

Humidification Performance of Passive and Active Humidification Devices Within a Spontaneously Breathing Tracheostomized Cohort

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BACKGROUND: Most heat-and-moisture exchangers (HMEs) for patients with tracheostomy and spontaneously breathing are small and have suction ports that allow some expiratory gas to escape, which loses vapor held in the expired gas. Recently, a heated-and-humidified high-flow system for spontaneously breathing patients with tracheostomy was developed. Little is known, however, about the humidifying performance of HMEs or heated-and-humidified high-flow systems for spontaneous breathing patients with a tracheostomy. **OBJECTIVE:** To investigate the humidifying performance of the HMEs and heated-and-humidified high-flow systems for spontaneously breathing patients with tracheostomy. **METHODS:** Adult spontaneously breathing subjects with tracheostomy and were enrolled when their respiratory parameters and S_{pO_2} were stable. We measured absolute humidity, relative humidity, and temperature by using a capacitance-type moisture sensor at the outlet of the tracheostomy tube. Heated-and-humidified high flow was delivered via the a humidifier and tracheostomy interface, and a selected HME. The subjects received heated-and-humidified high flow, after which an HME was used for humidification before switching back to a heated-and-humidified high-flow system. **RESULTS:** Ten subjects (5 men, 5 women; mean \pm SD age, 72 ± 12 y) were enrolled. The admission diagnoses were neurologic (5 subjects), respiratory failure (3), and cardiac arrest (2). The APACHE (Acute Physiology and Chronic Health Evaluation) II score was 24 (interquartile range, 20–27). Tracheostomy was performed on day 7 (interquartile range, 5–11 d) after endotracheal intubation, and the duration of mechanical ventilation was 10 d (interquartile range, 6–11 d). The temperature with the HME was $29.9 \pm 1.0^\circ\text{C}$ and, during heated-and-humidified high-flow use was $35.3 \pm 0.8^\circ\text{C}$ ($P < .001$). With both the HME and the heated-and-humidified high-flow system, the relative humidity reached 100%; the absolute humidity with HME was 30.2 ± 1.8 mg/L, and, with the heated-and-humidified high-flow system, was 40.3 ± 1.8 mg/L ($P < .001$). **CONCLUSIONS:** In spontaneously breathing subjects with tracheostomy, an heated-and-humidified high-flow system achieved higher absolute humidity than did an HME. *Key words:* heat and moisture exchanger; heated and humidified high flow; tracheostomized patients. [Respir Care 0;0(0):1–•. © 0 Daedalus Enterprises]

Introduction

Tracheostomy has a number of advantages, including improved patient comfort, easier oral hygiene, and earlier

weaning from mechanical ventilation.¹ Normally, inspiratory gas is heated in the pharynx and trachea: humidity in the trachea has been measured in the range of 36 to 40 mg/L, and the optimal absolute humidity below the carina is 44 mg/L (100% relative humidity at 37°C).² Because the

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upper airway is bypassed in patients who have a tracheostomy, warming and humidification of inspired gases are often inadequate. To prevent destruction of airway epithelium, inadequate airway secretion, and airway obstruction, humidification is necessary.² For mechanically ventilated patients, the American Association for Respiratory Care recommends that absolute humidity of passive humidification be >30 mg/L and the absolute humidity of active humidification be between 33 and 44 mg/L.³ The optimal humidity spontaneously breathing for patients with tracheostomy remains unclear.

Humidifying devices are used to compensate for the bypassed functions of the upper airway. Heated humidifiers and heat-and-moisture exchangers (HMEs) are commonly used for patients on mechanical ventilation. When reporting the results of a recent bench study, Chikata et al⁴ found that a heated-and-humidified high-flow system achieved better humidification than did an HME. Little is known, however, about performance of heated-and-humidified high-flow and HME in spontaneous breathing of patients with tracheostomy. We, therefore, carried out a crossover study to investigate the humidification performance of an HME and a heated-and-humidified high-flow system in spontaneously breathing tracheostomized subjects.

Methods

Study Design and Settings

We conducted a crossover study at Tokushima University Hospital. This study was approved by the clinical research ethics committee (approval 2033). At enrollment, written informed consent was obtained from the subjects or their legal representative.

