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A novel method of evaluation of three heat-moisture exchangers in six different ventilator settings

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Abstract *Objective:* The purpose of this study was to assess and compare the humidification, heating, and resistance properties of three commercially available heat-moisture exchangers (HMEs). To mimic clinical conditions, a previously validated, new, realistic experimental set-up and measurement protocol was used.
Design: Prospective, comparative experimental study.
Setting: Surgical Intensive Care Unit, University Hospital of Rotterdam.
Materials: An experimental set-up consisting of a patient model, measurement systems, and ventilator and three different HME types.
Interventions: The air flow, pressure in the ventilation circuit, pressure difference over the HME, and partial water vapour pressure and temperature at each side of the HMEs were measured. Measurements were repeated every 30 min during the first 2 h and every hour up to 24 h for each HME at six different ventilator settings. The mean inspiratory and maximum expiratory resistance, flow-weighted mean absolute humidity and temperature outputs, and humidification and heating efficiencies of HMEs were calculated.
Measurements and results: The Dar Hygroster had the highest humidity output, temperature output, humidification efficiency, and heating efficiency values throughout the study ($32.8 \pm 21.$ mg/l, 32.2 ± 0.8 °C, 86.3 ± 2.3 %, and 0.9 ± 0.01 %, respectively) in comparison to the Humid-Vent Filter (25.3 ± 3.2 mg/l, 31.9 ± 0.8 °C, 72.2 ± 5.3 %, 0.9 ± 0.02 %, respectively) and the Pall Ultipor BB100 breathing circuit filter (23.4 ± 3 mg/l, 28.3 ± 0.7 °C, 68.8 ± 5.9 %, 0.8 ± 0.02 %, respectively). The inspiratory and expiratory resistance of the HMEs remained below clinically acceptable maximum values (2.60 ± 0.04 and 2.45 ± 0.05 cmH_2O/l per s, respectively).
Conclusion: The Dar Hygroster filter was found to have the highest humidity and temperature output of all three HMEs, the Humid-Vent filter had a satisfactory humidity output only at low tidal volume flow rate and minute volume settings, whereas the Pall Ultipore BB 100 never achieved a sufficient humidity and temperature output.

Key words Humidity · Heat and moisture exchangers · Mechanical ventilation · Temperature · Resistance

Introduction

The upper airways heat and humidify inspiratory air and provide 65 % of the humidity of inhaled air [1, 2]. As a consequence, the inspiratory air reaching the lower airways is fully saturated with water vapour at body temperature. Bypassing the upper airways by endotracheal intubation or tracheostomy interferes with the normal process of humidification and warming. This effect is potentiated by the use of cold, dry medical gases during mechanical ventilation. Inadequate heating and moisturizing of inspiratory gas can produce severe airway damage and cause pulmonary function to deteriorate [3–10]. Therefore, it is imperative that inspired gases are heated and humidified during mechanical ventilation. Either heated humidifiers (HH) or heat-moisture exchangers (HMEs) are used artificially to replace upper airway functions during mechanical ventilation. However, HHs have some disadvantages, such as condensation in the tubing sets, bacterial colonization of the condensed or reservoir water, over- and underhumidification, and overheating [11–15]. On the other hand, HMEs, with their bacterial filtration properties in combination with their heat-humidity conserving functions, are good alternatives to HHs, although there is some doubt about their humidification capabilities and resistances to airflow [11, 16–19].

Several experimental studies have been done to test these properties of HMEs, where gravimetric humidity measurements and resistance measurements have been made outside the ventilation system by using a constant dry air flow [11, 16, 18, 20–28]. Gravimetric humidity measurements are only reliable during long-term studies and give only an average value. The use of a constant dry air flow to measure resistance outside the ventilation system may produce an underestimation. Furthermore, the expiratory resistance of the HME to characteristic decreasing air flow is as important as inspiratory resistance.

Because of the diverse techniques and methods used in studies performed so far, it is difficult to compare their results. The available standards for testing HMEs also have some shortcomings [11, 29–31]. For these reasons the humidity and temperature outputs of three conventionally used HMEs in relation to their resistances were tested and compared with each other in this study using a new set-up and method [29]. We conducted an experimental study on three HMEs by using a new, more realistic experimental model where the test lung was able to produce stable heat and water vapour output at different ventilatory settings [29].

The aims of this study were to measure and compare the humidity and temperature outputs and humidification and heating efficiencies of the HMEs continuously in relation to their inspiratory and expiratory resistance over 24 h at different ventilator settings.

The optimal requirements for inspiratory air conditioning during mechanical ventilation are not well established. Recent data suggest that the lower humidity level of inspired air should be in the range of 24–27 mg/l and the upper level in the range of 32–35 mg/l [1, 2, 4, 7, 30–35]. The temperature level should be between approximately 29 and 35 °C [1, 2, 30–35]. Endotracheal tube occlusions related to insufficient HME humidity output have been reported [17, 36]. The humidity output of HMEs in occlusion has been reported to occur between 10 and 28 mg/l [11, 20, 22, 27, 28, 37, 38]. These results suggest that adequate inspiratory humidity ranges should be smaller, 28 mg/l being the lower limit. These ranges were used to interpret our results and to judge the efficacy of the different HMEs.

