Performance of breathing filters under wet conditions: a laboratory evaluation

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Introduction. Heat and moisture exchangers in combination with a bacterial and viral filter (HMEF) are widely used during general anaesthesia. Excess patient secretions occluding the HMEF have been responsible for previous case reports of airway obstruction. A previous study suggested that differences in HMEF design might contribute to filter obstruction under wet conditions.

Methods. We tested 14 types of HMEF under wet conditions to establish which design features contributed to HMEF obstruction. Incremental amounts of saline were added to each filter. The pressure across the filter was measured with an air flow of 60 litre min−1.

Results. We observed that saline added to the filter was often not easily visible to the casual observer. This concealment volume varied between filters. Ceramic hydrophobic pleated-membrane filters did not absorb saline and their resistance did not change. The composite filter where the moisture exchange component was either polyurethane foam or cellulose absorbed saline and contributed to a rise in resistance of 70–480% with the higher value more typical of the cellulose-paper-based HMEF.

Conclusion. The ideal HMEF for use during general anaesthesia should prevent the passage of viral, bacterial and prion material, should provide this filtration performance even under wet conditions, should supplement humidification of the inspired air and anaesthetic gases and should not increase respiratory work. We have identified large variations in HMEF performance under wet conditions. Users should be aware of performance variation in HMEFs and use a filter suited to the intended application.

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Heat and moisture exchangers in combination with a bacterial and viral filter (HMEFs) are widely used during general anaesthesia. The moisture exchange component passively humidifies the inspired air by returning a percentage of the patient’s expired moisture. The filter component of the HMEF reduces the risk of viral1 and bacterial cross-contamination between patients.2,3 Despite the widespread acceptance of HMEFs during general anaesthesia,4 serious complications have been reported. These include an increase in the work of breathing,5 airway obstruction6–8 and lithium toxicity.9 Airway obstruction develops when moisture, typically patient secretions, nebulized drugs10 or moisture from within the circle circuit, occludes the pores within the HMEF, leading to a significant increase in resistance. Fortunately, moisture levels typically seen in routine use do not result in obstruction.11,12 However, collection of excess moisture within the body of the HMEF may not be apparent to the user and can lead to inappropriate clinical management in the event of difficulty in ventilation.8

A previous study13 suggested that differences in design lead to differences in performance of HMEFs under wet conditions. We applied this test to 14 HMEFs currently available in the UK. The objective was to assess the risk of HMEF obstruction under wet conditions, and to investigate whether there were particular features of HMEF construction that made obstruction more or less likely.

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Furthermore, we wished to relate the risk of occlusion to other performance measures and to determine which, if any, of the currently available devices acts as an ideal HMEF, i.e. one with a small dead space, a high filtration efficacy, a high moisture output and little risk of causing occlusion or increased work of breathing.

Methods

Filter types tested

The filters tested were from 10 leading suppliers of HMEFs in the UK. The Intersurgical 1941, Airsafety Comfortfit and Airsafety Slimline, Siemens Servofilter, Datex Ohmeda 1000 and Vital Signs F2 are composite filters with the moisture exchange component made of polyurethane foam impregnated with calcium chloride and the filter component made of polypropylene fibre (Fig. 1A). The Draeger Hygrovent S, Dar Hydrobac S, Gibeck 19402, and Rusch Arios are also composite filters but the moisture exchange component is made of corrugated cellulose fibre (cotton or wood pulp) impregnated with calcium chloride (Fig. 1B); again, the filter component is made of polypropylene fibre. The Pall BB25, Pall BB100, Airsafety Maxipleat (Fig. 1C) and Intersurgical 1741 are ceramic pleated-membrane hydrophobic filters.

