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An evaluation of the heat and moisture exchange performance of four ventilator circuit filters

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Abstract. *Objective:* To compare the heat and moisture exchange efficiency of 4 commonly used ventilator circuit filters – DAR Hygroster (DHS), DAR Hygobac (DHC), Pall Ultipor BB50 (PUBC) and Intersurgical filtatherm (IFT). *Design:* Prospective randomized study. *Setting:* Intensive care unit of a university teaching hospital. *Patients and Participants:* 80 patients requiring post-operative mechanical ventilation were entered into the study. A total of 40 patients were studied after 1 h and 40 after 24 h. Due to technical errors 6 of the 1 h studies and 2 of the 24 h studies were excluded from analysis. *Interventions:* Mean wet and dry ceramic-platinum thermal probes were inserted in the inspiratory side of a divice which separated inspiratory and expiratory gas flows on the patient side of the ventilator circuit filter. Humidification efficiency was calculated with reference to these wet and dry bulb temperatures. Tracheal temperature was measured by a similar thermal probe in the tracheal tube. *Measurements and results:* Absolute humidity was greatest in group DHS (30.4 ± 3.5 versus 22.9 ± 1.5 mg/l at 1 h and 27.3 ± 3.5 versus 20.7 ± 2.4 mg/l at 24 h). The differences in absolute humidity reached statistical significance as follows: $p = 0.0001$ for DHS versus all others at 1 h and for DHS and DHC versus PUBC and IFT at 24 h. *Conclusion:* Better humidification capabilities were obtained with groups DHS and DHC than PUBC and IFT.

Key words: Heat and moisture exchange filters – Airway humidification – Positive pressure ventilation

The importance of delivering warm, humidified gas to patients ventilated through a tracheal tube is widely appreciated [1]. Endotracheal intubation bypasses the normal heat and moisture exchanging process of inspired gas. A continuous loss of heat and moisture occurs during continuous mandatory ventilation (CMV) which predisposes serious airway damage. This is because medical compressed gases delivered at room temperature have negligible water content. Ventilation with dry gases leads to dehydration and dysfunction of epithelial cells in the upper tracheobronchial tree [1–3], destruction of cilia and mucous glands, subsequent altered pulmonary function (fall in functional residual capacity) and heat loss [4–7]. Therefore the protection of the respiratory tract during artificial ventilation ideally includes the administration of a humidified gas mixture.

Heated water humidifier systems have proved effective in overcoming the problems associated with ventilation with dry gases, and have been used widely in the ICU. They supply the patient with gases heated up to 29–33 °C with a relative humidity of 95–100%. These devices have some disadvantages, not least the potential to deliver excessive heat with the consequent problem of thermal injury [8] excessive water with the consequent problem of water intoxication [9–11], and of acting as a reservoir for bacterial growth resulting in nosocomial intection [12–15]. They require continuous monitoring of humidity and fluid levels with servocontrol mechanisms.

The heat and moisture exchanging (HME) filter is a simple solution to the problems of humidification of inspired gases and contamination of ventilator circuits. Hygroscopic and hydrophobic HMEs conserve heat and moisture during expiration and return them to the inspired gas. Adequate humidification during controlled ventilation requires output water levels greater than 21–24 mg/l at 23–29 °C [16]. Not all HMEs fulfil these criteria, especially in the presence of larger tidal volumes [17–19]. Although there are numerous laboratory studies of HME efficiency, few data are available in ICU patients. Additionally, HME filters act as a barrier to the passage of bacteria. Some manufacturers claim their products prevent the passage of 99.99% of bacteria for up to 24 h. Thus, HME filters offer attractive advantages such as low cost, convenience, no need for an additional filter in the ventilator circuit and no requirement for an electric power source. Furthermore, these HME filters may prolong the use of breathing circuits [20] and reduce the need to decontaminate ventilator equipment [21].

