit, distal to the Y-piece. During ventilation, as gas passed through the condenser, some of the water vapor condensed into liquid and was collected. The remaining water vapor in the gas was calculated based on temperature and relative humidity measurements at the distal end of the condenser. The sum of the condensate and the calculated water vapor provides the total water vapor in the gas.

We conducted 2 sets of experiments. First, we tested our setup with a calibrated water pump, to test the accuracy of our method for measuring water-vapor delivery. Second, we measured water-vapor delivery with non-heated-wire humidification and heated-wire humidification, over a wide range of \dot{V}_E .

Determination of Water Vapor Delivery

Our bench model of a ventilator circuit included a ventilator (7200, Puritan Bennett, Pleasanton, California), in-

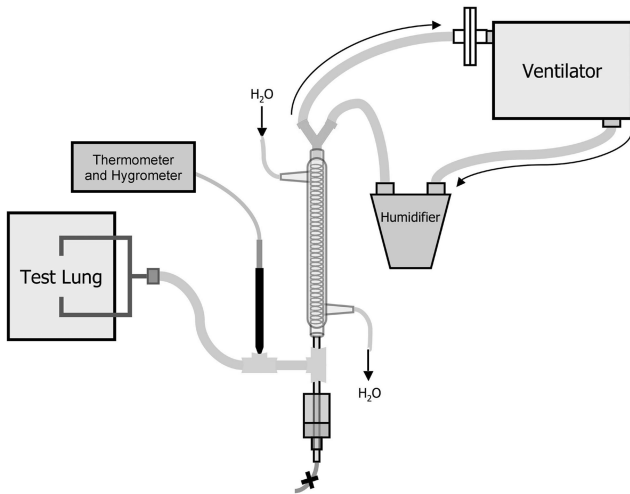


Fig. 1. Experimental set-up for measuring water-vapor delivery. During inspiration, dry inspiratory gas from the ventilator is heated and humidified by either non-heated-wire or heated-wire humidification. The humidified gas passes through the Y-piece into the condenser. Some water vapor is condensed, drained, and measured; the remaining water vapor in the gas is calculated from the temperature and relative humidity measured distal to the condenser.

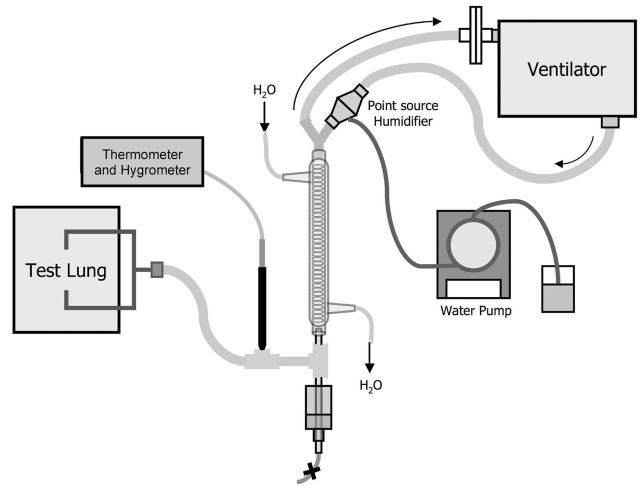


Fig. 2. Calibration setup to validate our water-vapor-delivery measurement technique. The conventional humidifier shown in Figure 1 was replaced with a point-source humidifier that vaporizes all water presented to it by the calibrated water pump. The water vapor at the Y-piece is measured by adding the condensate value to the remaining-vapor value, which is calculated from the temperature and relative humidity measured at the distal end of the condenser.

spiratory and expiratory tubing, a Y-piece, and a test lung (VentAid Training Test Lung, Michigan Instruments, Grand Rapids, Michigan). Compressed air and oxygen tanks provided inspiratory gas with the fraction of inspired oxygen set at 21%. In all the experiments the ventilator was run with an inspiratory flow of 70 L/min, no bias flow, and a ramp waveform. The inspiratory/expiratory ratio was not fixed, but varied depending on the respiratory rate.