Materials and methods

The experimental set-up

The experimental set-up includes a patient model, measurement systems, and a ventilator, as shown in Fig. 1. The patient model consists of a 1-litre training thorax (Übungs-thorax, M 13333, Dräger, Germany), a calibration bag with a capacity of 650 ml, a heated humidifier (Conchatherm 3, Kendall, London, UK), standard ventilator tubing, two one-way valves, connectors, and an incubator (Intensivpflege-Incubator 6500, Drägerwerk, Lübeck, Germany). The output of the patient model is adjusted to produce a relative humidity of 100 % at 34.5 ± 1.0 °C. The incubator is kept at 36.0 ± 1 °C to prevent condensation.

A heated flowmeter (Fleisch No. 2, Sensormedics, Bilthoven, The Netherlands), located between the training thorax and the HH, connected to a pneumotachograph (Type 17212, Godart-Statham, Bilthoven, The Netherlands) is used to measure the inspiratory and expiratory flow rate ($\dot{V}_I$ and $\dot{V}_E$). Two sampling ports are used to introduce the temperature probes, humidity sampling capillary, and pressure lines; one sampling port is located between the patient model and HME ("P" site), and the other is located between the HME and Y-piece of the ventilator tubing ("V" site). Temperature and partial water pressures at "P" and "V" sites are measured with two small bead NTC thermistors (Fenwal Electronics, American Power Devices, Mass., USA) and with a quadrupole mass spectrometer (MGA 3000, Case, Biggin Hill, UK). A differential pressure transducer (Hewlett-Packard model 270, HP International, Calif., USA) and a signal conditioner (Hewlett-Packard model 8805B carrier amplifier, HP International) are used to measure the pressure difference between the "P" and "V" site (ΔP_{HME}). The incubator and room temperatures (T_{inc}, T_{room}) are measured by two mercury thermometers with an accuracy of ±0.2 and ±0.1 °C, respectively. The technical details and calibration procedures of the measurement equipment have been described previously in more detail [29].

A ventilator (Servo 900 A, Siemens, Sweden) is used to ventilate the patient model in six different ventilator settings (Table 1). Central medical air with a dew point of −20 °C (equal to 0.1 kPa or 0.85 mg/l humidity) is used to ventilate the patient model.

Dar Hygroster (DHS) (Dar SpA Mirandola, Italy), Pall Ultipor BB100 breathing circuit filter (PUBB100) (Pall Biomedical, Fajardo, Puerto Rico) and Humid-Vent Filter (HVF) (Gibeck Respiration, Uppsala, Sweden) are compared in this study.

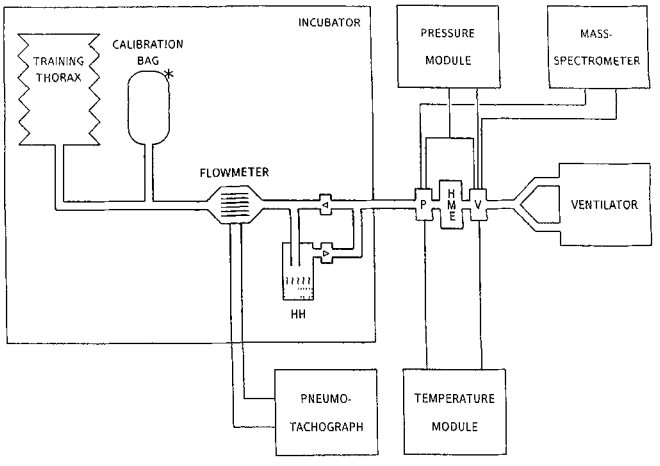

Fig. 1 Experimental set-up. ◁ denotes the direction of the flow on the one-way valve

Measurement protocol

The patient model is ventilated for 2 h to stabilize the system without an HME before every measurement period. After HME is attached, the signals are saved on a PC every 30 min during the first 2 h and every hour up to 24 h. Besides these periodic recordings, the signals are plotted continuously.

Calculated parameters include [29]: (1) mean inspiratory, mean expiratory, and maximum expiratory flow rates of five successive breaths ($V_I$mean, $V_E$mean, $V_E$max); (2) inspiratory and expiratory mean tidal volumes of five successive breaths; (3) mean respiration frequency; (4) flow-weighted mean inspiratory and mean expiratory partial water vapour pressures at the "P" and "V" sites of five successive breaths (P_{H_2O} $(P)_{I,mean}$, P_{H_2O} $(P)_{E,mean}$, P_{H_2O} $(V)_{I,mean}$, P_{H_2O} $(V)_{E,mean}$); (5) flow-weighted mean inspiratory and mean expiratory temperature values at the "P" and "V" site of five successive breaths ($T(P)_{I,mean}$, $T(P)_{E,mean}$, $T(V)_{I,mean}$, $T(V)_{E,mean}$); (6) mean inspiratory and mean expiratory absolute and relative humidity values at the "P" and "V" site of five successive breaths ($AH(P)_{I,mean}$, $AH(P)_{E,mean}$, $AH(V)_{I,mean}$, $AH(V)_{E,mean}$, $RH(P)_{I,mean}$, $RH(P)_{E,mean}$, $RH(V)_{I,mean}$, $RH(V)_{E,mean}$); (7) mean inspiratory and maximum expiratory resistance of the HME ($R(HME)_{I,mean}$ $R(HME)_{E,max}$); (8) humidification and heating efficiencies of the HME (H_{EFF}, T_{EFF}).

