RESPIRATORY CARE Paper in Press. Published on February 05, 2013 as DOI: 10.4187/respcare.02093

Humidification performance of humidifying devices for tracheostomized patients with spontaneous breathing: a bench study

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Abstract

Background

Heat and moisture exchangers (HMEs) are commonly used for humidifying respiratory gases administered to mechanically ventilated patients. While they are also applied to tracheostomized patients with spontaneous breathing (SB), their performance in this role has not yet been clarified. We carried out a bench study to investigate the effects of spontaneous breathing parameters and oxygen flow on the humidification performance of the HMEs.

Methods

We evaluated the humidification provided by 11 HMEs for tracheostomized patients, and also by a system delivering high-flow continuous positive air pressure (CPAP), and an oxygen mask with nebulizer heater. SB was simulated with a mechanical ventilator, model lung, and servo-controlled heated humidifier at tidal volumes (V_T) of 300, 500 and 700 mL and respiratory rates of 10 and 20 breaths per minute. Expired gas was warmed to 37°C. The high-flow CPAP system was set to deliver 15, 30 and 45 L/min. With the 8 HMEs that were equipped with ports to deliver oxygen and with the high-flow CPAP system, measurements were taken when delivering 0 and 3 L/min of dry oxygen. After stabilization, we measured the absolute humidity (AH) of inspired gas with a

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hygrometer.

Results

AH differed among HMEs applied to tracheostomized patients with SB. For all HMEs, as V_T increased, AH decreased. At 20 breaths a minute, AH was higher than it at 10. For all HMEs, when oxygen was delivered, AH decreased below 30 mg/L. With an oxygen mask and high-flow CPAP, at all settings, AH exceeded 30 mg/L.

Conclusion

No HME provided adequate humidification when supplemental oxygen was added. In the ICU, caution is required when applying HMEs to tracheostomized patients with SB, especially when supplemental oxygen is required.

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Introduction

During everyday spontaneous breathing (SB) inspiratory gases are normally heated and humidified in the nasal cavity and pharynx: by the time the second bronchial bifurcation is reached, inspired gas temperature is 37°C and absolute humidity (AH) is 44 mg/L [1]. In mechanically ventilated patients, because the anatomy that provides this natural conditioning is bypassed by an artificial airway, administered gases require artificial conditioning. If humidification is inadequate, inspissation of airway secretions, destruction of airway epithelium, and hypothermia [2] may occur. The American Association for Respiratory Care (AARC) recommends that inspiratory gas temperature should reach more than 30°C and AH more than 30 mg/L [3]. Heat and moisture exchangers (HMEs) and heated humidifiers are commonly employed to warm and humidify medical gases, and are widely used with adult patients undergoing mechanical ventilation [4]. Their performance has been thoroughly investigated, and results suggest that performance depends on brand [5], location in the ventilator circuit, tidal volume (V_T), and minute volume [6, 7]. HMEs are also applied to tracheostomized patients who are able to breathe spontaneously. The configuration of HMEs for tracheostomized patients with SB differs from applications for mechanically ventilated

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patients: some of the vapor in expired gas escapes to the atmosphere without being trapped by the HME, and room air that has bypassed the HME is inspired. Some HMEs have a port for delivering oxygen to hypoxemic patients, and administration of dry, cold oxygen may further decrease the temperature and AH of inspired gas. While the moisturizing ability of HMEs for daily use of active patients has been thoroughly evaluated [8, 9], we found no published results showing how well HMEs provide humidification to patients in intensive care units. Consequently, for tracheostomized patients with SB, we designed a bench study to investigate the effects of SB parameters and oxygen flow on the performance of humidifying devices.

