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REVIEW ARTICLE

Heat and moisture exchangers and breathing system filters: their use in anaesthesia and intensive care. Part 2 – practical use, including problems, and their use with paediatric patients

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Summary

Heat and moisture exchangers and breathing system filters are intended to replace the normal warming, humidifying and filtering functions of the upper airways. The first part of this review considered the history, principles of operation and efficiency of these devices. The aim of this part of the review is to summarise recent guidelines on the use of these devices and outline the problems that can occur. In particular, the effect of these devices on gas analysis, dead space, resistance to gas flow and blockage of the breathing system is considered. In children, it is important to consider the addition of dead space and resistance to gas flow. A body weight of 2.5 kg is probably the lower weight limit for use with heat and moisture exchangers, and 3 kg for filters. The resistance to gas flow of a heat- and moisture-exchanging filter added to a Mapleson F breathing system can cause a delay in the induction of anaesthesia.

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As discussed already in the first part of this review [1], heat and moisture exchangers (HMEs) are intended to conserve a portion of the patient's exhaled heat and moisture and condition inspired gas by warming and humidifying it [2]; breathing system filters are intended to reduce the transmission of microbes and other particulate matter in breathing systems [3] when the patient's upper airways have been bypassed during anaesthesia and intensive care. Heat- and moisture-exchanging filters (HMEFs) provide both functions.

To humidify gases and protect the breathing system from expired infective droplets, the device is placed between the patient and the breathing system [4]. In this position, it adds to the dead space, thus increasing rebreathing (necessitating an increase in ventilation or allowing permissible hypercapnia), and it also adds to the resistance to gas flow, thus increasing the work of breathing. Blockage can also occur if liquid enters the device. So, although the patient might benefit from the addition of the device to the breathing system, some harm might also occur. Guidelines have been formulated for the use of these devices for patients with specific diseases, or on preventing patients from succumbing to particular diseases. Some of these guidelines distinguish between the two main types of breathing system filters: 'pleated' and 'electrostatic'. For an explanation of these terms, see the first part of this review [1].

In this part of the review, problems that can occur with the use of HMEs and filters are described, current guidelines on the use of these devices are reviewed and further recommendations are developed.

Complications associated with the use of HMEs and filters

Effect on resistance to gas flow and ventilation

When HMEs or filters are added to the breathing systems, they increase the resistance to gas flow and hence the work of breathing. In a study comparing a large electrostatic HMEF with a heated humidifier in patients

receiving non-invasive ventilation who had hypercapnic acute respiratory failure, it was demonstrated that the minute ventilation was significantly higher when the filter was used and that this was also associated with a marked increase in the work of breathing [5].

Iotti et al. compared a large-pleated HMEF with an HME-only device and a heated humidifier in patients receiving pressure support ventilation for acute respiratory failure [6] and demonstrated that ventilation increased significantly with the HMEF, and that airway resistance increased significantly with both the HME and the HMEF. Iotti et al. concluded that 'artificial noses' remained an attractive alternative to heated humidifiers, but that preference should be given to the use of low-volume and low-resistance devices.

The resistance to gas flow can increase markedly during mechanical ventilation of the lungs in the intensive care unit (ICU), especially if liquid collects in the filter [7], although, in this particular study, there were no important sequelae arising from this.

However, in a study investigating the effect of three HMEs and HMEFs on the level of auto positive end expiratory pressure (PEEP) and dynamic hyperinflation of the lungs, assessed by measuring the functional residual capacity (FRC) in ICU patients with chronic obstructive lung disease receiving mechanical ventilation, the devices did not have a significant effect on either auto PEEP or FRC after 12 hours of use [8]. In addition, there were no other sequelae.

Dead space

Heat and moisture exchangers and filters add to the dead space of the breathing system when they are connected between the patient and the breathing system, so that a greater proportion of the exhaled carbon dioxide is returned in the next breath. Adding a filter with a large internal volume, rather than a humidifier, can cause a significant increase in spontaneous respiratory rate and arterial partial pressure of carbon dioxide [9]. During weaning trials, the additional dead space of the filter compared with a heated humidifier needs to be taken into account [10]. When comparing devices, some smaller devices tend to have greater resistance to gas flow than larger ones. Thus, although the larger device can cause an increase in ventilation, smaller devices increase the ventilatory drive and work of breathing [11]. However, in this particular study, increasing the pressure support from 5 to 10 cmH_2O compensated for the increase in the work of breathing.