At the Middlesex Hospital we have used a hydrophobic HME (Pall Ultipor BB50 breathing circuit filter) for 3 years. However, during this period we have experienced a number of episodes of tracheal tube occlusion. Cohen and co-workers [20] have also reported an increase in endotracheal tube occlusion because of inadequate airway humidification using the Pall BB50 filter. In view of this concern we studied the HME efficiency of 4 commonly used ventilator circuit filters. These included the hydrophobic Pall Ultipor (BB50) breathing circuit filter (PUBC), and 3 hygroscopic-hydrophobic filters; DAR Hygroster (DHS); DAR Hygobac (DHC) and Intersurgical Filtatherm (IFT).

Materials and methods

The study was approved by the ethical committee of the Middlesex Hospital. A total of 80 adult patients requiring intermittent positive pressure ventilation (IPPV) post-operatively were recruited for the purpose of the trial, and assigned by a randomisation code to 1 of 4 HME groups – PUBC, DHS, DHC and IFT. There were 10 patients studied in each filter group after 1 h IPPV and a further 10 in each group after 24 h IPPV. All patients had been ventilated for up to 2 h intra-operatively with dry gases or for longer with a PUBC filter. Demographic details of the patients are given in Table 1. Patients requiring positive end expiratory pressure (PEEP) and/or those with cardiovascular instability were excluded from the trial.

A standardised breathing circuit was used for all patients with the HME filter inserted between the catheter mount and the 'Y'piece. Patients were ventilated with Blease Manley or Engström Erica ventilators using CMV modes and volume cycling. Respiratory rates and tidal volumes were adjusted to maintain $PaCO_2 < 5.8$ kPa. The FiO_2 was adjusted between 0.28 and 0.6 to maintain a $PaO_2 > 10$ kPa. A device to separate inspiratory and expiratory gas flow was inserted between the HME filter and catheter mount (Fig. 1) for the period of measurement. HME efficiency was calculated from temperatures measured by 15 mm length wet and dry ceramic-platinum thermal probes in the inspiratory limb of the monitoring device. Tracheal temperature was measured by a similar thermal probe inserted into the tracheal tube at a distance of 20 cm. The response times of the thermal probes were as follows: in air at a flow rate of 1 m/s time to 50% temperature equilibration was 1.25 s and time to 90% temperature equilibration was 4.1 s; in water at a flow rate of 0.02 m/s time to 50% temperature equilibration was 0.15 s and time to 90% equilibration was 0.6 s. The temperatures were displayed on a chart recorder (Yokogawa, No. T4153HA323928, Japan). After a period of 1 h, to allow achievement of thermal equilibrium, mean temperatures (independent of ventilatory phase) were recorded from the wet, dry and tracheal probes. Relative humidity (RH) was calculated by reference to a psoriometric diagram [22]. Absolute Humidity at saturation point (AHs) was determined from the following interpolation formulae [22] and used to calculate absolute humidity (AH):

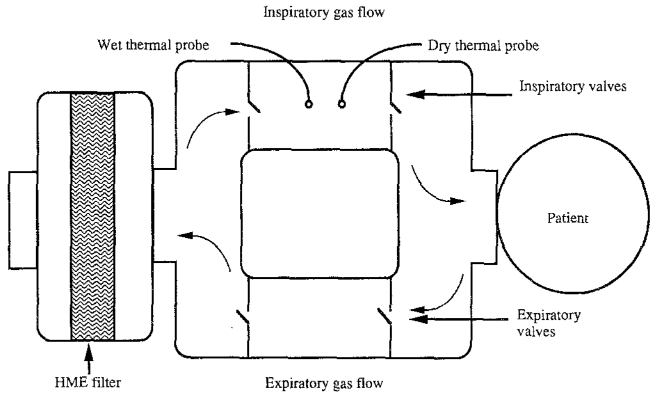

Fig. 1. Humidification monitoring head used to separate inspiratory and expiratory gas flows between the HME and catheter mount

For a dry probe temperature of 24.1 – 38 °C

$$AHs = 16.41563 - 0.731T + 0.03987T^2 \quad (1)$$

For a dry probe temperature of 10 – 24 °C

$$AHs = 6.0741 + 0.1039T + 0.02266T^2 \quad (2)$$

$$AH = \frac{AHs \times RH}{100} \quad (3)$$

where AHs (mg/l) is absolute humidity at saturation point (100% of RH), T (°C) is the dry bulb temperature, AH (mg/l) is absolute humidity.