Statistical analysis

Results are expressed as mean ± SD over 24 h (n = 26). The results were statistically evaluated using two-way analysis of variance and correlation analysis. Correlation analysis was done separately for each HME and for each respiratory frequency to evaluate the effects of the different variables on the results. Differences are compared with the Student-Newman-Keuls procedure; $p < 0.05$ is considered significant.

Results

The ventilation parameters measured are shown in Table 1 together with their ventilator settings.

$T(P)_{E,mean}$ and P_{H_2O} $(P)_{E,mean}$ of the test lung were 34.4 ± 1.3 °C and 5.1 ± 0.9 kPa, respectively, during the whole study (equal to an absolute humidity of 37.5 ± 2.3 mg/l or a relative humidity of 98.3 ± 4.2 %). The room temperature was 25.7 ± 0.5 °C. The mean inspiratory fresh air temperature and humidity level were 25.3 ± 0.7 °C and 0.34 ± 0.05 kPa (equal to an absolute humidity of 2.46 ± 0.4 mg/l or a relative humidity of 10.5 ± 1.4 %). Absolute humidity output, temperature output, humidification efficiency, and heating efficiencies of the HMEs in different ventilator settings with the inspiratory and expiratory resistances of the HMEs are shown in Table 2. The humidity output of the HMEs, although not stable, did not show a progressive increase during the 24-h measurement periods. Fluctuations in the humidity output were more remarkable with the HVF. The stabilization time of the humidity output was dependent on the HME used and the ventilator setting. The mean stabilization time was 1.5 h for PUBB100 and 2 h for HVF and DHS and in some ventilator settings was either reduced to 10 min or extended to 3–4 h. Temperature outputs of the PUBB100 were significantly lower than for the others at all ventilator settings. There was no significant difference between the temperature outputs of the DHS and HVF at the first three ventilator settings; however, HVF temperature outputs were significantly lower than DHS outputs at ventilator settings 4, 5, and 6 (Table 2). Temperature

Table 1 Different settings and measured variables of the ventilator (VT_e mean expiratory tidal volume, f mean respiration frequency, I/E inspiratory/expiratory ratio, VT_I mean inspiratory tidal volume of five successive breaths, $\dot{V}_I$ inspiratory flow rate, $\dot{V}_E$ max maximum expiratory flow rate, $\dot{V}_E$ max maximum expiratory flow rate, $\dot{V}_E$ mean mean expiratory flow rate)

Ventilator settings	Settings				Measured values			
	VT_e (ml)	f (/min)	I/E	VT_I (ml)	f (/min)	$\dot{V}_I$ (ml)	$\dot{V}_E$max (ml)	$\dot{V}_E$mean (ml)
1	600	10	1/2	639.6 ± 9.4	10.1 ± 0.03	508.6 ± 18.3	780.7 ± 10.2	160.6 ± 6.1
2	800	10	1/2	834.4 ± 6.2	10.1 ± 0.02	633.8 ± 2.8	906.7 ± 14 + 1	221.6 ± 2 + 3
3	1000	10	1/2	1015.2 ± 10.0	10.1 ± 0.03	780.2 ± 18.3	1001.4 ± 29.3	256.9 ± 10.9
4	600	15	1/2	597.1 ± 12.3	15.1 ± 0.04	686 ± 4	787.9 ± 7.2	238.1 ± 2.4
5	800	15	1/2	766.9 ± 5.2	15.2 ± 0.1	875 ± 8.6	904.8 ± 14 + 9	306.3 ± 2.9
6	1000	15	1/2	1038.0 ± 11.0	15.2 ± 0.04	1185.9 ± 12 + 3	939.1 ± 24 + 9	395.2 ± 24 + 7

Table 2 Mean temperature and humidity output of the three HMEs at different ventilator settings, together with heating and humidifying efficiencies, and inspiratory and expiratory resistances ($AH(P)_{I,mean}$ mean inspiratory absolute humidity value at the "P" site of five successive breaths, $T(P)_{I,mean}$ flow-weighted mean inspiratory temperature at the "P" site of five successive breaths, HUM_{EFF}, $TEMP_{EFF}$ humidification and heating efficiencies of HME, $R(HME)_{I,mean}$, $R(HME)_{E,max}$, mean inspiratory resistance and mean maximum expiratory resistance of the HME)