In a study comparing the effect of a heated humidifier, an HME (with a dead space of 28 ml) and a filter (with a dead space of 90 ml) on respiratory variables in both spontaneously breathing and paralysed patients receiving mechanical ventilation in the ICU [12], ventilation increased with the use of the HME and the filter, and the increase in ventilation was correlated with the size of the dead space. Smaller devices can have lower moisture outputs than larger devices. In this study, it was concluded that, when choosing a passive humidifier, the one chosen should have the smallest dead space but meet the desired moisture output requirements.

To reduce the risk of lung trauma or injury during prolonged mechanical ventilation in ICU, the target tidal volume should be reduced. This will have an effect on the size of breathing system filter that can be used (see below).

Blockage with liquid

Liquid can flow into HMEs and filters from either the patient (sputum or pulmonary oedema), or from the breathing system (if condensation is present). This can cause an increase in resistance to gas flow and, in some cases, complete occlusion, preventing adequate ventilation of the lungs [13, 14]. The high resistance to gas flow of the HME or filter can be sufficient to prevent the activation of a ventilator disconnect alarm [15]. Identification of the cause of a substantial increase in peak airway pressure because of a blocked filter is not always immediately obvious as the filter may be hidden under drapes [16]. Even if the filter is visible, it may be difficult to identify the build-up of liquid in it [17, 18]. If a filter is placed below the level of the patient's lungs, liquid can flow easily into the filter and cause obstruction. Sufficient volume of liquid can prevent the patient expiring, but allow the ventilator to deliver the next breath, so that the filter acts as a one-way valve [19]. To reduce this risk, the filter should be placed at a level higher than that of the patient's lungs, with the filter layer in a vertical, rather than a horizontal, orientation [19].

Filters on the expiratory limb can occlude if the patient expectorates bloody secretions [20, 21] and if condensation collects within the filter [22]. This is particularly an issue if a filter is used in conjunction with a heated humidifier [23]. Blockage of filters can also occur when a filter is used in conjunction with nebulised drugs [24].

Effect on capnography

Heat and moisture exchangers and filters can affect the capnography waveform. This is particularly likely where the internal volume of the filter is a significant proportion of the tidal volume: in extreme cases the capnography trace can disappear altogether [25]. The sample of gas for analysis can be taken from either the patient- or machine-side of the filter. There can be differences in the displayed level of carbon dioxide depending on which side of the filter the sample is taken from [26]; this effect appears to be greater for larger filters or when the tidal volume is

small [27, 28]. However, the sample of gas should be removed from the machine-side of filters where possible because this sample will be filtered, reducing the risk of contamination, and it will generally be drier. A similar effect can occur with the measurement of tidal volume where the use of an HME can cause an underestimation of tidal volume compared with a heated humidifier [29].

Other effects

There is evidence to suggest that prolonged exposure (>4 h) to high levels of desflurane (2 MAC) reduces the filtration performance of some electrostatic filters intended for use with adults [30] and children [31]. Lawes described other effects that the use of HMEs and filters can have on monitoring patients during anaesthesia [32]. However, the presumption that the use of HMEs and filters in anaesthesia can cause desiccation of the carbon dioxide absorbent is unlikely, as the reaction of the exhaled carbon dioxide with the absorbent generates water, so that the absorbent is very unlikely to dry out when used with patients. Further problems related to the desiccation of the absorbent (inaccuracy of pulse oximetry and production of compound A from volatile anaesthetic agents) are therefore also very unlikely to occur.

Guidelines

Ventilator-associated pneumonia

Between 8% and 28% of patients requiring mechanical ventilation develop ventilator-associated pneumonia (VAP) [33]. The mortality rate for VAP is comparatively high, ranging from 24% to 50%, while the mortality rate can be as high as 76% in some specific situations or when lung infection is caused by particularly high-risk pathogens. The predominant organisms responsible are *Staphylococcus aureus*, *Pseudomonas aeruginosa* and *Enterobacteriaceae*.

Ventilator-associated pneumonia is associated with an increase in duration of mechanical ventilation. In a large case control study, patients with VAP had significantly longer mean (SD) duration of ventilation (14.3 (15.5) days compared with 4.7 (7.0) days) [34]. Safdar et al. estimated that VAP caused an increase in duration of stay in the ICU of 6.1 days [35].