Study Population

Adult spontaneously breathing subjects with tracheostomy without ventilatory support were consecutively enrolled. We excluded patients with the following: age < 18 y old; copious secretions that caused expulsion difficulties; severe respiratory or hemodynamic instability; had a requirement for >1 L/min of oxygen or $F_{IO_2} > 0.25$.

Study Protocol

This study was undertaken to compare the performance of an HME (Trach-Vent+, Gibeck, Sweden; in the manufacturer's specifications: absolute humidity, 27.0 mg/L; dead space, 10 mL) and a heated-and-humidified high-flow device (MR850 and Optiflow tracheostomy interface, Fisher and Paykel Healthcare, Auckland, New Zealand) in

QUICK LOOK

Current knowledge

Humidification for spontaneously breathing patients with tracheostomy is often poor. Heat-and-moisture exchangers (HMEs) are small and light but do not necessarily supply enough water vapor, especially when used with oxygen. Recently, a heated-and-humidified high-flow system for spontaneously breathing patients with tracheostomy was developed.

What this paper contributes to our knowledge

Inspiratory gas humidity was measured with an HME and a heated-and-humidified high-flow system in spontaneously breathing subjects with a tracheostomy. The heated-and-humidified high-flow system delivered higher humidity than the HME. In the present study, both the HME and heated-and-humidified high-flow system supplied absolute humidity at least higher than the American Association for Respiratory Care recommendations.

spontaneously breathing subjects with tracheostomy. The HME was used with room air only or with added low-flow oxygen (1 L/min). A heated-and-humidified high-flow system delivers 40 L/min flow at F_{IO_2} of 0.21 or 0.25. The heated humidifier system was set to deliver gas at a water chamber temperature of 37°C and end-inspiratory circuit temperature at 40°C. To lessen the time-series bias, the protocol for each subject comprised 3 phases, each lasted 60 min, in the following order: heated-and-humidified high flow, HME, and heated-and-humidified high flow (Fig. 1).

After each period, we measured the temperature and relative humidity of inspired gas by using a capacitance-type moisture sensor (Moiscope, Senko Medical, Tokyo, Japan) (response time, 3 s in the range of 40–100%) that was calibrated by using a cooler-heater water source (HHC-51, Senkoika, Tokyo, Japan). One-way valves prevented mixing of inspired and expired gases (Fig. 2). All signals from the hygrometer led to an analog-digital converter and were recorded at 50 Hz/channel with data-acquisition software (Windaq, Dataq Instruments, Akron, Ohio). Before taking internal measurements, we recorded the ambient temperature and humidity readings for 20 s. Once stabilized values were obtained for each parameter, inspired gas measurements were recorded for 1 min. Absolute humidity was calculated from the corresponding temperature and relative humidity.⁵ At the end of each phase, we collected readings for breathing frequency, S_{pO_2} , and hemodynamics (heart rate, systolic blood pressure, and mean blood pressure), and, for 1 min, measured tidal volume

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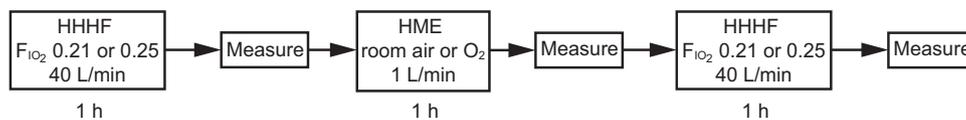


Fig. 1. Time course of measurements. Subjects received heated-and-humidified high-flow (HHHF), after which a heat-and-moisture exchanger (HME) was used for humidification before switching back to HHHF system.