Absolute humidity (AH), relative humidity (RH), tracheal temperature and IR were compared after 1 h and 24 h for each HME filter using an unpaired, two-tailed Student's *t*-test. Inter-group data were compared between HME filter groups using a single factor analysis of variance with Fisher's protected least significant difference test for post-hoc analysis.

Results

The mean values for tracheal, dry and wet temperatures between HME filter groups at 1 and 24 h are displayed in Tables 2 – 3. Due to technical errors (wet bulb temperatures reading persistantly higher than dry bulb temperatures) 6 studies were excluded from analysis at 1 h and 2 at 24 h. There were significant differences between the groups for RH after 1 and 24 h (Fig. 2). The highest mean (± SD) RH was achieved in group DHS (99.8 ± 0.3% and 97.7 ± 1.9%) after 1 and 24 h respectively. The lowest mean (± SD) RH was found in group IFT (93.3 ± 0.7% and 86.2 ± 5.8%) after 1 and 24 h respectively. Similarly

Table 1. Demographic data for patients studied. *p* not significant between groups at 1 h or 24 h

	1 h				24 h			
	DHS	DHC	PUBC	IFT	DHS	DHC	PUBC	IFT
n	9	9	7	9	10	9	10	9
Age	60.1 ± 14.0	67.1 ± 7.0	65.0 ± 8.3	61.4 ± 11.3	60.1 ± 8.0	63.6 ± 12.3	60.1 ± 9.4	64.4 ± 6.6
Sex	3 F, 6 M	2 F, 7 M	4 F, 3 M	3 F, 6 M	2 F, 8 M	4 F, 5 M	2 F, 8 M	3 F, 6 M
Weight	73.4 ± 16.8	76.8 ± 11.1	75.2 ± 12.8	73.4 ± 10.4	77.2 ± 9.6	75.4 ± 10.3	77.2 ± 12.8	76.4 ± 10.3
FiO_2	0.48 ± 0.8	0.45 ± 0.8	0.48 ± 0.8	0.47 ± 0.9	0.46 ± 0.8	0.48 ± 0.9	0.47 ± 0.9	0.47 ± 0.8
f	13.3 ± 1.4	13.1 ± 1.1	12.6 ± 1.0	12.9 ± 1.1	12.6 ± 1.0	13.1 ± 1.1	12.6 ± 1.1	13.1 ± 1.1
V_t	0.67 ± 0.08	13.1 ± 0.06	0.69 ± 0.08	0.65 ± 0.05	0.69 ± 0.05	0.71 ± 0.06	0.69 ± 0.07	0.64 ± 0.06

f, Respiratory rate; V_t, tidal volume

Table 2. Mean temperatures between HME filter groups at 1 h. *p*-values relates to between group analysis for each variable

Group	DHS	DHC	PUBC	IFT	*p*
n	9	9	7	9	
Mean tracheal temperature	34.4±2.0	34.2±1.5	33.6±1.3	33.0±1.6	NS
Mean dry temperature	29.9±2.0	28.1±2.3	26.1±1.7	26.1±1.2	0.0003[a]
Mean wet temperature	28.7±1.3	27.5±2.4	25.1±1.0	25.4±1.2	0.0001[b]

[a] DHS vs DHC, PUBC and IFT; DHC vs PUBC and IFT
[b] DHS vs PUBC and IFT; DHC vs PUBC and IFT

Table 3. Mean temperatures between HME filter groups at 24 h. *p*-value relates to between group analysis for each variable

Group	DHS	DHC	PUBC	IFT	*p*
n	10	9	10	9	
Mean tracheal temperature	35.7±2.3	34.2±1.5	34.1±1.5	32.9±2.2	0.025[a]
Mean dry temperature	28.4±2.2	28.3±2.1	27.2±2.0	25.7±1.7	0.023[b]
Mean wet temperature	27.8±2.3	26.6±1.6	25.0±2.0	23.0±2.0	0.0001[c]