Gallagher et al. recommended the use of a breathing system filter, placed between the patient and the Y-piece of the breathing system, as the sole means of humidification in patients receiving mechanical ventilation in the ICU based on a reduction in infection and colonisation of patients with *Pseudomonas aeruginosa* in an unmatched case–control study [36]. In the period from January to June 1984, 380 patients were admitted to the ICU; 66 required controlled ventilation and received humidification from a hot water bath humidifier, of whom 35 were either colonised or infected with *Pseudomonas aeruginosa*. In the period January to June 1985, 384 patients were admitted; 75 required ventilation and received humidification from the filter only, of whom only 16 were either colonised or infected with *Pseudomonas aeruginosa*.

A number of prospective randomised controlled trials have subsequently been carried out comparing the effect of a humidification device (HME, HMEF or heated humidifier) on the incidence of ventilator-associated pneumonia (Table 1). The only study to show a significant advantage of HMEFs was that of Kirton et al. [49], and the only study to show a significant advantage of heated humidifiers was Lorente et al.'s [53]. However, in this particular study, the passive device was an HME-only product and not a filter.

Four meta-analyses and two evidence reviews have been carried out comparing the incidence of VAP when either HMEs or humidifiers were used (Table 1). The conclusions reached depended on the studies included in the analysis. However, in spite of the fact that some of the conclusions were in favour of the use of passive humidification devices, the evidence lacked power.

Kola et al. reported that the reduction in the incidence of VAP when using an HMEF is more marked during prolonged ventilation [39]. This was also found in the study by Kranabetter et al., where the difference between the filter and humidifier group was only significant for patients requiring ventilation for more than 2 days [55].

Guidelines have been published on methods to prevent VAP. Recent guidelines are conflicting in some of their advice. In relation to heat and moisture exchangers and breathing system filters:

- The Centers for Disease Control and Prevention [56] made several recommendations:
  - Using high-efficiency bacterial filters at various positions in the breathing circuit (e.g. at the Y-piece or on the inspiratory and expiratory sides of the circuit) has been advocated and shown to decrease contamination of the circuit. However, the efficacy of bacterial filters in preventing health care-associated pneumonia has not been demonstrated.
  - No recommendation can be made for the preferential use of either HMEs or heated humidifiers to prevent pneumonia in patients requiring mechanically assisted ventilation, and this remains an unresolved issue.
  - An HME that is in use on a patient should be changed if it malfunctions mechanically or becomes visibly soiled, but HMEs should not be routinely changed more frequently than every 48 h.
  - In the absence of gross contamination or malfunction, the breathing circuit attached to an HME should not be changed routinely while it is in use on a patient.

Table 1 Comparison of heat and moisture exchangers (HMEs) and heated humidifiers (HH) on the incidence of VAP (ventilator-associated pneumonia). Values are number (proportion) and relative risk (95% CI).

	Comparison	Outcome	Included in meta-analysis				Systematic review	
Study	HME(F) vs HH	Incidence of VAP	Cook et al.* [37]	Hess et al.† [38]	Kola et al. ‡ [39]	Siempos et al § [40]	Collard et al. ¶ [41]	Dodek et al.** [42]
Martin et al. †† [43]	PUBCF vs heated humidifier (unspecified)	HME 2/31 (6%) vs HH 8/42 (19%), 0.34 (0.08–1.49)	✓	✓	✓	✓	✓	✓
Roustan et al. [44]	BB22-15 vs Aquaport	HME 5/55 (9%) vs HH 9/61 (15%), 0.62 (0.22–1.73)	✓	✓	✓	✓	✓	✓
Dreyfuss et al. [45]	Hygrobac vs various HHs	HME 6/61 (10%) vs HH 8/70 (11%), 0.86 (0.32–2.34)	✓	✓	✓	✓	✓	✓
Branson et al. [46]	Baxter HME‡‡ vs MR730	HME 3/49 (6%) vs HH 3/54 (6%), 1.10 (0.23–5.21)		✓	✓	✓		
Boots et al. [47]	Humid-Vent Filter Light vs MR730	HME 14/75 (19%) vs HH 7/41 (17%), 1.09 (0.48–2.49)			✓	✓		✓
Hurni et al. [48]	Hygroster vs various HH	HME 5/59 (8%) vs HH 7/56 (13%), 0.68 (0.23–2.01)	✓			✓	✓	
Kirton et al. [49]	BB100 vs Marquest	HME 9/140 (6%) vs 22/140 (16%), 0.41 (0.20–0.86)	✓	✓	✓	✓	✓	✓
Kollef et al. [50]	Duration vs MR730	HME 15/163 (9%) vs HH 15/147 (10%), 0.90 (0.46–1.78)		✓	✓	✓		✓
Memish et al. [51]	Hudson HME Filter vs HH	HME 14/123 (11%) vs HH 19/120 (16%), 0.72 (0.38–1.37)			✓	✓		✓
Lacherade et al.[52]	Hygrobac vs MR730	HME 47/185 (25%) vs HH 53/184 (29%), 0.88 (0.63–1.23)				✓		
Lorente et al. [53]	Edith Flex‡‡ vs MR850 & Aerodyne 2000	HME 21/53 (40) vs HH 8/51 (16), 2.53 (1.23–5.18)				✓		
Boots et al. [54]	Humid-Vent Filter Compact vs MR730	HME 24/190 (13%) vs HH 23/191 (12%), 1.05 (0.61–1.79)				✓		