The basis of the calculation is the water vapor delivered at a given \dot{V}_E over one hour. A condenser tube (Corning, Corning, New York) was incorporated vertically in the circuit, at the Y-piece, and cooled with tap water at 18°C. A water trap at the distal end of the condenser measured the condensate. We measured the temperature and relative humidity (Traceable, Fisher Scientific, Pittsburgh, Pennsylvania) at the distal end of the condenser, and calculated the water-vapor content of the gas that exited the condenser. We calculated¹⁴ the absolute humidity at saturation (100% relative humidity) for the measured temperature as:

$$\text{Absolute humidity at saturation} = 16.41563 - (0.731 \times T) + (0.03987 \times T^2)$$

in which T is temperature. Absolute humidity was calculated with the measured relative humidity of the gas at the distal end of the condenser:

$$\text{Absolute humidity} = \text{absolute humidity at saturation} \times \text{relative humidity}$$

The volume of gas in the system is the \dot{V}_E , so the amount of water vapor inspired over one hour is:

$$\begin{aligned} \text{Water-vapor delivery (mL H}_2\text{O/h)} &= \text{measured condensate (mL H}_2\text{O/h)} \\ &+ [\text{absolute humidity (mg H}_2\text{O/L)} \\ &\quad \times \dot{V}_E \text{ (L/min)}] \times (60 \text{ min/h)} \end{aligned}$$

in which we assume that 1,000 mg H₂O = 1 g H₂O = 1 mL H₂O.

Validation of the Bench Model

We tested our bench model for measuring water-vapor delivery with a point-source humidifier (Pari Respiratory Equipment, Midlothian, Virginia), which delivered a known quantity of water vapor to the Y-piece (Fig. 2). A calibrated pump delivered a fixed water flow to a heated plate that vaporized the water, which entered the inspiratory gas at 35°C. We quantified water delivery from the pump by multiplying the number of minutes in the experiment (60 min) by the pump rate (g H₂O/min), and the bench model measured the water vapor supplied by the pump.

Table 1. Breathing Patterns During Measurement of Water Vapor Delivery*

Respiratory Rate (breaths/min)	Minute Volume (L/min)			
	At V_T 400 mL	At V_T 500 mL	At V_T 600 mL	At V_T 750 mL
10	4.00	5.00	6.00	7.50
15	6.00	7.50	9.00	11.25
20	8.00	10.00	12.00	15.00
25	10.00	12.50	15.00	18.75

* Additional settings were inspiratory flow 70 L/min, no bias flow, and ramp waveform. The inspiratory-expiratory ratio was not fixed, but varied depending on the respiratory rate.
 V_T = tidal volume

Humidification Setups

We tested 2 types of humidification that have for years been used at our hospital: heated-wire and non-heated-wire. The humidifier was a Concha IV (Hudson RCI, Temecula, California), which can serve as a heated-wire or non-heated-wire humidifier (ie, the heating wire is either connected or not). In all the experiments the humidifier was set to deliver gas at 35°C to the Y-piece. We chose 35°C based on the American Association for Respiratory Care guidelines, which recommend setting the heated humidifier to deliver gas at $33 \pm 2^\circ\text{C}$.³ For heated-wire humidification, the temperature gradient between the Y-piece and the humidifier was set at either 0°C, +3°C, or -3°C (ie, column temperatures of 35°C, 38°C, and 33°C, respectively). We use column temperatures to specify the gradient, because the humidifier's "gradient" settings can be confusing. In non-heated-wire humidification, no temperature gradient can be set.

We measured water-vapor delivery with various breathing patterns and a clinically realistic \dot{V}_E range for adults (Table 1). After the Y-piece temperature stabilized at $35.0 \pm 0.2^\circ\text{C}$, we ran each breathing pattern for 60 min and measured/calculated the water-vapor delivery. Each run was performed at least twice. We plotted water-vapor delivery versus \dot{V}_E to determine humidifier performance at clinically relevant \dot{V}_E values. To compare physiologic variables, we calculated water-vapor delivery at 100% saturation and 37°C (saturated/37°C) and plotted it against the humidifier data, which represents the amount of water vapor that a humidifier would need to supply to the patient with an absolute humidity of 44 mg H₂O/L at a given \dot{V}_E . That value represents fully saturated gas under alveolar conditions (37°C and 100% relative humidity). We also calculated the ISO minimum of 75% saturation (33 mg H₂O/L) over the range of \dot{V}_E (ISO standard).