[a] DHS vs IFT
[b] DHS vs IFT; DHC vs IFT
[c] DHS vs PUBC and IFT; DHC vs IFT; PUBC vs IFT

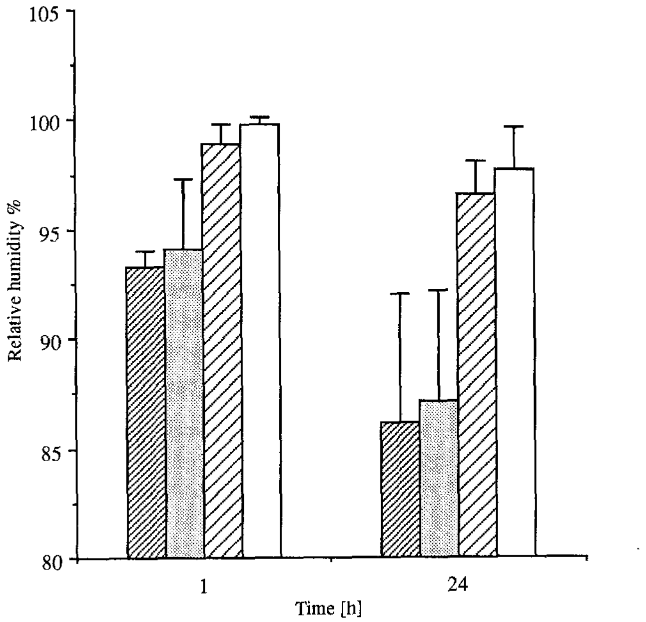

Fig. 2. Relative Humidity at 1 and 24 h. $p = 0.0001$ for DHS and DHC vs PUBC and IFT at 1 h and 24 h. ▨ DHS ▦ DHC ▧ PUBC □ IFT

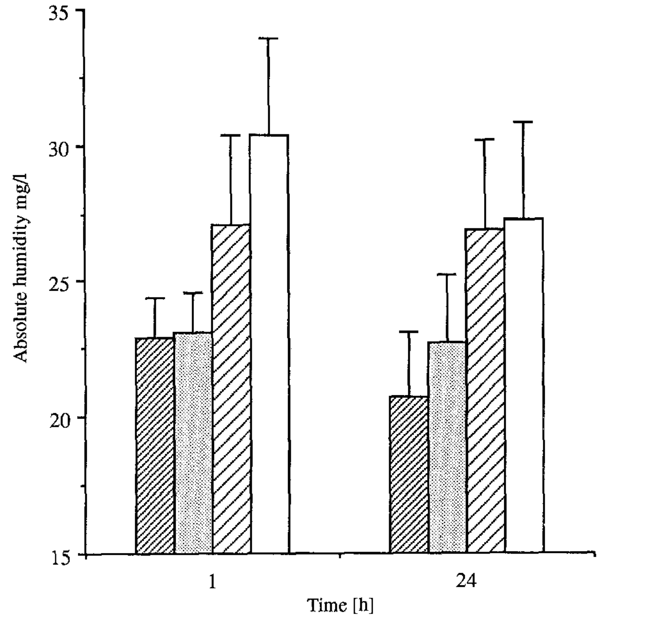

Fig. 3. Absolute humidity at 1 and 24 h. $p = 0.0001$ for DHS vs DHC, PUBC and IFT and DHC vs PUBC and IFT at 1 h and for DHS and DHC vs PUBC and IFT at 24 h. ▨ DHS ▦ DHC ▧ PUBC □ IFT

there were significant differences between groups for AH after 1 and 24 (Fig. 3). The highest mean (±SD) AH was achieved in group DHS (30.4±3.5 mg/l and 27.3±3.5 mg/l) after 1 and 24 h respectively. The lowest mean (±SD) AH was found in group IFT (22.9±1.5 mg/l and 20.7±2.4 mg/l) after 1 and 24 h respectively. Between 1 h and 24 h RH was significantly reduced for all groups ($p < 0.001$). There was also a significant difference between AH from 1 to 24 h for the IFT filters ($p < 0.0001$), but not for the hygroscopic filters DHS and DHC or the hydrophobic PUBC filters.