Pressure across the filter

The resistance to air flow across a filter will increase if the HMEF is contaminated by fluid. In this study we measured the change in pressure across an HMEF in the presence of incremental amounts of saline introduced into the filter housing. A medical air cylinder provided a continuous air flow of 60 litre min$^{-1}$. The pressure difference across each filter was measured using a certified calibration analyser (RT–200, Allied Healthcare Products). Saline 0.9% was added to the HMEF at the patient end in 5-ml increments. The filter was gently agitated and mounted vertically in the test apparatus. To mimic inspiration the air flow was towards the patient end of the filter, with the patient end uppermost and the filter reversed to mimic expiration with the patient end dependent. The test was stopped when saline was ejected from the filter. A new filter was used for each test, and each test was performed 10 times; therefore 20 filters were used to measure the expiratory and inspiratory pressure across the filter with each increment of saline.

Concealment volume

Secretions within the housing of an HMEF may be concealed or apparent. Retained and concealed moisture within the HMEF housing can lead to airway obstruction and difficulty in diagnosis. Concealment volume is a subjective measure of the potential tendency of filters to conceal

![Fig 1](A) Composite filter divided in two parts to illustrate polyurethane foam HME (left) and the polypropylene viral/bacterial filter (right). (B) Coiled corrugated cellulose paper HME removed from the HMEF housing. (C) An example of a pleated ceramic filter (Airsafety Maxipleat). Fluid level at ‘x’ indicated visible excess fluid within filter housing.
secretions from the user. Increments (5 ml) of saline 0.9% were added to each filter at the patient end. Two observers (DT and PCF) considered that the saline was concealed if free fluid was not easily visible within the housing of the HMEF. The concealment volume was recorded as that volume of saline present before the saline was easily visible within the housing of the filter.

Retention volume
Increments (5 ml) of saline 0.9% were added to the filter at the patient end. The filter was agitated and then inverted. The retention volume was that volume of saline that did not result in loss from the filter when inverted.

Patient-side dead-space volume
The dead-space volume often quoted in the product literature is the total volume of the filter housing. The dead-space volume in this study is the internal volume of the HMEF on the patient side of the filter layer. This allows measurement of the relationship between the retention volume and the dead space. With the filter held vertically, saline 0.9% was instilled at the patient end in 1-ml increments. The dead space was that volume of saline that did not result in spillage. The filter dead space, the retention volume and the concealment volume were tested five times with each filter model. All filters were tested once only and then discarded.

Statistics
Graphical presentations, means, standard deviations and t-tests were calculated using the Statistical Package for the Social Sciences (SPSS 10; SPSS Inc., Chicago, IL).

Results

Pressure across the filter
Each filter was tested until it was apparent to the observer that excess saline was present within the filter housing, demonstrated by ejection of saline from the filter. In the absence of easily visible fluid within the filter housing this would most likely lead to filters being changed during clinical use. The hydrophobic ceramic membrane filters performed well in this test as they were unable to retain any saline and the maximum pressure across the filter was the same as that when the filter was dry (Table 1). The cellulose-fibre- and foam-based filters tended to absorb water, and the pressure across the filter was related to the concealment volume (Fig. 2).

Concealment volume
Concealment volume is a subjective measure of the volume of saline retained within the filter housing that is not apparent to the user without close inspection. The performances of the hydrophobic pleated-membrane filters were similar (Table 1). These filters do not absorb saline, and saline instilled at the patient end is easily visible to the user (Fig. 1C). The foam-based composite filters (Fig. 1A) tended to absorb saline, leading to a rise in pressure across the filter (Fig. 3A). Furthermore, the saline within the filter was not easily visible, i.e. it was concealed. However, there was considerable variation in the performance of the foam-based filters, which may be due to the different physical characteristics of the polyurethane foam. All filters where the heat and moisture exchange element was cellulose fibre (Fig. 1b) were impregnated with calcium chloride to increase hygroscopicity. These filters tended to absorb water, leading to both an elevated pressure across the filter (Fig. 3b) and a high concealment volume.

Retention volume
The retention volume reflected the concealment volume (Fig. 2). The hydrophobic pleated-membrane ceramic filters retained no saline, whereas the foam- and cellulose-based filters varied in retention volume, with the Datex Ohmeda retaining 45 ml of saline. However, this volume of liquid contamination is unlikely to be met under most clinical conditions.