Ventilator settings	HME	$AH(P)_{I,mean}$ (mg/l)	$T(P)_{I,mean}$ (°C)	HUM_{EFF} (%)	$TEMP_{EFF}$ (%)	$R(HME)_{I,mean}$ (cmH_2O/l per s)	$R(HME)_{E,max}$ (cmH_2O/l per s)
I	DHS	$32.0 \pm 2.1^{*,b}$	$31.3 \pm 0.3^{\S,b}$	$87.7 \pm 1.5^{i,j}$	$0.92 \pm 0.01^{*,a}$	$1.99 \pm 0.05^{*,a}$	$2.31 \pm 0.10^{*,p}$
	HV	$27.1 \pm 3.4^{\S,d}$	$31.4 \pm 0.5^{\S,i}$	$78.9 \pm 4 + 2^{*,a}$	$0.94 \pm 0.01^{*,a}$	$1.48 \pm 0.04^{*,a}$	$1.84 \pm 0.03^{*,s}$
	PUBB100	$23.9 \pm 0.8^{\S,a}$	$27.2 \pm 0.2^{\S,a}$	$73.3 \pm 0.8^{\S,a}$	$0.84 \pm 0.01^{*,a}$	$1.70 \pm 0.04^{\S,a}$	$2.01 \pm 0.04^{\S,a}$
II	DHS	$34.2 \pm 0.6^{*,c}$	$32.5 \pm 0.4^{\S,f}$	$86.5 \pm 0.9^{\S,k}$	0.90 ± 0.01^{m}	$2.21 \pm 0.06^{\S,a}$	$2.43 \pm 0.05^{*,r}$
	HV	$27.9 \pm 2.1^{*,d}$	$32.5 \pm 0.3^{\S,c}$	$75.9 \pm 3.3^{\S,a}$	0.90 ± 0.01^{c}	$1.65 \pm 0.03^{\S,a}$	$1.85 \pm 0.02^{*,s}$
	PUBB100	$25.7 \pm 0.3^{*,a}$	$28.8 \pm 0.2^{*,c}$	$69.7 \pm 0.3^{\S,a}$	$0.80 \pm 0.01^{*,n}$	$1.63 \pm 0.03^{*,a}$	$1.90 \pm 0.05^{\S,a}$
III	DHS	$32.7 \pm 2.0^{i,b}$	$31.5 \pm 0.9^{\S,b}$	$88.4 \pm 2.0^{*,b}$	$0.88 \pm 0.01^{*,a}$	$2.40 \pm 0.06^{*,a}$	$2.45 \pm 0.06^{*,r}$
	HV	23.2 ± 2.5^{a}	$31.5 \pm 1.1^{\S,i}$	68.6 ± 2.7^{a}	$0.92 \pm 0.01^{*,a}$	$1.89 \pm 0.01^{*,e}$	$1.91 \pm 0.01^{*,a}$
	PUBB100	22.5 ± 1.7^{e}	$27.8 \pm 0.3^{*,a}$	67.5 ± 2.2^{e}	$0.77 \pm 0.01^{*,a}$	$1.82 \pm 0.02^{*,a}$	$1.93 \pm 0.01^{*,a}$
IV	DHS	$33.9 \pm 1.2^{\S,c}$	$32.8 \pm 0.8^{*,g}$	$86.9 \pm 0.7^{*,l}$	$0.91 \pm 0.01^{*,a}$	$2.14 \pm 0.03^{*,a}$	$2.16 \pm 0.03^{*,a}$
	HV	$24.9 \pm 1.3^{*,a}$	$32.1 \pm 0.4^{i,c}$	$70.8 \pm 0.9^{*,a}$	$0.91 \pm 0.01^{*,c}$	$1.68 \pm 0.01^{*,a}$	$1.68 \pm 0.01^{\S,a}$
	PUBB100	$27.0 \pm 0.6^{*,a}$	$28.7 \pm 0.3^{i,c}$	$75.7 \pm 0.9^{*,a}$	$0.83 \pm 0.01^{*,a}$	$1.76 \pm 0.01^{*,a}$	$1.83 \pm 0.02^{\S,a}$
V	DHS	$33.8 \pm 0.7^{*,c}$	$32.6 \pm 0.2^{*,f}$	$85.2 \pm 0.5^{\S,a}$	0.90 ± 0.01^{m}	$2.18 \pm 0.02^{\S,a}$	$2.09 \pm 0.05^{*,a}$
	HV	$27.1 \pm 1.1^{*,d}$	$32.4 \pm 0.3^{*,c}$	$73.3 \pm 1.4^{\S,a}$	0.90 ± 0.01^{c}	1.89 ± 0.01^{e}	1.78 ± 0.01^{a}
	PUBB100	$22.5 \pm 1.1^{\dagger,e}$	$28.9 \pm 0.1^{i,c}$	$67.8 \pm 0.7^{\dagger,e}$	$0.81 \pm 0.01^{*,o}$	1.88 ± 0.00^{a}	1.77 ± 0.01^{a}
VI	DHS	$30.2 \pm 1.9^{\dagger,a}$	$32.3 \pm 0.7^{i,h}$	$82.8 \pm 2.0^{\S,a}$	$0.89 \pm 0.01^{*,a}$	$2.60 \pm 0.04^{\S,a}$	$2.31 \pm 0.03^{\S,p}$
	HV	$21.0 \pm 0.5^{\dagger,a}$	$31.1 \pm 0.7^{\dagger,i}$	$64.6 \pm 1.0^{*,a}$	$0.88 \pm 0.02^{*,a}$	$2.02 \pm 0.01^{*,a}$	$1.62 \pm 0.01^{*,a}$
	PUBB100	$17.8 \pm 0.4^{\dagger,a}$	$28.6 \pm 0.2^{\dagger,a}$	$57.1 \pm 0.7^{*,a}$	$0.81 \pm 0.01^{*,h}$	$2.32 \pm 0.00^{*,a}$	$1.95 \pm 0.04^{\S,a}$