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Materials and Methods

We tested 11 types of HME, all commercially available in Japan, intended for use with tracheostomized patients with SB. In addition, we tested apparatus comprising an oxygen mask (Tracheomask, Intermed Japan, Tokyo, Japan) with a nebulizer heater (AQUATHERM III, Hudson RCI, Durham, NC) and a high-flow CPAP system (AIRVO, Fisher & Paykel, Auckland, NZ) for tracheostomized patients(table.1). Using a mechanical ventilator (Puritan-Bennett 840, Covidien, Carlsbad, CA), model lung (TTL model 1601, Michigan Instruments, Grand Rapids, MI) and heated humidifier (MR730, Fisher & Paykel, Auckland, NZ), we simulated real-life SB (Fig. 1). To simulate SB, the muscle and lung compartments of the TTL were connected, then the muscle compartment was inflated by the Puritan-Bennett 840 and the lung compartment inspired ambient air through an HME. Expired gas from the lung compartment went through a servo-controlled heated humidifier, and was warmed and humidified to 37°C and 100% relative humidity (RH). The insertion of one-way valves prevented mixing of inspired and expired gases. Our model was similar to that of Lellouche [5]. Compliance of the lung compartment was set at 0.05 L/cmH2O and the Puritan-Bennett 840 was set in assist control mode with respiratory rates of 10 and 20

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breaths/min, V_T of 300, 500, and 700 mL, inspiratory time of 1.0 s, and positive end-expiratory pressure of 3 cmH_2O. A ventilator self-test was performed before the study. Since the ventilator has compression volume correction, we did not measure the V_T of the lung compartment. For testing, the oxygen mask with nebulizer heater was set at F_IO_2 0.33 and 0.98, and the high-flow CPAP system was set at 15, 30, and 45 L/min. The high-flow CPAP system had a port to deliver oxygen, as did 8 of the 11 HMEs: for each of these 9 systems, oxygen was delivered at 0 and 3 L/min (temperature was 24 ± 0.2°C and RH 0%). We measured AH, RH, and temperature using a capacitance-type moisture sensor (response time was 3 sec for 40% to 100%)(Moiscope, Senko Medical, Tokyo, Japan). It was two-point calibrated by a cooler/heater water source (HHC-51, Senkoika, Tokyo, Japan). After changing experimental settings, we waited for at least 1 hour. Because condensation on sensor surfaces compromises sensor performance, we did not insert sensors in the circuit during waiting. Usually we measured RH and temperature for ten minutes, and after confirming stabilization of RH and temperature, we recorded AH, RH, and temperature for the last 5 min. All experiments were performed in an air-conditioned room with ambient temperature set at 24°C. Ambient temperature and humidity were monitored with the same sensor. All signals from the hygrometer were led to an analog/digital converter and recorded at 50 Hz/channel on a

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computer using data acquisition software (WINDAQ; Dataq Instruments, Akron, OH). For each experimental setting, we measured temperature and AH for 5 breaths, and results were expressed as mean ± SD.

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Results

Room temperature was 23.7±0.3°C and ambient RH was 57.2±4.0%. AH of the simulated expired gas was 34.7±1.4 mg/L (RH100% at 32.5±0.8°C). Among the tested HMEs, AH varied from 25.3 to 30.7 mg/L. With high-flow CPAP, AH was 37.7±2.8 mg/L and with the oxygen mask with nebulizer heater, 31.9±2.2 mg/L (table.2). When the F_IO_2 of the oxygen mask with nebulizer heater was changed from 0.33 to 0.99, AH changed from 30.9±2.2 mg/L to 32.9±2.7 mg/L. Administration of oxygen at 3 L/min decreased AH and none of the HMEs continued to maintain AH above 30 mg/L. In the high-flow CPAP system, with 3 L/min oxygen (Fig. 2), AH was 37.8±2.5 mg/L.

As V_T increased, AH statistically significantly decreased in all the HMEs and in the system delivering high-flow CPAP via oxygen mask and nebulizer heater (Fig. 3). For all tested devices, as respiratory rate increased, AH increased: the percentage difference between respiratory settings of 10 and 20 breaths per min was around 5%.

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Discussion

Taking into account the effects of supplemental dry oxygen, as well as of variations in V_T, and respiratory rate, we assessed the humidifying capabilities of HMEs for tracheostomized patients with SB and for a system delivering high-flow CPAP and oxygen mask with nebulizer. While AH was not evidently related to respiratory rate, it was profoundly affected by V_T and oxygen supplementation. In each instance when 3 L/min of oxygen was supplied through HMEs equipped with suitable ports, AH declined to below 30 mg/L. Meanwhile, with all devices, as V_T increased, AH decreased.