VAP, ventilator-associated pneumonia; PUBF, Pall Ulpitor breathing circuit filter.
*Lower VAP rates may be associated with avoidance of humidifiers and use of HMEs.
†Although the evidence suggests a lower VAP rate with passive than active humidification other issues preclude a general recommendation for the general use of passive humidifiers.
‡Reduction in the risk of VAP in the HME group particularly in mechanical ventilation for at least 7 days.
§The available evidence does not support the preferential performance of either passive or active humidifiers in mechanical ventilation in terms of VAP incidence, mortality or morbidity.
¶Not listed amongst preventive practices with strongest supportive evidence. Meta-analysis would help to determine whether HMEs are associated with lower rates of VAP.
**Recommended: HMEs in the absence of contra-indications.
††Study stopped early due to death of a patient in the HME group from a blocked tracheal tube.
‡‡HME only device.

  - No recommendation can be made for placing a bacterial filter in the breathing system or patient circuit of anaesthesia equipment; this is an unresolved issue.
- The American Thoracic Society stated that heat-moisture exchangers decrease ventilator circuit colonisation, but do not significantly reduce the incidence of VAP. Therefore they cannot be regarded as a tool to prevent VAP [57].
- The European Care Bundle for prevention of VAP ranked 'HMEs to be preferred' (over heated humidifiers) only eleventh in order of importance out of 16 measures recommended [58].
- Although not one of the 20 consensual points reached by the European hospital-acquired pneumonia working group [59], it was noted (by reference to Cook et al. [37]) that patients using HMEs had a significantly lower incidence of VAP when compared with those using heated humidifiers.
- The working party on hospital-acquired pneumonia of the British Society for Antimicrobial Chemotherapy recommended the use of HMEs rather than heated humidifiers 'as HMEs are more effective in reducing the incidence of VAP' [60]. When choosing an HME, the working party recommended that adequate moisture output to minimise the risk of airway obstruction is required. Furthermore, HMEs do not need to be changed routinely. The working party recommended that appropriate filters are used to protect mechanical

ventilator circuits from bacterial contamination and, in anaesthesia, filters should be changed between patients.
- The Society for Healthcare Epidemiology of America/ Infectious Diseases Society of America did not specifically mention the use of HMEs or filters [61].
- The VAP Guidelines Committee and the Canadian Critical Care Trials Group did not make any recommendations for the type of humidification, but did not recommend the use of filters [62]. If HMEs are used, it was recommended to change them for each patient, every 5–7 days and as clinically indicated. However, earlier guidelines from the same group [42] had recommended the use of HMEs in the absence of contraindications with weekly changes, although the group concluded that there was only a slightly decreased incidence of VAP compared with heated humidifiers. Cost considerations favoured the use of HMEs.

Tuberculosis

Tuberculosis (TB) was responsible for an estimated 1.3 million deaths worldwide in 2008 [63]. It is estimated that one person is newly infected every second and that one third of the world's population is currently infected with the TB bacillus. Cross-infection occurs by airborne transmission of bacilli when infected patients cough, sneeze and talk. Each person with active TB disease will infect on average between 10 and 15 people every year if they are left untreated [63]. The infectious dose is estimated to be less than 10 bacilli [64]. Care and treatment of patients with TB may involve the use of mechanical ventilation.