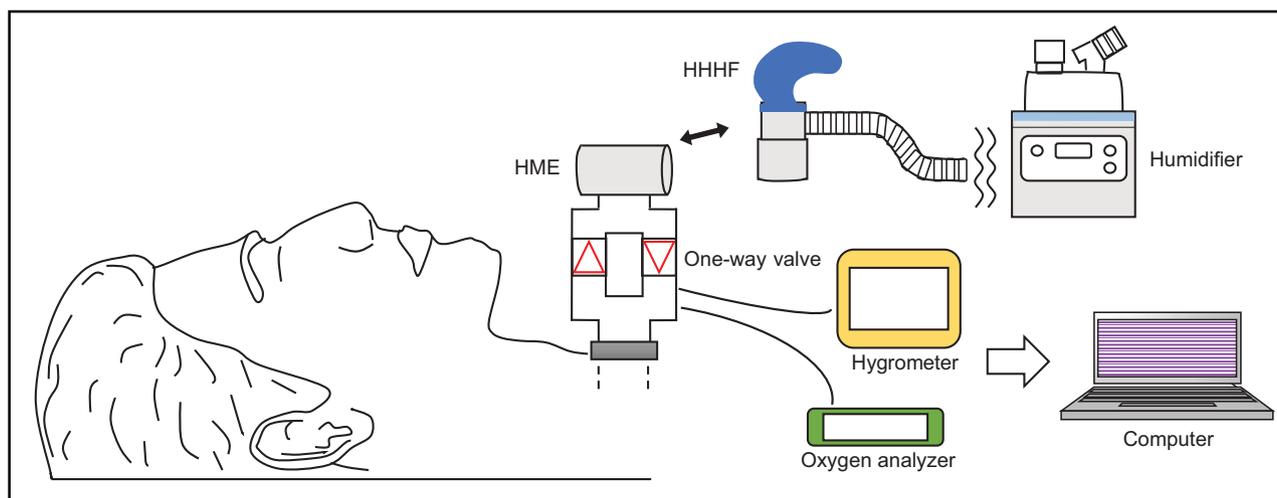


Fig. 2. We measured the temperature and relative humidity of inspired gas by using a capacitance-type moisture sensor. One-way valves prevented mixing of inspired and expired gases. All signals from the hygrometer were sent to an analog-digital converter and recorded at 50 Hz/channel with data-acquisition software. HME = heat-and-moisture exchanger, HHHF = heated-and-humidified high-flow.

(V_T) and end-tidal carbon dioxide (P_{ETCO_2}) by using an S/5 Aespire (Dtex-Ohmeda, Helsinki, Finland).

Statistical Analyses

Normally distributed data are shown as mean \pm SD, whereas non-normally distributed data are presented as median (interquartile range [IQR]). We compared variables obtained during each study phase by using 1-way analysis of variance for repeated measures or the Friedman test. Post hoc correction for multiple comparisons was performed with the Dunnett comparison. Data analysis was conducted by using JMP statistical software version 13.1.0 (SAS Institute, Cary, North Carolina). All statistical tests were 2-tailed, and the chosen type-1 error rate was $P < .05$.

Results

We enrolled 10 subjects (5 men, 5 women; mean \pm SD age, 72 ± 12 y). The admission diagnoses were neurologic (5 subjects), respiratory failure (3 subjects), and after cardiac arrest (2 subjects). The APACHE (Acute Physiology and Chronic Health Evaluation) II score was 24 (IQR, 20–27). All the subjects required mechanical ventilation before tracheostomy. Tracheostomy was performed at day 7

(IQR, 5–11 d) after endotracheal intubation, and the total duration of mechanical ventilation was 10 (IQR, 6–11) d. Six subjects did not require oxygen, and 4 required 1 L/min of oxygen at F_{IO_2} of 0.25. The demographic data are presented in Table 1.

No statistically significant differences were observed in ambient conditions (Table 2). Temperature with the phase 1 heated-and-humidified high flow system, phase 2 HME, and phase 3 heated-and-humidified high-flow system were $35.3 \pm 0.8^\circ\text{C}$, $29.9 \pm 1.0^\circ\text{C}$, and $35.5 \pm 0.8^\circ\text{C}$, respectively ($P < .001$). Relative humidity reached 100% with both the HME and during heated-and-humidified high flow ($P = .39$). The mean \pm SD absolute humidity with the HME was 30.2 ± 1.8 mg/L and, with heated-and-humidified high-flow, was 40.3 ± 1.8 mg/L (1st phase) and 40.6 ± 1.7 mg/L (2nd phase) ($P < .001$) (Fig. 3).