When Lellouche et al evaluated the performance of 48 commercially available HMEs for mechanically ventilated patients, it was found that only one in three devices maintained AH at 30 mg/L or more [5]. HMEs for mechanically ventilated patients and those for tracheostomized SB patients are configured differently. All the HMEs we tested have a suction port through which patients inspire ambient air. When V_T increases, more ambient air is present in the inspired mixture. At 300 mL V_T, 8 of the 11 HMEs maintained AH at above 30 mg/L; when 700 mL V_T was tested, only a single unit was able to maintain this adequate level of humidification. V_T greatly affects the

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performance of HMEs for SB patients. Assessing HMEs for mechanically ventilated patients, Lucato et al have already reported that HMEs are more efficient when used with low V_T ventilation [7]. HME for tracheostomized patients with SB is applied differently than for mechanically ventilated patients. The use of a suction port causes the escape of some expiratory gas which does not pass through the HME, resulting in the loss of the vapor contained in the expired gas. HME performance is impaired along with increasing volume of loss to the atmosphere [10]. These results are not directly comparable to the results we obtained for HMEs for mechanically ventilated patients. When supplemental oxygen was not provided, AH varied among the investigated HMEs. These findings are in line with those in the Lellouche study [5]. One of the great advantages of bench study is that it enables the investigation and comparison of medical devices under the same conditions. Even so, it was not possible to maintain all environmental and simulated SB conditions. Ambient temperature and humidity, and the temperature and AH of the gas expired from the model lung differed among HMEs. Since these values are important determinants of HME performance, care is required when using these results to directly compare the performance of HMEs.

When 3 L/min of oxygen was added, none of the HMEs with an oxygen port were able to maintain AH at above 30 mg/L. As far as we know, this is the first report to

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evaluate the ability of HMEs to return vapor for tracheostomized patients with SB. In addition to V_T, supplemental oxygen statistically significantly affected AH (Fig. 3). ICU patients have diverse individual needs but, after liberation from mechanical ventilation, supplemental oxygen is often required. Moreover, V_T may also vary among patients. To avoid the risk of insufficient humidification and attendant complications, our findings suggest that it is prudent to consider use of a Tracheomask or a high-flow CPAP system rather than an HME for patients who require supplemental oxygen or who demonstrate SB with high VT.

In our bench study, to accurately measure the AH of inspired gas, we inserted one-way valves to prevent overestimation owing to admixture, in the ventilator tubing, of water vapor from expired gases. As evaluated thoroughly in Zuur's study, when measuring the AH of breathing gas, it is important to control the durations of the inspiratory and expiratory phases. In our protocol, inspiratory time was 1 s and expiratory time was either 5 s (10 breaths/min) or 3 s (20 breaths/min). If we had measured AH at the beginning of inspiration, we might have underestimated the actual values. We traced raw data and measured the highest value to evaluate HME performance. We cannot discount the possibility of underestimation, however, according to Zuur's study, any differences are likely to have been small. We suspect that

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previously published higher AH (34±2.6 mg/L) readings for tested HMEs probably reflects contamination with fully humidified expiratory gas. On the other hand, using a servo-controlled heated humidifier to simulate physiological effects, our model maintained the expired gas temperature at 37°C, resulting in slightly higher than previously reported AH of expired gas [5].

Our study has several limitations. Obviously, based on a model-lung simulation, the findings do not directly correspond to clinical situations. Moreover, because our observation period was relatively short, our findings offer no evidence that HMEs for SB patients can be used reliably and safely for prolonged periods. One of the advantages of bench-study is to compare devices under same experimental settings. However, it is not possible to keep environment constant. Measured values in HME studies are influenced by environment. We did an experiment in the air-conditioned room, and tried to keep temperature and humidity constant, however, they varied.

In conclusion, with supplemental oxygen, humidification decreased below AARC recommended values. When supplemental oxygen is required, humidification is insufficient with HME for tracheostomized patients with spontaneous breathing in ICU.

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Figure legends

Fig 1. Experimental set up

When the ventilator sends gas to the model lung muscle compartment, the lung compartment attached to the muscle compartment starts inspiration. During simulated inspiration, ambient air is drawn into the lung compartment through the HME and hygrometer. When gas from the muscle compartment is sent to the ventilator, gas in the lung compartment is sent though the HME and expired into ambient space. The expiratory circuit incorporatesd a heated humidifier, a limb with a heating wire and one-way valve, and the expiratory gas that passes through them is warmed to 36°C at the camber outlet of the heated humidifier and to 37°C at the end of the limb. Expiratory AH was measured just before one-way valve, see fig 1.