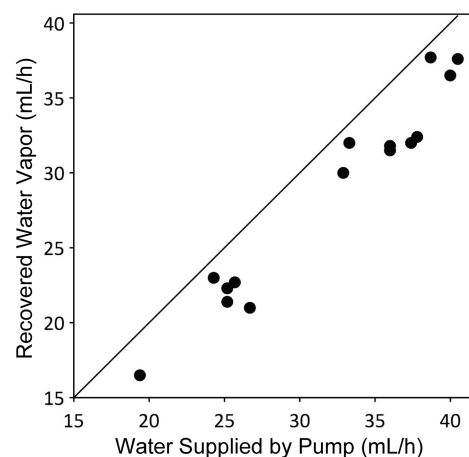


Fig. 3. Data from the setup described in Figure 2. Total water vapor (ie, measured condensed water plus calculated water vapor that exited the condenser) versus water supplied by the water pump. The measured data closely approximate the line of identity, but the data points indicate a small bias toward underestimation of water vapor. We attribute that underestimation to condensation in the expiratory limb of the circuit.

Statistical Analysis

We plotted water vapor recovered by the bench model against water vapor supplied by the calibrated pump (Fig. 3) and used the Bland-Altman method to compare those 2 measurements, with an analysis of the differences between the measurements, the bias, the mean difference, the standard deviation around that mean, and the relationship of the difference in measurements over the range of the magnitude of water-vapor delivery.¹⁶

Our statistical analysis (SPSS 15.0, SPSS, Chicago, Illinois) included univariate analysis, analysis of covariance, and tests for unequal slopes of regression lines for water-vapor delivery on \dot{V}_E with non-heated-wire humidification and heated-wire at the 3 temperature gradients.

Results

There was a close correlation ($r^2 = 0.95$, see Fig. 3) between the water supplied by the calibrated water pump and the water vapor measured/calculated with our bench model. The data closely approximate the line of identity, but our bench model slightly underestimated the water supplied by the water pump. The mean \pm SD measurement bias was 3.38 ± 1.49 mL/h (95% confidence interval -2.5 to -4.2), and the underestimate was over the whole range of tests. Per the Bland and Altman method (mean of differences $\pm 1.96 \times$ SD of the mean of differences), the 95% limits of agreement range was -0.47 to -6.29 mL/h.

Figure 4 shows water-vapor delivery versus \dot{V}_E (range 4-18.75 L/min). With the model set to heat the gas to