In phase 1 heated-and-humidified high flow, phase 2 HME, and phase 3 heated-and-humidified high flow, P_{ETCO_2} was 34.4 ± 3.7 mm Hg, 35.9 ± 3.9 mm Hg, and 34.2 ± 3.7 mm Hg, mean \pm SD respectively ($P = .01$), and, for minute ventilation, was 6.2 ± 1.4 L/min, 7.3 ± 1.4 L/min, and 6.0 ± 1.2 L/min, mean \pm SD respectively ($P = .02$). Heart rate, blood pressure, and S_{pO_2} remained stable across the phases, and the percentage difference of V_T and breathing frequency were close to 5%.

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Table 1. Subjects' Characteristics

Variable	Result
Age, mean \pm SD y	72 \pm 12
Men/women	5/5
Body mass index, median (IQR) kg/m ²	21.5 (20.0–24.2)
APACHE II score, median (IQR)	24 (20–27)
Day of tracheostomy, median (IQR) d	7 (5–11)
Duration of mechanical ventilation, median (IQR) d	10 (6–11)
ICU length of stay, median (IQR) d	11 (10–23)
ICU admission category, <i>n</i>	
Neurologic	5
Respiratory failure	3
Cardiac arrest	2
Body temperature, mean \pm SD °C	37.4 \pm 0.7
F _{IO₂} 0.21/F _{IO₂} 0.25	6/4

N = 10.
IQR = interquartile range
APACHE = Acute Physiology and Chronic Health Evaluation II

Discussion

In this study, we compared the humidification performance of an HME and a heated-and-humidified high-flow device in spontaneously breathing subjects with tracheostomy, and found that the absolute humidity was higher during heated-and-humidified high flow. Because the heated-and-humidified high flow system delivered >33 mg/L and the HME delivered >30 mg/L, both systems satisfied the American Association for Respiratory Care minimum humidification requirements for patients on mechanical ventilation.³

However, International Organization for Standardization 8185⁶ recommends an absolute humidity of >33 mg/L, which is also what Williams et al² considered the minimum acceptable level of humidity for inspired gases. When comparing 11 HMEs in a bench study, Chikata et al⁴ found the highest absolute humidity was 30.7 mg/L with Trachvent+. After measuring the absolute humidity of 48 HMEs used in mechanical ventilation, Lellouche et al⁷ reported the average absolute humidity as 27.5 \pm 4.4 mg/L, and the highest as 31.9 \pm 0.6 mg/L. Our current findings with the subjects with tracheostomy showed an HME that delivered comparable levels of absolute humidity as in these bench studies.^{4,7}

In the present study, absolute humidity with the heated-and-humidified high-flow system was higher than in our previous bench study.⁴ Four factors may account for the discrepant results. In the bench study, the Airvo 2 delivered 37.7 mg/L of absolute humidity,⁴ but the absolute humidity in our subjects was 40.3 \pm 1.8 mg/L, mean \pm SD. This higher inspiratory absolute humidity may have resulted from the adaptability of subjects' breathing pat-

terns. Humidification performance varies according to V_T and breathing frequency. Low V_T and, possibly, high breathing frequency increase absolute humidity.⁴ We found a lower V_T (248 vs 300–500 mL) and higher breathing frequency (24 \pm 6 vs 10–20 breaths/min) than in our bench study.⁴ The results may also differ owing to the use of 1-way valves to separate expiratory gas; however, we could not completely exclude the possibility of overestimation owing to admixture of water vapor from expired gases.

As discussed previously, it is difficult to measure humidification correctly.⁸ In addition, the environmental conditions differed. At <100% relative humidity, absolute humidity is dependent on inspiratory gas temperature. The Optiflow tracheostomy interface connected to the tracheostomy tube was exposed to the ambient temperature, and incoming heated air was cooled at the airway opening of the tracheal tube.⁹ In the study by Chikata et al,¹⁰ room temperature was lower than in the ICU (24.0°C vs 25.0°C), which possibly resulted in more heat loss. Finally, heated-and-humidified high-flow devices are different. Although the mechanisms are not disclosed, the MR850 humidifier and Airvo 2 have different temperature-control mechanisms; in practice, the Airvo 2 provides better humidification than did the MR850 humidifier.