Fig 2. Effect of dry oxygen gas on absolute humidity

The figure shows AH results for all the HMEs and the effect of adding 3 L/min oxygen: AH fell below 30 mg/L in all HMEs. The high-flow CPAP system was not affected by oxygen supplementation.

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Fig 3. Effect of tidal volume on absolute humidity

This figure shows AH at different V_T without supplemental oxygen.

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Table 1. Tested humidifying devices

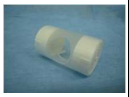
device	pictures	AH manufacture's data	Water loss (mgH_2O/L) manufacture's data	recommended V_T (mL)	dead space (mL)	type of humidifier	oxygen port
Trach-Vent+		27.0	8.4	>50	10	Passive	YES
Trach-Vent		27.0	8.4	>50	10	Passive	NO
Tracheolife II		28.5	11.0	100–1000	29	Passive	YES
Aqua+ T		24.0	13.6	75–1000	15	Passive	YES
Hydro-Trach II		26.0	No mention	<1500	19	Passive	YES
Thermovent T2		25.0	15.6	>70	11	Passive	YES
Thermovent T		25.0	15.6	>70	9	Passive	NO
Trachgard-HC		24.0	20.0	75–1000	18	Passive	YES
Aqua+ TS		24.0	13.6	75–1000	15	Passive	YES
Trach Phone		20.5	No mention	50–1000	9.5	Passive	YES
Pharma Trach Basic		26.0	18.0	150–1500	12	Passive	NO
Airvo		-	-	-	-	Active	YES
Tracheomask		-	-	-	-	Active	-

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Table 2. Environment and gas conditions

device	measured AH (mg/L)	environment conditions		expiratory gas	
		temp (°C)	AH (mg/L)	temp (°C)	AH (mg/L)
Trach-Vent+	30.7	23.7	10.8	32.2	34.1
Trach-Vent	30.5	23.9	12.6	31.1	32.2
Tracheolife II	30.1	22.8	12.0	33.1	35.8
Aqua+ T	30.0	23.6	10.2	32.1	33.9
Hydro-Trach II	29.7	23.9	11.7	32.2	34.1
Thermovent T2	29.5	23.8	12.9	31.2	32.3
Thermovent T	29.2	23.5	12.6	33.1	35.8
Trachgard-HC	28.6	23.6	12.7	33.1	35.8
Aqua+ TS	27.3	23.9	13.0	33.0	35.6
Trach Phone	26.0	23.5	12.7	32.1	33.9
Pharma Trach Basic	25.3	23.7	11.9	33.2	36.0
Airvo	37.7	23.8	12.8	33.3	36.2
Tracheomask	31.9	23.9	13.0	33.1	35.7