Cross-infection of TB in the healthcare setting has been reported. Jereb et al. described how 10 patients in a renal transplant unit were infected with TB, five of whom died [65]. The median incubation period for TB in this immunocompromised group of patients was 7.5 weeks. Transmission has also occurred between the patient and healthcare workers [66]. The TB bacillus can pass through anaesthetic breathing circuits, including soda lime canisters, and remain viable [67]. The bacilli remain airborne unless the flow of gas through the breathing system is stopped for more than 1 h.

Pleated hydrophobic filters prevent the transmission of Mycobacterium bovis (a test surrogate for *Mycobacterium tuberculosis*) [68] and *Mycobacterium chelonae* [69]. Two types of electrostatic filter had filtration efficiencies of > 99.999% when challenged with Mycobacterium chelonae [69].

The Centers for Disease Control and Prevention (CDC) recommends placing a bacterial filter on either the tracheal tube or the expiratory limb of the breathing system [70]. When choosing a filter, CDC recommends one that filters particles 0.3 μm in size with an efficiency of more than 95% in both the unloaded and loaded states at the maximum flow rate of the ventilator. This flow will be greater than the flows generally used to determine filtration performance (15 and 30 $l.min^{-1}$ for filters intended for use with paediatric and adult patients, respectively [3]); increasing flow reduces the filtration efficiency of breathing system filters [71].

Severe acute respiratory syndrome

Severe acute respiratory syndrome (SARS) was an atypical pneumonia that spread rapidly from south-east Asia to Canada and many other countries in the Americas, Europe and Australasia in late 2002 and early 2003. By 7 August, 2003, there had been 8422 reported definite cases of patients with SARS, out of whom 916 had died [72]. SARS was unusual in that a large proportion of those who became infected were healthcare workers: in one cohort of 144 patients with SARS in the Greater Toronto Area, 73 (51%) were healthcare workers [73]. Spread of the virus was predominantly by infectious droplets and contact. In Toronto, six healthcare workers contracted SARS after participating in a difficult and prolonged tracheal intubation. Some healthcare workers became infected despite wearing full personal protective equipment, including N95 respirator filters.

The Emergency Care Research Institute recommended that breathing system filters be incorporated in the expiratory limb of any ventilator used on a patient with SARS [74]. They stated that breathing circuit filters having bacterial and viral filtration efficiencies of 99.97% or greater will offer protection equal to or better than high-efficiency particulate air filters. Furthermore, they suggested considering the use of HMEs (or heated wire circuits) to minimise the moisture in the breathing system and thereby the moisture load on the filter. This is because moisture accumulating in the filter could cause an increase in expiratory resistance or cause an obstruction.

Thiessen et al. recommended the use of filters with a filtration performance equivalent to a N100 respirator facemask, i.e. 99.97% efficiency [75]. Such a filter placed between the patient and the Y-piece of the breathing system should have a moisture output of at least 32 $g.m^{-3}$. Alternatively, an HME could be used at the Y-piece and N100-equivalent filters placed on the inspiratory and expiratory limbs of the breathing system at the ventilator.

In an editorial, Kamming et al. stressed the importance of planning ahead when tracheal intubation of a patient with SARS was required [76], including the use of a high-efficiency hydrophobic filter between the facemask and breathing system or between the facemask and self-inflating bag. In the operating theatre, Kamming et al.

recommended placing a high-efficiency bacterial/viral hydrophobic filter on the expiratory circuit of the ventilator.

Peng et al. reported their practice for preventing the spread of SARS when dealing with infected patients in anaesthesia [73]. High-efficiency, low-volume, hydrophobic filters were used on both the inspiratory and expiratory limbs of the anaesthetic machine. Electrostatic filters were not considered as, according to Peng et al., they allow the passage of viruses when wet.

Influenza (H1N1 and H5N1)

Avian flu (H5N1) and swine flu (H1N1) are both types of influenza A virus that have spread rapidly around the world in the last few years. Some patients contracting avian or swine flu have required treatment in ICU. The mode of transmission of these viruses is generally considered to be by respiratory droplet from person to person.