Several mechanisms may account for the beneficial effects of heated-and-humidified high-flow therapy, such as lower P_{ETCO_2} and minute ventilation, reductions that might result from decreased lung dead space and better CO₂ washout. Breathing frequency and V_T slightly decreased without statistical significance ($P = .06$ and $.08$, respectively), which possibly indicated a little less work of breathing. There also are anatomic differences in the way the gas is delivered by the heated-and-humidified high-flow system and high-flow nasal cannula, which encroach on nasopharyngeal dead space. Heated-and-humidified high-flow system supports ventilation directly at the tracheal airway opening, and such proximity to the lung may enable more-effective lung inflation and escape of gas. However, the current investigation was not designed to investigate these effects, and the mechanisms have yet to be resolved.

The cost of the heated-and-humidified high-flow system and the HME should be taken into account. The cost of HMEs is approximately \$2, and it needs to be changed every 48 h.¹¹ However, the cost of a heated-and-humidified high-flow system is higher than an HME because high-flow systems need a tracheostomy interface, heated wire circuit, distilled water, and high-flow oxygen.¹¹ However, for patients who are critically ill, the heated-and-humidified high-flow system is justified because it reduces complications related to inadequate humidity and the risk of re-intubation.¹²

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Table 2. Effects of HME and HHHF

Variable	HHHF (1st phase)	HME	HHHF (2nd phase)	<i>P</i>
Ambient condition				
Room temperature, median (IQR) °C	25.0 (24.6–26.0)	24.9 (24.7–26.0)	25.0 (24.6–26.1)	.57
Relative humidity, median (IQR) %	32.5 (13.8–48.7)	31.6 (12.9–48.5)	31.1 (12.5–47.8)	.50
Absolute humidity, median (IQR) mg/L	7.7 (3.2–11.3)	7.6 (3.0–11.5)	7.4 (2.8–11.4)	.86
Subject data				
Temperature, mean ± SD °C	35.3 ± 0.8*	29.9 ± 1.0	35.5 ± 0.8*	< .001
Relative humidity, median (IQR) %	100 (100–100)	100 (100–100)	100 (100–100)	.39
Absolute humidity, mean ± SD mg/L	40.3 ± 1.8*	30.2 ± 1.8	40.6 ± 1.7*	< .001
P _{ETCO₂} , mean ± SD mm Hg	34.4 ± 3.7*	35.9 ± 3.9	34.2 ± 3.7*	.01
V _T , median (IQR) mL	248 (227–276)	272 (244–333)	237 (228–283)	.064
Frequency, mean ± SD breaths/min	24 ± 6	26 ± 5	25 ± 7	.08
Ṁ _E , mean ± SD L/min	6.2 ± 1.4*	7.3 ± 1.4	6.0 ± 1.2*	.02
S _{pO₂} , mean ± SD %	96 ± 2	96 ± 1	96 ± 1	.43
HR, mean ± SD beats/min	85 ± 16	87 ± 13	85 ± 14	.14
SBP, mean ± SD mm Hg	133 ± 21	126 ± 21	130 ± 27	.58
MBP, mean ± SD mm Hg	90 ± 11	87 ± 11	88 ± 15	.90

* Significant at $P < .05$ (post hoc Dunnett test vs HME).