Inspiratory and expiratory pressure across the filter
For a comparable volume of saline added at the patient end there was frequently a difference between the inspiratory and expiratory pressures. When the maximum expiratory pressure achieved for a given volume of saline was compared with the inspiratory pressure at the same volume, the expiratory pressure was greater in nine of the 14 filters tested. The difference was not statistically significant (P=0.35). However, in some filters this difference may predispose to hyperinflation during controlled or spontaneous ventilation, and consequently may be of clinical significance (Fig. 4).

Discussion
Although saline is an unlikely filter contaminant during clinical use, it is readily available in a standardized solution. However, it is similar to condensation seen in a circle system. Solutions that resemble tracheobronchial fluid or pulmonary oedema would require standardization if this test was to be widely applied. Furthermore, the aim of this study was to make an objective comparison between HMEFs under wet conditions, and to consider which design features may lead to filter obstruction.

A medical air cylinder generated the air flow of 60 litre min⁻¹, in contrast with previous studies where the air flow was generated with a ventilator and lung model. We believed that the air cylinder flow model was easier to
Table 1  Concealment volume, maximum inspiratory and expiratory pressures achieved during testing. *Moisture output values taken from medical devices agency data and published commercial information. ND, salt penetration performance is not available for all filters tested because of discontinuation of product or filter data not yet available; NA, moisture output is not available for all filters tested because of discontinuation of product since completion of study. Data are mean (SD)

<table>
<thead>
<tr>
<th>Model</th>
<th>HMEF design</th>
<th>Concealment volume (ml)</th>
<th>Maximum volume of saline added during expiratory testing (ml)</th>
<th>Maximum expiratory pressure (cm H$_2$O) at 60 litre min$^{-1}$ air flow</th>
<th>Maximum volume of saline added during inspiratory testing (ml)</th>
<th>Maximum inspiratory pressure (cm H$_2$O) at 60 litre min$^{-1}$ air flow</th>
<th>Moisture output* at 0.5 litre tidal volume and 20 bpm (mg litre$^{-1}$)</th>
<th>Filtration performance$^a$ (% penetration)</th>
</tr>
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<tbody>
<tr>
<td>Intersurgical Hydroguard Mini 1744</td>
<td>Ceramic pleated-membrane filter</td>
<td>0</td>
<td>10</td>
<td>9.3 (2.4)</td>
<td>0</td>
<td>4.5 (0.3)</td>
<td>22.4</td>
<td>ND</td>
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<td>Airsafety Maxipleat</td>
<td>Ceramic pleated-membrane filter</td>
<td>0</td>
<td>0</td>
<td>3.3 (0.1)</td>
<td>0</td>
<td>3.18 (0.1)</td>
<td>28.7</td>
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<tr>
<td>Pall BB100</td>
<td>Ceramic pleated-membrane filter</td>
<td>0</td>
<td>0</td>
<td>2.0 (0.1)</td>
<td>0</td>
<td>1.9 (0.1)</td>
<td>30.6</td>
<td>0.022</td>
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<tr>
<td>Pall BB25</td>
<td>Ceramic pleated-membrane filter</td>
<td>0</td>
<td>0</td>
<td>3.7 (0.1)</td>
<td>0</td>
<td>3.6 (0.1)</td>
<td>24.7</td>
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<td>Intersurgical Filtertherm1941</td>
<td>Foam-based composite filter</td>
<td>10</td>
<td>5</td>
<td>4.1 (0.2)</td>
<td>10</td>
<td>5.9 (0.4)</td>
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<td>0.275</td>
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<td>Airsafety Comforfit</td>
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<td>10</td>
<td>3.7 (0.2)</td>
<td>15</td>
<td>4.9 (0.3)</td>
<td>30.2</td>
<td>ND</td>
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<td>Airsafety Slimline</td>
<td>Foam-based composite filter</td>
<td>25</td>
<td>10</td>
<td>10.1 (3.8)</td>
<td>5</td>
<td>5.2 (1.7)</td>
<td>NA</td>
<td>ND</td>
</tr>
<tr>
<td>Datex Ohmeda 1000</td>
<td>Foam-based composite filter</td>
<td>45</td>
<td>30</td>
<td>11.1 (3.3)</td>
<td>25</td>
<td>6.3 (0.5)</td>
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<td>4.49</td>
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<tr>
<td>Vital Signs F2</td>
<td>Foam-based composite filter</td>
<td>15</td>
<td>10</td>
<td>12.5 (4.1)</td>
<td>5</td>
<td>4.9 (0.7)</td>
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<td>ND</td>
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<tr>
<td>Siemens Servo-filter 172</td>
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<td>20</td>
<td>15</td>
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<td>9.8 (1.1)</td>
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<td>ND</td>
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<td>Gibeck 19402</td>
<td>Cellulose-paper-based filter</td>
<td>10</td>
<td>5</td>
<td>6.8 (0.8)</td>
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<td>13.4 (1.6)</td>
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<td>6.7 (0.3)</td>
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<td>Rusch Arios</td>
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<td>20</td>
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<td>20</td>
<td>10.9 (2.6)</td>
<td>33</td>
<td>ND</td>
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<td>Tyco Health Care Dar Hygrobac S</td>
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<td>20</td>
<td>9.1 (2.6)</td>
<td>20</td>
<td>8.2 (1.9)</td>
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<td>11.4</td>
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reproduce, and, as the air flow was unidirectional, individual assessment of expiratory and inspiratory resistance was possible. Discrepancies between measures of HMEF resistance under wet conditions could be explained by these differences in study design.\textsuperscript{8}\textsuperscript{14} We measured the filter resistance immediately that the air flow was turned on, as we had observed that the measured resistance declined over time. We speculated that this decline was due to the development of channels created in the filter media.