Healthcare workers and other patients within one metre of an infected patient are at risk of contamination because of the release of infected droplets [77]. The use of high frequency oscillatory ventilation (HFOV) may benefit some patients, but standard HFOV circuits without a viral filter may be an infection hazard [77]. Thus, HFOV circuits with a viral filter are preferred.

In a special report on the epidemiology, prevention and implications for anaesthesia of avian flu, Edler et al. reported that, when general anaesthesia was required for patients with avian flu, hydrophobic filters were placed on both the inspiratory and expiratory limbs of the breathing system to decrease the spread of droplets [78].

Daugherty et al., in an article on preparation for responding to patients with the H1N1 virus, suggested that the evidence was weak on the use of filters on ventilators, but acknowledged that filters should be used on the inlet port of ventilators that draw in room air, and that heat and moisture exchangers with filters may reduce environmental contamination [79]. However, this was at an increased risk of tracheal tube occlusion and increase in resistance to gas flow.

Recommendations have been published recently by the European Society of Intensive Care Medicine's Task Force for ICU triage for use during an influenza epidemic or mass disaster [80]. Recommendations included the use of a 'high-quality bacterial/viral filter' on the expiratory port of ventilators, a 'high-quality bacterial/viral heat and moisture exchanger and filter' on the tracheal or tracheostomy tube, and a bacterial/viral filter attached to the expiratory port of the bag-mask ventilation device with another filter between the mask and valve. The use of heated humidifiers on ventilators should be avoided. Furthermore, the recommendation included the use of 'pleated filters of correct specification' on the catheter mount and exhalation port.

Ramsey et al. recommended that the ventilatory management of hypoxaemic respiratory failure attributable to infection with the H1N1 virus should be based on the acute respiratory distress syndrome (ARDS) network protocol, with a target tidal volume of 6 $ml.kg^{-1}$ [81]. This therefore has an effect on the HMEs and filters that can be used with these patients, in that devices with a large dead space would be unsuitable.

Acute lung injury and ARDS, and the ARDS network protocol

Patients receiving prolonged mechanical ventilation are susceptible to acute lung injury (ALI). This can develop further into ARDS. The use of large tidal volumes during mechanical ventilation significantly increases the risk of developing ALI [82] in addition to increasing mortality in those already suffering from ALI or ARDS [83, 84]. The use of smaller tidal volumes has implications for the use of HMEs and filters, which, when connected between the patient and the breathing system, add to the dead space of the breathing system. If the tidal volume is reduced, the fraction of the dead space attributable to the HME or filter increases and may become unacceptable.

The ARDSNet mechanical ventilation protocol summary (http://www.ardsnet.org) recommends setting the ventilator to achieve an initial tidal volume of 8 $ml.kg^{-1}$ predicted body weight and then reducing the tidal volume by 1 $ml.kg^{-1}$ at intervals of less than 2 h until the tidal volume is 6 $ml.kg^{-1}$ predicted body weight. The peak plateau pressure should be no more than 30 cmH_2O. If it is greater than this, then the tidal volume should be reduced, to a minimum of 4 $ml.kg^{-1}$. During weaning from mechanical ventilation, the goal for spontaneous tidal volume is at least 4 $ml.kg^{-1}$.

As an example, a 'standard' male patient with a predicted body weight of 70 kg would have a tidal volume of no more than 420 ml during mechanical ventilation. If the peak plateau pressure is high or during weaning from mechanical ventilation, the tidal volume could be as low as 280 ml. Some HMEs and filters have internal volumes of 100 ml or more [85]. This is more than one third of the patient's tidal volume in this case. Use of this type of device would increase rebreathing, thus increasing $P_{a}CO_2$ [86, 87].

If HMEs or HMEFs are used, their internal volumes should be as small as practical, although a high moisture output is still required. One method of expressing this is to divide the moisture output by the internal volume, to derive the moisture output per ml of internal volume [88, 89]. Heat and moisture exchangers tend to have higher moisture outputs per ml of internal volume than filters [88, 89].