Letters show statistically significant differences between the HMEs at same ventilator setting. Symbols show statistically significant differences between different ventilator settings with the same HME. * significantly different from other HMEs in same ventilator setting; § significantly different from PUBB100 in same ventilator setting; [a] significantly different from other ventilator settings; [b] significantly different from ventilator settings 2, 4, 5, 6; [c] significantly different from ventilator settings 1, 3, 6; [d] significantly different from the ventilator settings 3, 4, 6; [e] significantly different from ventilator settings 1, 2, 4, 6; [f] significantly different from ventilator settings 1, 3; [g] significantly different from ventilator settings 1, 2, 3, 6; [h] significantly different from ventilator settings 1, 3, 4; [i] significantly different from ventilator settings 2, 4, 5; [j] significantly different from ventilator settings 2, 5, 6; [k] significantly different from ventilator settings 1, 3, 5, 6; [l] significantly different from ventilator settings 3, 5, 6; [m] significantly different from ventilator settings 1, 3, 4, 6; [n] significantly different from ventilator settings 1, 3, 4, 5; [o] significantly different from ventilator settings 1, 2, 3, 4; [p] significantly different from ventilator settings 2, 3, 4, 5; [r] significantly different from ventilator settings 1, 4, 5, 6; [s] significantly different from ventilator settings 3, 4, 5, 6

outputs of HMEs at different ventilator settings were more stable than their humidity outputs during the 24-h recording periods.

Increasing tidal volume, inspiratory flow rate, and minute volumes decreased the humidification efficiencies of the HMEs to a different extent (Fig. 2 and Table 2). Although these parameters had little influence on the DHS, the humidification efficiency of the DHS was significantly decreased by the combination of high tidal volume, inspiratory flow rate, and minute volumes. The effect of these variables on the humidification efficiency of the PUBB100 was more pronounced than for the HVF. The humidification efficiency of the PUBB100 decreased linearly with increasing tidal volume, flow rate, and minute volumes, while the slope of the regression line depended on the combination of these variables (Fig. 2). The humidification efficiency of the HVF was decreased mainly by tidal volumes higher than 800 ml in addition to the effect of high flow rates. The PUBB100 had the lowest and the DHS the highest humidification efficiencies at each ventilator setting except 4, at which HVF was lowest (Table 2). Humidification efficiency values did not show a progressive increase over 24 h. However, a stabilization time was needed for each HME at each ventilator setting. Mean stabilization periods were approximately 120, 60, and 50 min for DHS, HVF, and PUBB100, respectively, although it was difficult to establish an exact stabilization time for each because of fluctuations in humidification efficiencies over 24 h. Fluctuation was more prominent with the HVF than with the others.

The heating efficiency of the DHS and PUBB100 inversely correlated with tidal volume, inspiratory flow rate, minute volume, and expiratory flow rate (Fig. 3). Heating efficiency of DHS and PUBB100 was increased by increasing ventilation frequency, especially at high tidal volume settings. Similarly to the others, the heating efficiency of the HVF was affected minimally by ventilator variables except when combining a high tidal volume, inspiratory flow rate, and minute volume. The