Despite several reports of HMEF occlusion\textsuperscript{6,7,8,15} the potential risk of hepatitis C cross-contamination via the anaesthetic breathing system\textsuperscript{116} and more recently the potential risks of prion-contaminated material from subclinical trauma during insertion of endotracheal tubes,\textsuperscript{17,18} has led to the widespread acceptance of HMEFs during general anaesthesia. The risk of filter occlusion varies with the filter media and the properties of the solution obstructing the filter. The risk of filter occlusion is greatest when the solution is clear and concealed within the filter housing. When reported, filter occlusion develops when secretions of patient origin contaminate the filter. We demonstrated the mixed performance of HMEFs under wet conditions in an earlier report. In this study we have considered the particular design features that lead to filter obstruction under wet conditions in more detail. In addition, we develop further the idea of concealment volume as a subjective measure of the risk of unobserved filter occlusion under wet conditions.

HMEFs are broadly of two main types. Hydrophobic pleated-membrane ceramic filters consist of mineral fibres coated with synthetic resin. The ceramic fibres within the pleated membrane are hydrophobic and moisture is returned by a condensation mechanism. Combined with a small pore size, these properties make them an excellent bacterial viral filter and act as a heat and moisture exchanger.\textsuperscript{17,19,20} The resistance of the small pore size is offset by the large surface area of the material produced by pleating the material in the HMEF housing. The other HMEF type is described as a composite HMEF. The viral filter is a polypropylene non-woven fibre and the moisture exchange component is reticulated polyurethane open-cell foam or cellulose fibre (either cotton or wood pulp). The polyurethane foam and the cellulose paper are typically impregnated with calcium chloride to increase their hygroscopicity and therefore their moisture output.