Hepatitis C

In 1994, Chant et al. described an incident of suspected cross-infection of hepatitis C virus (HCV) during a minor surgical list in New South Wales, Australia [90]. Two patients, who had been operated on during the list, were subsequently diagnosed with hepatitis. Neither patient was at a high risk of developing the disease. During further investigation, it was found that three other patients out of a total of 13 patients on the same list had also developed hepatitis C, with all five patients having the same genotype (1a) of hepatitis C. This cluster of patients was extremely unlikely to have occurred by chance. All five had shared the same breathing system, as it was common practice to only change the breathing system after each list. Breathing system filters had not been used. It was hypothesised that the first patient had coughed infected secretions into the breathing system which then acted as a reservoir of infection for the remaining four patients. The two patients presented with acute hepatitis C five and seven weeks following surgery.

A second incident of cross-infection of hepatitis C was reported in 2000 [91]. In this case, a patient presented with clinical symptoms of hepatitis seven weeks after surgery. A previous patient on the same list was positive for HCV antibody and positive for HCV polymerase chain reaction. Again, no filters were used for these patients.

The case described by Chant et al. highlights the importance of protecting the patient from a contaminated breathing system, either by using a new breathing system for each patient, or by placing an appropriate filter between the patient and the breathing system.

In addition, these cases highlight the risk of cross-infection from the transmission of liquid-borne microbes present in sputum particularly, blood-stained. Hence, breathing system filters should also prevent the transmission of liquid from the patient to the breathing system and vice versa.

Following the suspected cross-infection of hepatitis C described by Chant et al., the Blood Borne Viruses Advisory Panel of the Association of Anaesthetists of Great Britain and Ireland (AAGBI) published guidelines in 1996 [92], recommending that 'either an appropriate filter should be placed between the patient and the breathing system, a new filter being used for each patient, or that a new breathing system be used for each patient.'

It was also noted that 'of the filters currently available, only those which use a pleated, hydrophobic membrane reliably prevent contamination of the breathing system'.

Pleated hydrophobic filters prevent the transmission of HCV in vitro [93]. Electrostatic filters do not prevent transmission. This is caused by the ability of liquid to pass through electrostatic filters when pressure is applied, which would take viruses (and bacteria) through as well.

The AAGBI reiterated its advice on the use of a breathing system filter for each patient in guidelines published in 2002 [94] and updated in 2008 [95]. In 2002, it noted that 'although it appears that pleated hydrophobic filters have a better filtration performance than most electrostatic filters, the clinical relevance of this has yet to be established'.

In its publication, 'Checking anaesthetic equipment', in 2003 the AAGBI reiterated its recommendation that 'A new, single-use bacterial/viral filter and angle piece/catheter mount must be used for each patient', although the type or performance was not specified [96].

More recently, the German Society of Hospital Hygiene and the German Society for Anaesthesiology and Intensive Care have issued a joint recommendation on the use of filters to prevent infection during ventilation in anaesthesia [97]. If a filter is used, the breathing system can be used for up to 7 days provided that it is checked and is functioning as intended and that the manufacturer has declared this in the instructions for use. If a filter is used, its filtration performance for airborne particles, measured using particles of the most penetrating size, should be better than 99%, and it should be able to withstand an applied pressure of 60 hectopascals ($\approx$60 cmH_2O) without allowing liquid to pass through, or 20 hectopascals above the set pressure limit in the breathing system.

Use of HMEs and filters with paediatric patients

Provision of humidification and filtration of gases delivered to paediatric patients using HMEFs is controversial. This patient group is particularly susceptible to increases in dead space and resistance to gas flow. Furthermore, children are more likely to be susceptible to infection and less able to cope with reduced levels of humidity. In addition, the ability of filters intended for paediatric use to prevent the transmission of microbes effectively has been questioned. However, there is evidence that HMEs and HMEFs can be used successfully with this patient group.

The incidence of nosocomial pneumonia in children is about 22% in paediatric ICUs [98]. In intensive care, as with adult patients, children who succumb to an incident VAP have a greater need for mechanical ventilation (12 vs 22 ventilator-free days), longer ICU stay (6 vs 13 median ICU-free days), higher total median hospital costs ($308 534 vs $252 652) and increased absolute hospital mortality (10.5% vs 2.4%) than those without VAP [99]. However, the effect of the use of filters on the incidence of VAP in this group of patients has not been studied.

Use of ineffectively reprocessed breathing systems can lead to an increase in morbidity and mortality. In one reported this may outbreak of *Bacillus cereus* respiratory tract infections associated with the breakdown of a low

temperature steam disinfector used to reprocess breathing systems, six of thirteen neonates became infected, three of whom died [100].