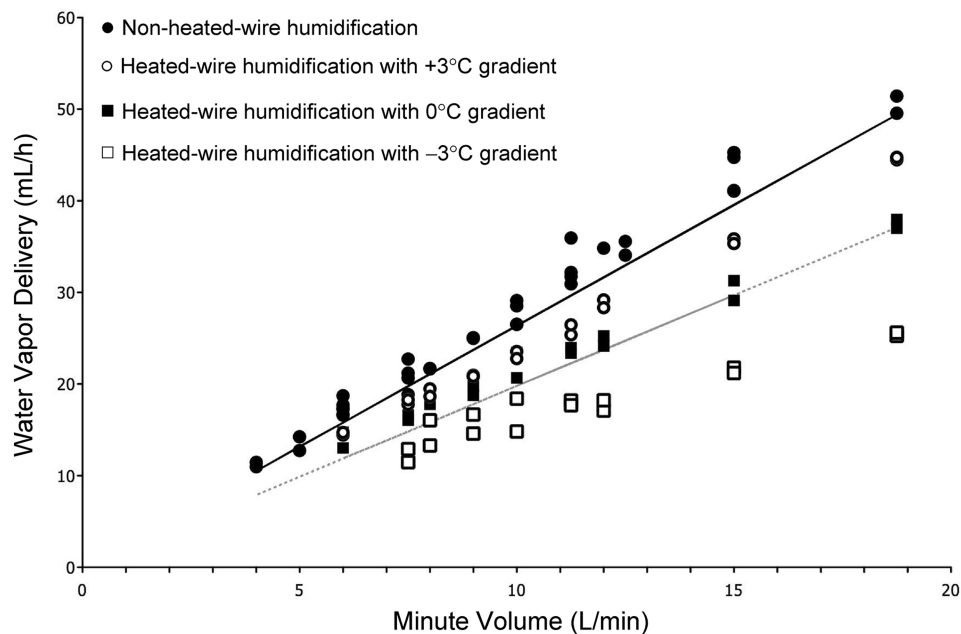


Fig. 4. Water-vapor delivery versus minute volume during non-heated-wire humidification and during heated-wire humidification with a temperature gradient of $+3^{\circ}\text{C}$, 0°C , and -3°C between the humidifier and the Y-piece. In all the experiments the Y-piece temperature was set to 35°C . The solid line represents water-saturated gas at 37°C (saturated/ 37°C). The dashed line represents the temperature and humidification recommended by the International Organization for Standardization (ISO standard). Water-vapor delivery with non-heated-wire humidification was significantly different from that during all the heated-wire humidification tests. Non-heated-wire humidification provided as much or more water-vapor delivery than that expected at the saturated/ 37°C conditions. Water-vapor delivery during heated-wire humidification was significantly less than at saturated/ 37°C and less than the ISO standard when the temperature gradient was -3°C .

35°C at the Y-piece, non-heated-wire humidification provided significantly more water vapor than heated-wire humidification at the higher \dot{V}_E settings. Analysis of covariance indicated that all 3 heated-wire-humidification column conditions were significantly different from the non-heated-wire data. The non-heated-wire water-vapor delivery often exceeded the physiologic target values (saturated/ 37°C). Heated-wire humidification did not increase water-vapor delivery, compared to non-heated-wire humidification, and with increasing \dot{V}_E the water-vapor delivery was often far below the physiologic target values. Heated-wire humidification with the -3°C gradient did not meet even the less stringent ISO requirements at $\dot{V}_E > 8 \text{ L/min}$.

Discussion

With the Y-piece temperature set at 35°C , there were significant differences between non-heated-wire and heated-wire humidification. The validation experiment indicated that our model slightly underestimated the actual water-vapor delivery. However, even if that underestimation is taken into account, the water-vapor delivery with the different humidification setups differed in the same direction and magnitude. The small systematic water-vapor loss may be due to escape of water from the condenser in exhaled gas. We did observe trace condensation

in the expiratory tubing, but not enough to collect and measure. An additional source of error could be the water pump, but it was calibrated to deliver a fixed water flow prior to the study.

To our knowledge, this is the first study to measure water-vapor delivery that did not rely on monitoring the temperature or humidity at only one point in the inspiratory limb. Our model is an independent method to evaluate humidifier performance under clinically relevant conditions.

Non-heated-wire humidification delivered significantly more water vapor than heated-wire humidification over a wide \dot{V}_E range. Heated-wire humidification provided significantly less water vapor than the saturated/ 37°C and ISO standard conditions. This indicates that heated-wire humidification with the 0°C and -3°C gradients does not adequately humidify the gas at $\dot{V}_E > 6 \text{ L/min}$. Maintaining the Y-piece at 35°C does not result in equivalent water-vapor delivery with heated-wire and non-heated-wire humidification, nor consistently achieve the ISO-recommended or physiologic humidification target. If the Y-piece temperature determined humidification, we would have found equal water-vapor delivery in all the test conditions, but it was greater with non-heated-wire than with heated-wire humidification. Thus, the answers to the first 4 questions posed in the introduction are all “no.”

Our results do not imply superiority of any of the tested humidification methods or setups. For example, non-heated-wire humidification delivered more water vapor at 35°C than “physiologically necessary at 37°C,” whereas heated-wire humidification delivered less. With each breath, a bolus of gas is delivered to the Y-piece, and the gas temperature may be unsteady and its water vapor content may be greater or less than would be expected at 35°C.