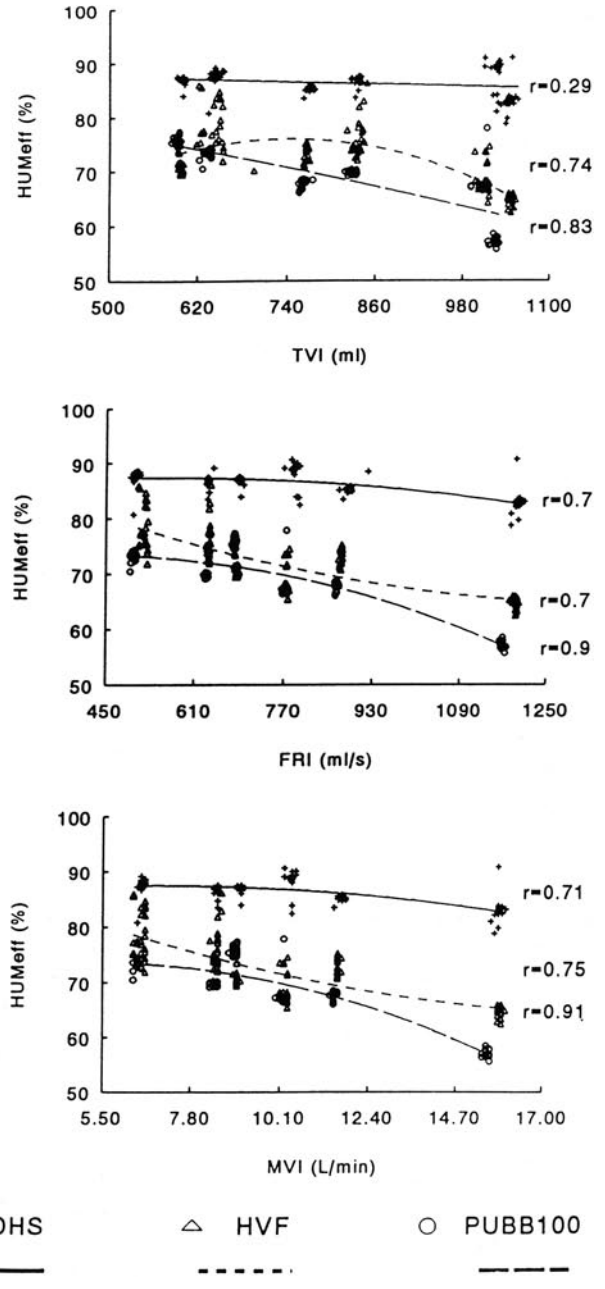

Fig. 2 Correlation of humidification efficiencies of HMEs *HUMeff* with tidal volume *TVI*, inspiratory flow rate *FRI*, and inspiratory minute volume *MVI*. Correlation coefficients(r) for each HME are shown next to the second-degree polynomial curve-fitting lines

heating efficiency of the PUBB100 was significantly lower than in the other filters at every ventilator setting. There were no statistically significant differences between the heating efficiency of the HVF and the DHS at ventilator settings 2 and 5. The heating efficiency of the HVF at ventilator settings 1 and 3 was significantly higher than for the DHS, whereas it was significantly higher for the DHS than for the HVF at ventilator settings 4 and 6 (Table 2). A stabilization time to achieve the optimal heating efficiency existed. During the stabilization period, which took 60–90 min, heating efficiency decreased, while humidification efficiency increased. This inverse relationship was more pronounced with the DHS.

The inspiratory resistance mainly correlated to the inspiratory flow rate (Fig. 4). We could not find any correlation between the inspiratory resistance and the humidification efficiency of the HMEs. However, there was an inverse correlation between the humidification efficiency and the resistance of the HVF ($r = -0.75$) and PUBB100 ($r = -0.86$). The inspiratory resistance of the DHS was higher at every setting than in the other HMEs. The expiratory resistance increased with increasing humidification efficiency and expiratory flow rates, which have an inverse relationship. The expiratory resistance of the DHS was the highest and of HVF the lowest at all settings (Table 2). There was no significant change in the inspiratory and expiratory resistance over the 24-h recording periods with different HMEs at the different ventilator settings. However, some short-lived changes were observed during the recordings, being more frequent in the expiratory resistance than the inspiratory resistance.

The expiratory flow pattern, temperature, and humidity output characteristics of the patient model used in this study, in addition to its mechanical properties, were comparable to those found in humans [1, 2, 32–34] and in agreement with the ISO standard [29–31]. The technical properties of the measurement equipment complied with the ISO standard as previously described [29–31].

Discussion

In our study, the DHS was the only HME able to produce heat and humidity within the ranges suggested in the current literature, at every ventilator setting. The temperature and humidity outputs of the DHS at all ventilator settings were comparable to those of HHs tested in different studies [38]. The humidity outputs of the HVF and PUBB100 were only within the recommended ranges at certain tidal volumes (600–800 ml), flow rates (520–870 and 500–680 ml/s), and minute volumes (6.5–11.6 and 6.4–8.9 l/min). The temperature output of the HVF was comparable to the DHS, while the PUBB100 was below 29 °C at every ventilator setting. The PUBB100 achieved the required humidity output of 27 mg/l only at low minute volume, tidal volume, and flow rate setting in combination with insufficient temperature output.

The HVF had an adequate temperature output at each ventilator setting in combination with a relatively