Breathing system filters are available for use with children weighing at least 3 kg to reduce the transmission of microbes [101]. Luchetti et al. demonstrated that two small electrostatic HMEFs, the Hygrobaby and Hygroboy, provided humidified gases to children weighing up to 10 kg and more than 10 kg, respectively, with moisture contents of more than 20 $g.m^{-3}$ throughout the operation, increasing up to 26 and 27 $g.m^{-3}$, respectively, by the end of the study period [102]. The moisture content of gases delivered to patients using a pleated filter-only product in a different study with older and larger children (mean (SD) 48 (20) months; 16 (3.5 kg) was about 22 $g.m^{-3}$ [103]. Heat and moisture exchanges also provide adequate humidification to children during anaesthesia [104, 105].

With very small children, the practice has been to use uncuffed tracheal tubes. This means that some of the moisture in the expired gas does not reach the HME because of the leak around the tracheal tube, and is therefore not available to humidify the gas delivered to the patient. This causes a reduction in the performance of HMEs [106] although this may still be adequate [107]. However, in a large randomised controlled trial comparing cuffed and uncuffed tracheal tubes, the use of cuffed tracheal tubes did not cause an increase in stridor and hence, by implication, did not cause an increase in trauma [108]. The routine use of cuffed tracheal tubes would improve the moisture-conserving performance of HMEs.

The performance of HMEs has been compared with heated humidifiers in intensive care. Fassassi et al. demonstrated that HMEs can provide moisture outputs of at least 28 $g.m^{-3}$ [109]; Schiffmann et al. measured moisture outputs of 34 $g.m^{-3}$ [110].

It is also important to consider the addition of dead space [111] and resistance to gas flow when using HMEs or filters in children. The lower weight limit of patients suitable for use with HMEs is probably 2.5 kg, and 3 kg for filters [112]. The work of breathing increases when HMEFs are used [113]. The resistance to gas flow of an HMEF added to a Mapleson F breathing system can cause a delay in the induction of anaesthesia [114]. The addition of an HME can cause hypercapnia if the internal volume of the HME is too large [115]. Loading an HME with water can cause an excessive increase in resistance to gas flow [116].

The Medicines and Healthcare products Regulatory Agency published a report in 2004 on the filtration performance of 104 different breathing system filters available on the UK market [85]. Thirty-four of the filters were intended for, or were an appropriate size for, use with paediatrics. Six filters, all electrostatic with an internal volume of 10 to 16 ml, were suitable for use with small infants. The penetration of particles through adult and paediatric filters was measured using a flow of air of 30 and 15 $l.min^{-1}$, respectively. However, the Association of Paediatric Anaesthetists considered that a flow of 15 $l.min^{-1}$ was too high for filters intended for use with small infants [117]. Further work has now demonstrated that penetration of particles through filters intended for use with small infants can be substantially lower (and hence the filtration efficiency is higher) when the flow is reduced [118, 119].

Conclusions

Patients can acquire infections from equipment used during anaesthesia and intensive care. Breathing systems can be a source of contamination. The use of filters is recommended to reduce the risk of cross-infection during anaesthesia if the breathing system is used for more than one patient.

During anaesthesia with circle breathing systems, where condensation can occur, the use of electrostatic filters might increase the risk of blockage because of ingress and absorption of water. However, this risk can be reduced by placing the filter above the level of the patient and the breathing system so that any liquid flows away from the filter. Condensation is easier to detect visually in pleated filters and these filters also prevent the transmission of water under normal ventilatory pressures. However, viscous sputum and nebulised drugs can block these filters. It is important that users are aware of this scenario and that the high pressures found in such situations are not misdiagnosed.

The use of HMEs or filters, rather than heated humidifiers, does not reduce the incidence of ventilator-associated pneumonia. However, the use of filters with patients known to have particularly infectious diseases is recommended to prevent cross-infection, although there is no evidence that the incidence of cross-infection is reduced by using filters. As an adequate moisture output is essential for patients receiving prolonged mechanical ventilation, a useful performance indicator for filters and HMEs is the moisture output per ml of internal volume.

Competing interests

This review was based on a project carried out for Covidien plc, funded though a contract between Covidien and Cardiff University. AW has received conference expenses from Pall Medical, and Cardiff University has received payment from Pall Medical for AW's speaking at a meeting. AW did not gain financially from either arrangement.

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