Discussion

The optimal requirements for HMEs used in ICU patients are not well established although several studies have been conducted to establish the optimal conditioning parameters of the gas mixture that prevention of mucociliary damage requires the AH of gases reaching the trachea to be maintained at 23–30 mg/l and 32 °C [23–26]. Others suggest higher temperature levels ranging from 35–37 °C with saturated gases and an AH of 37–41 mg/l [5, 26, 27]. Considering that the laryngotracheal temperature is normally between 32 and 34 °C and the temperature of expired gases is normally 3 – 5 °C below the body temperature under physiological conditions, a temperature of 30 °C and 100% RH (AH 27 mg/l) should be adequate [26 – 27]. All 4 filters fulfilled the humidification requirements suggested in these reports. However, there was a significant difference between the efficiency of the hygroscopic-hydrophobic HMEs (DHS and DHC), the hydrophobic HME (PUBC) and the hygroscopic-hydrophobic IFT after 1 and 24 h.

The performance of the PUBC and IFT in this study is in the lower part of the range of optimal inspired humidity and would therefore provide lower levels of humidification and heat to the airways of ventilated patients. Although this may not cause significant problems to patients ventilated for a short period, a minimum moisture output during prolonged ventilation could contribute to tracheal tube blockage from tenacious secretions. In these instances, tracheal instillation of 0.9% saline solution is required to provide adequate protection against tube occlusion. We agree with recent studies [23 – 26] suggesting that some hydrophobic HMEs provide an inadequate moisture output for ICU patients receiving long-term ventilation. Martin and colleagues [1], in their evaluation of humidification using the PUBC filter, found 6 episodes of tracheostomy tube occlusion in patients receiving CMV. In addition, over a period of 299 days, there were 4% of days in which tracheo-bronchial secretions were thick and tenacious and 23% of days during which hypothermia was reported. Martin et al. [1] concluded that tracheal instillation of saline was not sufficient to prevent tube occlusion. Although more frequent instillations could be considered, they may be hazardous in hypoxic patients on PEEP [1] and indeed we have not found that the institution of a humidification protocol on our ICU has prevented all tracheal tube occlusion.

The HME performance of ventilator filters is dependent on the minute volume at which they are used. Some HMEs are unable to provide humidification at high tidal volumes [18, 19]. Although Lowe [29] states that humidification remains adequate for volumes up to 20 l/min for the PUBC it would appear that performance is questionable when patients ventilated with volumes of more than 10 l/min. Patient water loss through ventilation with a PUBC is 8.7 mg/l (dry gas at 22 °C), at a tidal volume of 500 ml. This loss increases up to 11 mg/l at a tidal volume of 1000 ml [26, 29, 30]. Unfortunately no data are available on the other HMEs we tested in order to provide a comparison. In this study filters were used at a minute volume of 7.5 ± 1.3 l/min (NS between groups). In addition only 4.2% of patients received a minute volume greater than 10 l/min but all received less than 12 l/min. A number of patient variables can influence the performance of a filter, e.g. physical condition or temperature. It is therefore necessary to study the HMEs over a wide range of conditions and diagnoses, rather than relying on highly controlled in vitro tests. We have limited our study to post-surgical patients since admission to the ICU was predictable. We chose not to study individual patients at 1 h and 24 h since many patients were ventilated for less than 24 h. After randomisation we would have been forced to abandon the study of these patients. It is a limitation of our data that we are not able to present 1 h and 24 h data for the same patients and although we have stated the results of comparisons within the groups at these time periods this may have reduced the possibility of demonstrating a significant deterioration in HME efficiency. In conclusion, the hygroscopic-hydrophobic HMEs (DHS and DHC) had a better humidification capability than the hydrophobic HMEs (PUBC and IFT).

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