This study demonstrates that there are considerable differences between the performances of filters under wet conditions that are related to the type of media used as the moisture exchange component. The hydrophobic fibres in the ceramic HMEFs prevent penetration by moisture under the conditions of use specified by the manufacturer. However, the nebulization of drugs is invariably contraindicated and may disrupt the fibres of the filter, leading to device failure.\textsuperscript{7} In this study, ceramic HMEFs neither concealed moisture nor demonstrated an increase in resistance. Hydrophobic pleated-membrane filters also demonstrate an
excellent viral filtration performance\textsuperscript{3,19,21} that is sustained even in the presence of excess moisture. However, this is set against a poor moisture output that does not comply with American Society for Testing and Materials recommendations.\textsuperscript{19}

The physical properties of the polyurethane foam found within foam-based filters are described according to the foam density, the number of pores per inch (ppi) and the foam thickness. The ppi may vary from 10 to 110, and the foam density varies from 26 to 32 kg m\textsuperscript{-3}. The denser the foam and the greater the number of ppi, the greater is the moisture output. For example, the foam within the Airsafety Slimline and ComfortFit has 90 ppi whereas the Datex Ohmeda 1000 has 55 ppi. The different performance of these

![Diagram A](image)

**Fig 3** Change in pressure across (a) polyurethane-foam-based composite HMEFs and (b) cellulose-paper-based composite HMEFs with the addition of incremental amounts of saline. Air flow, 60 litre min\textsuperscript{-1}.
filters demonstrates that the foam with the highest ppi conceals less moisture and shows a smaller rise in resistance when wet. However, polyurethane foam with a high ppi tends to be more expensive to produce in the form used in the production of HMEFs.

The cellulose-paper-based filters are produced from wood pulp or cotton. The paper is corrugated and impregnated with calcium chloride and forms a spiral within the housing of the filter. In the Gibeck, the final product is fluted, i.e. the corrugated strip is glued to a flat strip before final rolling (Fig. 1B). Under moist conditions, the paper absorbs water and expands, and the resistance across the filter increases until the filter occludes or the saturated paper ejects the water. Manufacturers of cellulose paper suggest that filter occlusion is less likely to occur if the paper is thick and/or fluted. However, the paper-based products all demonstrate a large rise in resistance and, importantly for the user, the saline is concealed. Excess moisture retention within the housing of the composite filters leads to ineffectual particle filtration with the potential for cross-contamination.22

Anaesthetic associations worldwide recommend humidification of inspired air during general anaesthesia and the prevention of cross-contamination by viral and prion particles. The single-use HMEF is a simple device that performs these two functions. The International Standardization Organisation (ISO), the Medicines and Healthcare Products Regulatory Agency (MHRA), in-house testing and independent testing of HMEFs allow the user to assess the relative merits of each HMEF with regard to filtration efficiency and moisture output. However, despite the risk of HMEF occlusion, the performance of HMEFs under wet conditions is not often reported. This report demonstrates the variation in performance of filters under wet conditions. The hydrophobic ceramic pleated-membrane filters are least likely to occlude under our study conditions and, even when wet, they provide filtration properties that exceed those of the composite filters.19 However, the moisture output of ceramic filters does not meet International Standards for humidification.23 Nevertheless, when used with circle breathing systems, the moisture output may be acceptable, as the reaction of the exhaled carbon dioxide with the soda lime produces water, which augments that delivered from the filter. In contrast, the composite filters (foam and cellulose fibre) may offer greater moisture output, but with a greater risk of occlusion under wet conditions. The risk of occlusion varies according to the physical properties of the moisture exchange component of the HMEF. This study highlights the risk of unexpected filter occlusion during clinical use. Changing the HMEF should be considered when an unexpected elevation in breathing circuit resistance develops.

The ideal HMEF for use during general anaesthesia should prevent the passage of viral, bacterial and prion material, should provide filtration performance even under wet conditions, should supplement humidification of the inspired air and anaesthetic gases and should not increase respiratory work. For short-duration anaesthesia the user may consider prevention of patient cross-contamination more important than humidification, and a pleated ceramic filter may be appropriate. However, in a
device intended for long procedures or intensive care, effective humidification may be more important.

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