Our results agree with those of previous investigators. Lellouche et al and Pelosi et al used the dry/wet bulb technique to measure absolute humidity at the Y-piece.^{12,17} Nishida et al and Gilmour et al measured temperature and relative humidity at the Y-piece, and then calculated absolute humidity.^{6,18} With the absolute humidity data from those studies, and equation 3 from our methods, we calculated water-vapor delivery and found agreement between our data and theirs for the few points that had similar Y-piece temperature and \dot{V}_E .

We developed our water-vapor-measurement technique to determine if the average temperature and humidity at one point in the inspiratory circuit accurately indicate the water vapor content of the inspiratory gas bolus. We found that Y-piece temperature with a given humidification system/setup did not reflect device performance, and the conclusions from the above-referenced papers appear to agree with our findings. We also found a fairly wide range of water-vapor delivery in a wide range of clinically relevant \dot{V}_E .

Our water-vapor delivery findings might be specific to the Concha IV humidifier, which we have used at our institution for many years. However, our and others' data indicate that water-vapor delivery (particularly with heated-wire humidification) is sensitive to several factors, including the humidifier, the \dot{V}_E , the type of ventilator, the ventilation mode, the gas source, and the environmental conditions. For this initial study we chose 2 representative conditions typical in intensive care units: dry gas with zero-bias flow. We expect that setups with bias flow and/or room-air compressors will perform differently, and they are the subject of ongoing studies.

Are the measured differences between humidifiers clinically important? Studies have linked different forms of humidification to clinical or surrogate end points, such as, endotracheal tube narrowing or occlusion, and secretion clearance.¹⁹⁻²⁴ In a meta-analysis by Williams et al, reduction in inspiratory gas temperature or relative humidity was associated with an increase in mucociliary dysfunction score.² Similarly, in sheep, Kilgour et al²⁰ found that reducing the inspiratory gas temperature from 37°C to 34°C and 30°C (at 100% relative humidity) decreased the ciliary beat frequency and mucus-transport velocity and was associated with abnormal epithelial cell histology and total mucociliary failure over a 6-hour observation period.

In humans, Beydon et al found that, during mechanical ventilation, secretion viscosity and endotracheal-suction-catheter adherence increased as absolute humidity output from a heat-and-moisture exchanger decreased.¹⁹ In addition, Konrad et al found that impaired secretion-clearance increases the risk of ventilator-associated pneumonia.²¹ Both human clinical studies and animal studies of pathophysiology indicate that reducing the temperature or humidity below physiologic conditions can have adverse effects. Our data suggest that, under certain circumstances, heated-wire humidification can be inadequate for maintaining the integrity of the airway mucosa.

We could not study heat-and-moisture exchangers with our setup in this study, because with a heat-and-moisture exchanger water vapor is not delivered from a humidifier (active humidification); instead, the patient's exhaled water vapor is captured and returned on the subsequent inspiration.

Our bench setup was not designed to measure water-vapor delivery in vivo. Our interest was to quantify humidifier performance prior to designing in vivo studies of variables affected by water-vapor delivery, such as aerosol delivery and airway functioning. Also, we did not use an independent pneumotachograph to monitor \dot{V}_E .

Conclusions

Clinical trials are needed to study the airways effects of various humidification systems and setups. Our data indicate that, to assess the effects of water-vapor delivery in future clinical trials, it is important to quantify water-vapor delivery beforehand, under clinically relevant conditions.