HME = heat-and-moisture exchanger

HHHF = heated-and-humidified high flow

P_{ETCO₂} = end-tidal carbon dioxide

V_T = tidal volume

Ṁ_E = minute ventilation

HR = heart rate

SBP = systolic blood pressure

MBP = mean blood pressure

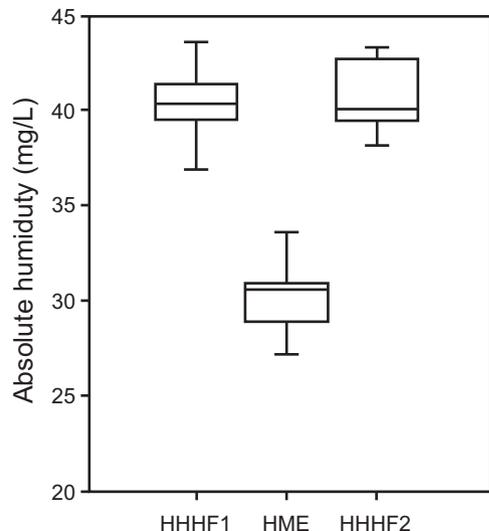


Fig. 3. Absolute humidity of each period. Both devices supplied >30 mg/L of vapor, whereas the HHHF system supplied higher vapor. HHHF = heated-and-humidified high flow, HHHF1 = HHHF (1st phase), HHHF2 = HHHF (2nd phase), HME = heat-and-moisture exchanger.

In spontaneously breathing subjects with tracheostomy the absolute humidity was higher during heated-and-humidified high flow than with the HME. Humidification is needed in all patients who are critically ill and receiving

ventilator support. Even so, the clinical benefits of different methods are still far from being demonstrated and remain to be elucidated. To avoid serious complications related to breathing dry gases, humidifiers should be chosen to provide adequate performance according to clinical conditions.

Limitations

Our study had several limitations. First of all, the sample size was small. Moreover, all the subjects had a stable respiratory status, and 4 of 10 subjects needed only low-flow oxygen. The absolute humidity would be lower in patients with high V_T and high inspiratory flow. Our test protocols were also brief. When evaluating the humidifying performance of an HME and a heated-and-humidified high-flow system for spontaneously breathing subjects with tracheostomy, we found higher absolute humidity during heated-and-humidified high flow.

REFERENCES

- Cheung NH, Napolitano LM. Tracheostomy: epidemiology, indications, timing, technique, and outcomes. *Respir Care* 2014;59(6):895-915; discussion 916-919.
- 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.

HUMIDIFICATION DEVICES FOR TRACHEOSTOMIZED SUBJECTS

3. American Association for Respiratory Care, Restrepo RD, Walsh BK. Humidification during invasive and noninvasive mechanical ventilation: 2012. *Respir Care* 2012;57(5):782-788.
4. Chikata Y, Oto J, Onodera M, Nishimura M. Humidification performance of humidifying devices for tracheostomized patients with spontaneous breathing: a bench study. *Respir Care* 2013;58(9):1442-1448.
5. Tilling SE, Hancox AJ, Hayes B. An accurate method of measuring medical humidifier output. *Clin Phys Physiol Meas* 1983;4(2):197-209.
6. ISO. Respiratory tract humidifiers for medical use: particular requirements for respiratory humidification systems. 3rd ed. 2007;8185.
7. Lellouche F, Taillé S, Lefrançois F, Deye N, Maggiore SM, Jouvét P, et al; Groupe de travail sur les Respirateurs de l'AP-HP. Humidification performance of 48 passive airway humidifiers: comparison with manufacturer data. *Chest* 2009;135(2):276-286.
8. Cuquemelle E, Lellouche F. Assessment of humidification performance: still no easy method! *Respir Care* 2013;58(9):1559-1561.
9. Chikata Y, Imanaka H, Onishi Y, Ueta M, Nishimura M. Humidification during high-frequency oscillation ventilation is affected by ventilator circuit and ventilatory setting. *Paediatr Anaesth* 2009;19(8):779-783.
10. Chikata Y, Izawa M, Okuda N, Itagaki T, Nakataki E, Onodera M, et al. Humidification performance of two high-flow nasal cannula devices: a bench study. *Respir Care* 2014;59(8):1186-1190.
11. Branson RD, Davis K Jr, Brown R, Rashkin M. Comparison of three humidification techniques during mechanical ventilation: patient selection, cost and infections considerations. *Respir Care* 1996;41(9):809-816.
12. Eaton Turner E, Jenks M. Cost-effectiveness analysis of the use of high-flow oxygen through nasal cannula in intensive care units in NHS England. *Expert Rev Pharmacoecon Outcomes Res* 2018; 18(3)331-337.