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Figure 1

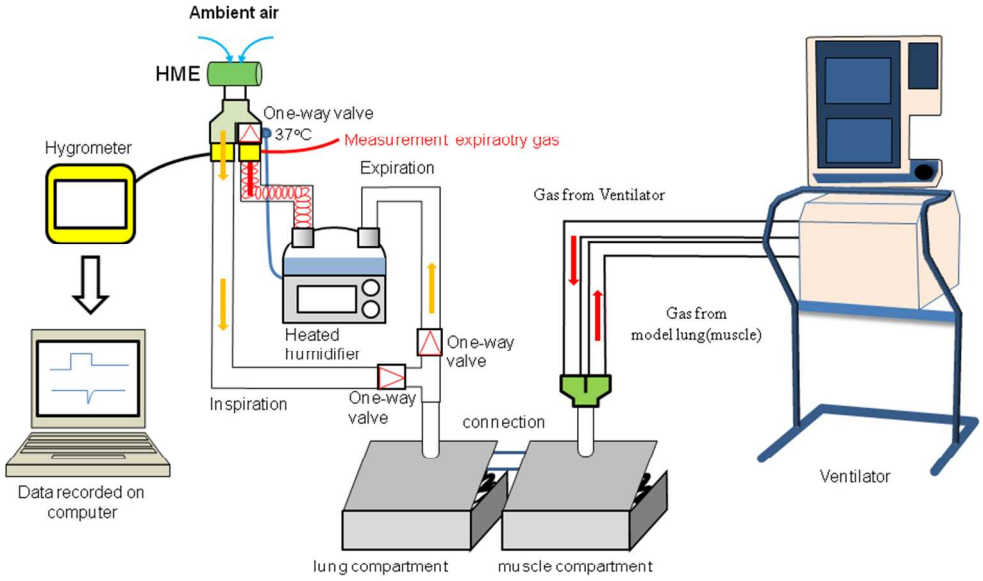

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Figure 2

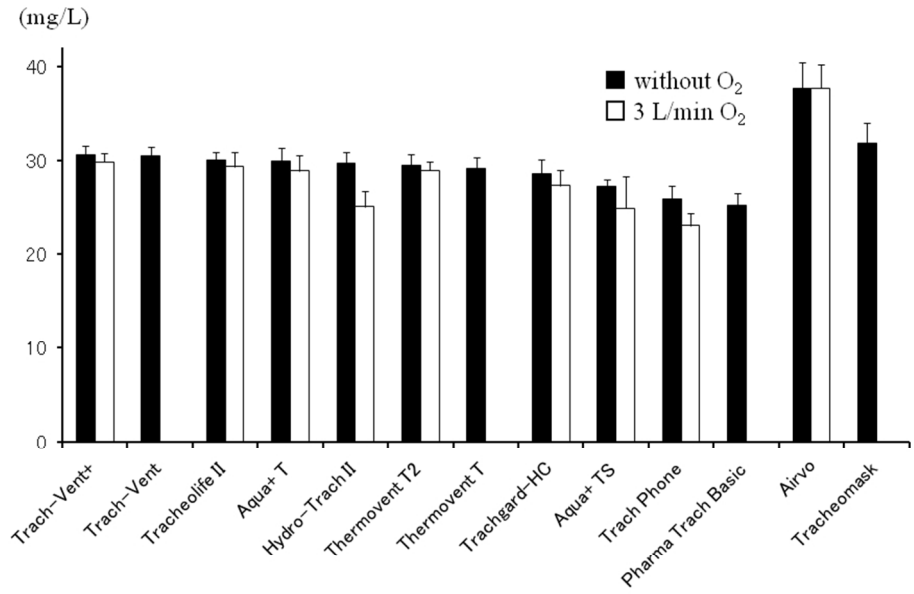

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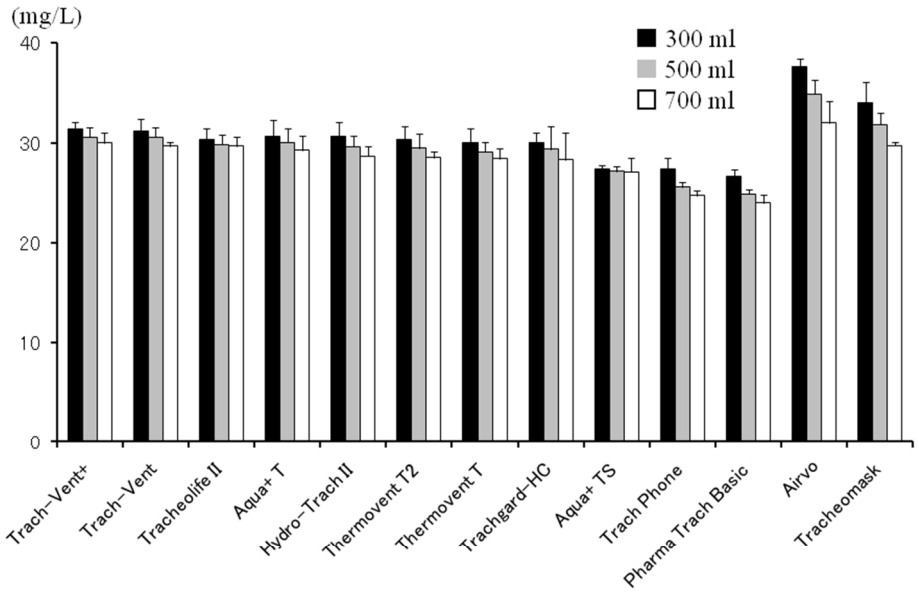
Figure 3



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