REFERENCES

1. Branson RD. The effects of inadequate humidity. *Respir Care Clin N Am* 1998;4(2):199-214.
2. Williams R, Rankin N, Smith T, Galler D, Seakins P. Relationship between the humidity and temperature of inspired gas and the function of the airway mucosa. *Crit Care Med* 1996;24(11):1920-1929.
3. American Association for Respiratory Care. Clinical practice guideline: humidification during mechanical ventilation. *Respir Care* 1992;37(8):887-890.
4. American Association for Respiratory Care. Evidence based clinical practice guidelines: care of the ventilator circuit and its relation to ventilator associated pneumonia. *Respir Care* 2003;48(9):869-879.
5. Dubini G, Fumero R. Humidity measurements in passive heat and moisture exchangers applications: a critical issue. *J Med Eng Technol* 2000;24(1):40-44.
6. Nishida T, Nishimura M, Fujino Y, Mashimo T. Performance of heated humidifiers with a heated wire according to ventilatory settings. *J Aerosol Med* 2001;14(1):43-51.
7. Peterson BD. Heated humidifiers. Structure and function. *Respir Care Clin N Am* 1998;4(2):243-259.
8. Ricard JD, Markowicz P, Djedaini K, Mier L, Coste F, Dreyfuss D. Bedside evaluation of efficient airway humidification during mechanical ventilation of the critically ill. *Chest* 1999;115(6):1646-1652.

9. Thomachot L, Viviand X, Lagier P, Dejode JM, Albanese J, Martin C. Measurement of tracheal temperature is not a reliable index of total respiratory heat loss in mechanically ventilated patients. *Crit Care* 2001;5(1):24-30.
10. Williams RB. The effects of excessive humidity. *Respir Care Clin N Am* 1998;4(2):215-228.
11. Humidifiers for medical use: general requirements for humidification systems, 2nd edition. International Organization for Standardization; 1997: 11-15.
12. Lellouche F, Taillé S, Maggiore SM, Qader S, L'Her E, Deye N, Brochard L. Influence of ambient and ventilator output temperatures on performance of heated-wire humidifiers. *Am J Respir Crit Care Med* 2004;170(10):1073-1079.
13. Martin C, Papazian L, Perrin G, Saux P, Gouin F. Preservation of humidity and heat of respiratory gases in patients with a minute ventilation greater than 10 L/min. *Crit Care Med* 1994;22(11):1871-1876.
14. Martin C, Thomachot L, Quinio B, Viviand X, Albanese J. Comparing two heat and moisture exchangers with one vaporizing humidifier in patients with minute ventilation greater than 10 L/min. *Chest* 1995;107(5):1411-1415.
15. Rathgeber J, Kazmaier S, Penack O, Züchner K. Evaluation of heated humidifiers for use on intubated patients: a comparative study of humidifying efficiency, flow resistance, and alarm functions using a lung model. *Intensive Care Med* 2002;28(6):731-739.
16. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986;1(8474):307-3(3):258-264.
17. Pelosi P, Chiumello D, Severgnini P, De Grandis CE, Landi L, Chierichetti LM, et al. Performance of heated wire humidifiers: an in vitro study. *J Crit Care* 2007;22(3):258-264.
18. Gilmour IJ, Boyle MJ, Rozenberg A, Palahniuk RJ. The effect of heated wire circuits on humidification of inspired gases. *Anesth Analg* 1994;79(1):160-164.
19. Beydon L, Tong D, Jackson N, Dreyfuss D; Groupe de Travail sur les Respirateurs. Correlation between simple clinical parameters and the in vitro humidification characteristics of filter heat and moisture exchangers. *Chest* 1997;112(3):739-744.
20. Kilgour E, Rankin N, Ryan S, Pack R. Mucociliary function deteriorates in the clinical range of inspired air temperature and humidity. *Intensive Care Med* 2004;30(7):1491-1494.
21. Konrad F, Schreiber T, Brecht-Kraus D, Georgieff M. Mucociliary transport in ICU patients. *Chest* 1994;105(1):237-241.
22. Cohen IL, Weinberg PF, Fein IA, Rowinski GS. Endotracheal tube occlusion associated with the use of heat and moisture exchangers in the intensive care unit. *Crit Care Med* 1988;16(3):277-279.
23. Jaber S, Pigeot J, Fodil R, Maggiore S, Harf A, Isabey D, et al. Long-term effects of different humidification systems on endotracheal tube patency: evaluation by the acoustic reflection method. *Anesthesiology* 2004;100(4):782-788.
24. Villafane MC, Cinnella G, Lofaso F, Isabey D, Harf F, Lemaire F, Brochard L. Gradual reduction of endotracheal tube diameter during mechanical ventilation via different humidification devices. *Anesthesiology* 1996;85(6):1341-1349.