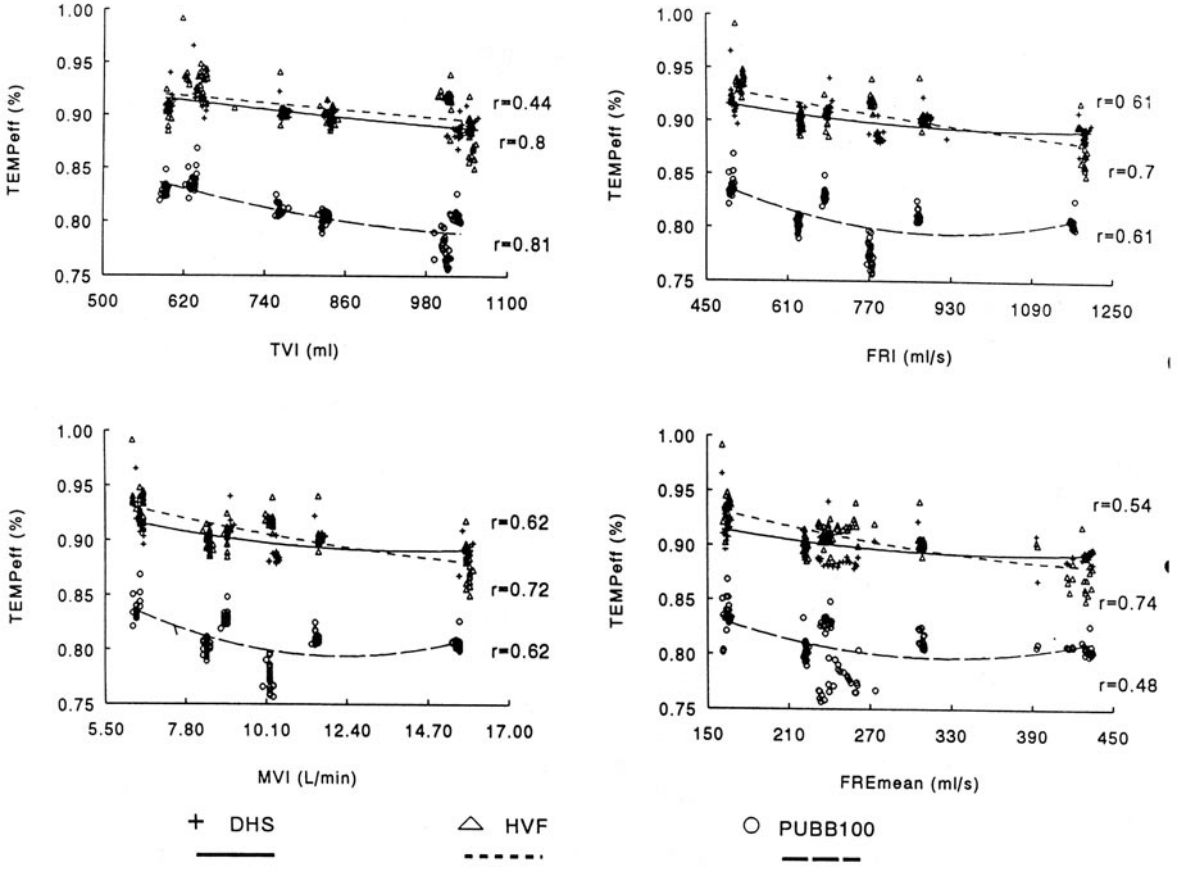

Fig. 3 Correlation of *TEMPeff* with tidal volume *TVI*, inspiratory flow rate *FRI*, inspiratory minute volume *MVI*, and mean expiratory flow rate *FREmean*. Correlation coefficients(r) for each HME are shown next to the second-degree polynomial curve-fitting lines

low humidity output. This resulted in a lower relative humidity output. Miyao et al. [39] have shown that relative humidity, rather than absolute humidity, is a dominant factor in cases of endotracheal tube and proximal tracheal occlusion. Therefore, the DHS is superior to the others because of a higher relative humidity output in addition to a higher absolute humidity output and high temperature output.

Another concern about the HMEs is the stabilization time of the humidity and temperature outputs. Stabilization time was longer with more efficient filters and at the ventilator settings where HMEs produce high outputs. Even though this time is longer with more efficient filters, the initial output of these filters is still higher than the mean output of less efficient filters. Therefore, stabilization time seems not to be an important factor in clinical use. The inverse relationship during the stabilization period between humidity and temperature outputs possibly originates from the inadequate water reserve in the HME. Until the water reserve of the HME reaches an optimal level, less evaporation occurs during inspiration in comparison with the condensed water during a previous expiration. Therefore, during the next inspiration less energy is used for evaporation until the water reserve of the HME increases and excessive energy may be used to heat inspiratory air. As a result, after connection of the HME to the ventilation circuit, the temperature output of the HME may be higher than the patient's (model's) expiratory temperature for a short time. The water reserve of each HME is different and possibly higher with efficient filters, as can be deduced from the results of studies which measure weight differences of the HMEs before and after use. Therefore, stabilization times depend on the ventilator setting and the type of HME. A progressive increase in the humidity output of the HMEs during 24 h has been found in some studies [20, 37, 40]. Although the humidity output of the HMEs tested showed some fluctuations, a significant increase after the stabilization period was not found in this study.

The efficacy of HMEs depends on their resistance and humidity and temperature outputs. Differences between test methods and conditions may produce inevitable changes in the humidity and temperature output of the HMEs. Changes in the environmental temperature

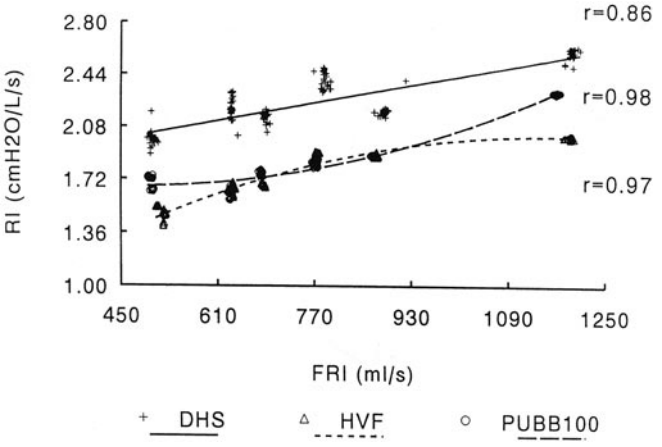

Fig. 4 Correlation of inspiratory resistance *RI* with inspiratory flow rate *FRI*. Correlation coefficients(r) for each HME are shown next to the second-degree polynomial curve-fitting lines

and temperature and humidity output of the patient model and the inspiratory fresh gas are circumstances which may produce differences in the temperature and humidity output. It is difficult to influence the variations in these parameters, or at least to prevent fluctuations in them in clinical and experimental studies. Even if the room temperature and patient model output are kept stable, the inspiratory fresh gas temperature and humidity levels will change according to the HME efficiency, as the ventilation circuit between the HME and Y-piece acts as an HME. As a result, the inspiratory fresh gas temperature and humidity level will be higher when a less efficient filter is tested. This will cause an overestimation of the temperature and humidity output of less efficient filters. Although the temperature and humidity of the patient model output and inspiratory fresh gas showed minimal changes throughout the study, the ventilator setting that gave the highest temperature or humidity output for any HME was different from the ventilator setting that displayed the highest humidity or temperature conserving efficiency for the HME.

Temperature and humidity outputs of HMEs have been reported to decrease with increasing tidal volume, inspiratory flow rate, and minute volumes [19, 22, 24, 25, 27]. The same results have been found in this study. However, the influence of these variables on the temperature and humidity efficiencies of each HME was different. It may be essential to know the ranges of these variables in which adequate heat and humidity efficiencies are achieved for each HME. The DHS has been found to be a very efficient HME at every ventilator setting used in this study, but the humidification efficiency of the PUBB100 and HVF was only sufficient at certain ranges of the ventilation variables. While the heating efficiency of the HVF was always sufficient, that of the PUBB100 was inadequate in all ranges. Therefore, the HVF should only be used in the ranges in which effective humidification efficiency is achieved, taking into consideration the importance of the relative humidity output in the upper airway secretions as mentioned above.

Most of the efficiency formulas are based on gravimetric humidity measurements and involve the unfavorable aspects of the gravimetric method [16, 21, 22, 27, 28]. The formulas calculating the efficiency of humidification during on-line measurements are relatively uncommon and inadequate. The use of flow-weighted mean temperature and humidity values offers a better method of describing HME efficiency.

Several studies have been done to test resistances of HMEs; however, there are some shortcomings in their methodology, such as separation of HMEs from the actual breathing system, a maximum of four resistance measurements in a 24-h measurement period using dry air flow, and the use of constant air flow in the measurement of expiratory resistance [16, 18–28, 40]. In this study, the shortcomings of these studies have been eliminated; the resistance measurements were done continuously in conditions closely resembling clinical conditions. The inspiratory and expiratory resistances of the HMEs tested in this study were always below the acceptable maximum resistance values established for inspiratory resistance of HMEs [22, 23, 30, 31, 35]. Conti et al. [41] have shown in a clinical study that HMEs had no effect on the lung mechanics of mechanically ventilated patients. Therefore, the inspiratory and expiratory resistance of HMEs tested in this study are not a likely obstacle for their clinical use. However, caution should be exercised in patients with heavy and copious bronchial secretions for an unexpected increase in resistance. Contrary to other studies, no significant increase in inspiratory and expiratory resistance has been observed during the 24-h recording periods, but some short-lived increases, being more frequent with the more efficient HMEs, have been observed particularly in expiratory resistance [8, 21, 22]. The progressive increases in resistance observed in some studies may be related to these short-lived changes, together with momentary and infrequent resistance measurements. Inspiratory and expiratory resistances were correlated with flow rates. A correlation between humidification efficiency and inspiratory resistance was not found. Contrary to other studies, an inverse relationship was found between the humidification efficiency and inspiratory resistance of the PUBB100 and HVF, showing the importance of the increasing flow rates on inspiratory resistance and humidification efficiencies. This finding is in agreement with the knowledge of the relationships between flow rate and humidification efficiency, and between flow rate and resistance [16, 18, 24, 25, 27]. This relationship was not found significant for the DHS, possibly because of its narrower humidification

efficiency range. In our opinion, the expiratory resistance is even more important than the inspiratory resistance because of its possible effects on lung mechanics and work of breathing. The expiratory resistance of the HME is related to the expiratory flow rate, which is mainly dependent on the mechanical time constant of the patient. In this study, we tried to imitate the expiratory flow profile of a mechanically ventilated patient in order to assess the influence of the HME on lung mechanics.

Based on the finding of the present study conducted on three HMEs at six different ventilator settings, we conclude the following: (1) The Dar Hygroster is a reliable HME with a high humidity and temperature output which is comparable to HHs at all ventilator settings and can even be used when there is an increased risk of endotracheal tube occlusion during long-term mechanical ventilation. (2) The Pall Ultipor BB100 breathing circuit filter did not achieve the required humidity and temperature output at any ventilator setting. (3) The humidification efficiency of the Humid-Vent Filter was within acceptable ranges when low tidal volume, flow rate, and minute volume were used. The temperature efficiency can be compared with the Dar Hygroster and is much higher than the Pall Ultipor BB100 breathing circuit filter. This results in a decreased relative humidity in contrast to the others, but caution has to be exercised when used in patients with a high risk of endotracheal tube occlusion. (4) The inspiratory and expiratory resistances of the HMEs tested are within the clinically acceptable ranges. (5) Humidification and heating efficiency calculations are useful to compare results measured in different conditions. (6) Adequate heating and humidifying efficiency ranges have been defined.

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